THE SIMULATION OF A JUMBO JET TRANSPORT AIRCRAFT
VOLUME II: MODELING DATA

D6-30643

Prepared by

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Wichita Division Wichita, Kansas

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Ames Research Center Moffett Field, California
PREFACE

This report summarizes all work conducted by The Boeing Company under Task II of Contract NAS2-5524, "Design for the Simulation of Advanced Aircraft". The National Aeronautics and Space Administration Technical Monitor was John Dusterberry of the Simulation Sciences Division. The Boeing Company Project Leader was Mr. C. Rodney Hanke of the Wichita Division Stability, Control and Flying Qualities Organization. Technical assistance was provided by Mr. Robert A Curnutt of the 747 Aerodynamics Staff in Everett, Washington.
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1.0 INTRODUCTION

The Boeing Company provided NASA-Ames Research Center with mathematical models and data to simulate the flying qualities and characteristics of the Boeing 747 on the NASA Flight Simulator For Advanced Aircraft (FSAA).

The contractual report is divided into two volumes. Volume I includes a description of:

1. The work performed under the contract.
2. Generalized equations and approximations used in the simulation.
3. The form of the data furnished to NASA.
4. Nomenclature used for the report.

Volume II contains only limited rights data. These data are to be retained within the Government until the Boeing Company chooses to treat the data as non-proprietary or until September 15, 1971, whichever occurs first.

This document has been prepared as a summary of the 747 aerodynamic data for use in flight simulator design. This introductory section contains a description of the 747 including its flight envelope, a general description of the control systems, and a short discussion of the simulation. The following six sections of the document present the airplane aerodynamic characteristics: lift, drag, pitching moment, rolling moment, yawing moment, and side force coefficients. The next three sections describe the control characteristics for pitch, roll and yaw in the various operating modes.

Sections 11, 12 and 13 describe the characteristics of the high lift system, propulsion system and landing gear. The final section contains the results of the simulation checkout.
The appendices contain a portion of the 747 Flight Manual, buffet characteristics, autothrottle, autopilot and revised simulation data.
AIRPLANE DESCRIPTION

The Boeing 747 is a very large four-fanjet intercontinental transport designed to operate from existing international airports. To obtain the necessary low speed characteristics the wing has triple-slotted trailing flaps and Krueger type leading edge flaps. The Krueger flaps outboard of the inboard nacelle are variable cambered and slotted while the inboard Krueger flaps are standard unslotted. The main landing gear consists of a pair of wing mounted four-wheel trucks and a pair of body mounted four-wheel trucks which are slightly aft of the wing. A load equalizing system between the trucks on each side with limited travel allows the center of pitch rotation to be midway between the two pairs of trucks. Longitudinal control is obtained through four elevator segments and a movable stabilizer. The lateral control employs five spoiler panels, an inboard aileron between the inboard and outboard flaps, and an outboard aileron which operates with flaps down only on each wing. The five spoiler panels on each wing also operate symmetrically as speedbrakes in conjunction with the most inboard sixth spoiler panel. Directional control is obtained from two rudder segments. A general arrangement drawing showing these controls and pertinent dimensions is on page 1.1-2. A summary of areas and dimensions necessary for simulation is on page 1.1-3. The airplane operating limits and placards are shown on page 1.1-4.
## SUMMARY OF AREAS AND DIMENSIONS

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Note: The transition between the ground and air values for the effective engine pitching arms, $Z_E$ and $Z_E$, is a function of the averaged main landing gear compression ratio, $\eta$.

For $0 < \eta < 1$, 
\[ Z_E = Z_{E\text{air}} + \eta \Delta Z_E \]
\[ Z_E = Z_{E\text{air}} + \eta \Delta Z_E \]

where \[ \Delta Z_E = Z_{E\text{ground}} - Z_{E\text{air}} = 1.9 \text{ Ft.} \]
\[ \Delta Z_E = Z_{E\text{ground}} - Z_{E\text{air}} = -5.4 \text{ Ft.} \]

and \[ \eta = \frac{1}{36} \sum_{n_E} \text{Main Landing Gear Oleo Compression (inches).} \]

SEE SECTION 19
FOR REVISED DATA
CENTER OF GRAVITY LIMITS

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CALC  CHECK  APR  INK  ODEGARD  LOW  1-20-70  REVISED  DATE

747

D6-30643  Vol. II

PAGE 1-1-5
Gross Weight - 10,000 lb

Izz, Body Axis Moment of Inertia

THE BOEING COMPANY

CALC
CHECK
APR
APR
DRN JUNE 1970

747

VOL II

PAGE 1.1-8
1.2 **FLIGHT CONTROL SYSTEMS**

All primary flight control surfaces are powered by irreversible hydraulic actuators supplied by four independent hydraulic systems. Each segment of the elevators, rudders and ailerons is driven by a single "dual-tandem" type actuator powered by various hydraulic system combinations. The flight and ground spoilers are driven by conventional single cylinder actuators individually supplied by three of the four hydraulic systems. A hydraulic schematic showing the distribution of the four hydraulic systems to the control surface actuators is shown on page 1.2-7.

All control actuators have input overtravel capability to allow unrestricted control input motion to the remaining surfaces when a given actuator is inoperative. There is no manual reversion capability on any surface in the event total hydraulic power is lost.

1.2.1 **Longitudinal Controls**

The longitudinal control system consists of four elevator segments and a trimmable stabilizer.

**Elevators**

Each of the four elevator segments is independently powered by dual-tandem actuators. Each inboard elevator actuator is powered by two hydraulic systems and each outboard elevator actuator by one hydraulic system as shown on page 1.2-7.

The inboard elevators are controlled from the aft quadrant while
the outboard elevators are slaved by a control cable system to
the opposite inboard elevator surface. If hydraulic power to
any segment is lost the segment will trail at an angle where
the hinge moment is zero.

An artificial feel system is used to program the feel forces
which consists of a hydraulic "q" spring modulated with sta-
bilizer setting and a mechanical centering spring. The system
is powered by hydraulic system numbers 2 and 3 normally with
number 1 as a backup to number 3. Any one system will provide
normal feel forces.

Stabilizer

The trimmable stabilizer is actuated by two hydraulic motors
driving a single jackscrew. The power available with one or
both motors is the same, but the trim rate with one motor is one-
half that with both motors operating. Each motor has a rate
control which varies the rate for both motors operating from
0.5 deg./sec. at low speeds to 0.2 deg./sec. at high speed.
Simultaneous control of both motors is obtained either elec-
tically by the thumb switch on each control wheel or mechanically
by the control stand levers which override any electrical input
signal. The autopilot system will operate either hydraulic
motor.

1.2.2 Lateral Controls

The lateral control system comprises a combination of inboard
and outboard ailerons and spoilers which also can be used as
1.2 speedbrakes. Two dual-tandem central control actuators located in the wheel wells drive independent cable systems to the left and right wing lateral control surfaces. Pilot input to the central control actuators is provided by a cable system from each of the pilot and co-pilot control wheels.

Ailerons

Both inboard and outboard ailerons are actuated by dual-tandem actuators. The inboard ailerons operate in all flight conditions, but the outboard ailerons operate with flaps down only. A lockout mechanism which is actuated electrically by a switch on the outboard flap follow-up linkage, positions the outboard aileron actuators to neutral with flaps up. When both hydraulic systems to any aileron surface are inoperative the surface will trail at an angle where the hinge moment is zero.

Spoilers

There are six spoiler panels on each wing, five which are modulated with lateral control and speedbrake inputs and one (the most inboard panel) which is an unmodulated speedbrake only. Each panel is actuated by a single hydraulic actuator which has a check valve to prevent the panel from floating up to a zero hinge moment angle when the hydraulic system is inoperative. The five modulated panels on each wing are controlled from two "mixer boxes" which sum the inputs from the pilot's speedbrake handle and the central
1.2 Control actuators. Lateral control inputs will move the spoiler panels up or down within the travel limits at any speedbrake setting.

The speedbrake operation of the spoilers is divided into two functions. Moving the speedbrake handle to the "inflight" detent will raise spoiler panels 3, 4, 5 and 8, 9, 10 which are controlled through one mixer box to full deflection or blowdown angle. Before the "inflight" detent is reached, moving the speedbrake handle will raise spoiler panels 6 and 7 which are controlled directly by a two position solenoid valve, to full deflection or blowdown angle.

Further handle movement to the ground detent position is possible only on the ground and will raise the remaining panels through the other mixer box.

Wheel forces are provided with a simple spring loaded follower and cam arrangement. Trim is obtained by rotating this mechanism with an electric servo motor and shifting the zero wheel force datum to the wheel angle desired. The servo motor is operated by a switch on the control stand.

1.2.3 Directional Controls

The directional control system consists of two rudder segments, each being actuated by a dual-tandem actuator. Rudder limiting is provided by a "q" programmed gear ratio changer which limits the rudder available from full pedal travel. Each rudder has a ratio changer with a comparator circuit to monitor their operation. If the two ratio changers disagree beyond the system tolerance
1.2 limits, a warning light in the cockpit is activated. There are certain conditions such as one hydraulic system off operation where rudder available will be limited by actuator force capability to smaller angles than the ratio changer allows.

The rudder pedal forces are programmed by a spring loaded follower and cam arrangement similar to the lateral feel system. However, the ratio changer varies the pedal force required to obtain a given rudder angle with airspeed. This is done by installing the ratio changer between the feel system and the actuator input.

Rudder trim is obtained by rotating the feel unit with the trim knob on the control stand. The trim authority is also a function of airspeed due to the ratio changer function.

A series type yaw damper and turn coordinator system is incorporated into each rudder actuator. Rudder inputs from these systems will add to the inputs from the pedals or trim but will not feed back through the control system.

1.2.4 Flaps

The flap system consists of leading edge flaps and trailing edge flaps as shown on page 1.1-2.

The leading edge flaps comprise four sets per wing, each set being powered by a separate air motor or, as a backup, by a separate electric motor. The leading edge flaps are two-positioned (fully retracted or extended) and are programmed to operate in conjunction
1.2 with the trailing edge flaps. Group A comprising leading edge flap sets (6, 7, 8), (11, 12, 13) / (14, 15, 16), (19, 20, 21) extend fully when the outboard trailing edge flaps extend to flaps 1. As the inboard trailing edge flaps extend to flaps 5, group B comprising the remaining leading edge flap sets (1, 2, 3, 4, 5), (9, 10) / (17, 18), (22, 23, 24, 25, 26) extend fully.

The two inboard trailing edge flaps are actuated by one power drive system, the two outboard by another. Each drive system consists of a hydraulic motor (see page 1.2-7) coupled through gears to a torque tube extending laterally along both wings. Each trailing edge flap is driven by two ball screw actuators powered by the turning of the appropriate torque tube. Each drive system has an electric motor for backup power. During trailing edge flap extension or retraction, an inboard trailing edge flaps asymmetry monitor automatically causes hydraulic shutoff to the inboard trailing edge flaps when the position difference between the right and left inboard trailing edge flaps exceeds a predetermined amount. An outboard trailing edge flaps asymmetry monitor operates similarly.
DISCUSSION OF THE SIMULATION

An aircraft in motion is acted upon by external forces and moments resulting from thrust and gravity effects, landing gear forces, and aerodynamic loads. These force and moment components comprise the coefficients of the airplane equations of motion, which are the key to a realistic description of the aircraft's flight characteristics.

Aircraft flight simulation, then, requires continuous, real-time solution of these equations of motion, as well as an accurate representation of those systems and characteristics necessary to allow the pilot to "fly" the simulator with sufficient realism.

This document contains data which describe the forces and moments created by aerodynamic loads on the airplane. They may be functions of several variables, including altitude, airspeed, Mach number, angle of attack, rotation rates, center of gravity, ground proximity and geometry changes, such as control deflections and gear and flap extensions.

The data contained in the following sections are computed about stability axes \((x_b, y_b, z_b)\) as shown on page 1.3-4. Stability axes differ from body axes in that the x- and z-axes are rotated about the y-axis through the angle of attack; that is, the \(x_b\)-axis lies in the plane determined by the relative wind and the body y-axis. This \(x_b\)-axis also lies in the \((x-z)\) plane of symmetry of the
1.3 airplane and is thus rotated about \( z_b \) away from the relative wind (Cont'd) by sideslip angle, \( \beta \). Forces and moments measured in this system are presented as dimensionless coefficients which are broken down into separate terms (stability derivatives) showing the effects of each important parameter.

While the use of stability axes simplifies the presentation of the aerodynamic functions, the forces and moments must be resolved to the appropriate axes systems for solution of the equations of motion. The schematic flow chart on Page 1.3-5 presents the method used to solve the dynamic equations in which the aerodynamic forces and moments are transformed into body axes. Note that the appropriate axis transformation here is to the fuselage reference line (FRL) body axes, or through the angle \( \alpha \) F.R.L. This allows the direct use of body axis inertias, \( I_{xx}, I_{yy}, I_{zz}, \) and \( I_{xz} \) without any inertia transformations. Note also that the wing angle of attack \( (\alpha_{W.D.P.} = \alpha_{F.R.L.} + 20^\circ) \) is used only in conjunction with the aerodynamic data curves - it is not used for any axis transformations.

A second item of importance is the simulation of forces and moments due to thrust. Flight testing has shown that a simple effective engine moment-arm representation accounts for thrust.
At present, the thrust vector may be considered to be inclined up (Cont'd) $2.5^\circ$ from the fuselage reference line, with each engine canted inward by $2^\circ$. The corresponding thrust effects are as follows:

\[
T_x = T_{\text{eng.} \ #1} + T_{\text{eng.} \ #2} + T_{\text{eng.} \ #3} + T_{\text{eng.} \ #4}
\]

\[
T_y = .0349 \ (T_{\#1} + T_{\#2} - T_{\#3} - T_{\#4})
\]

\[
T_z = -.0436 \ T_x
\]

\[
L_T = .0436 \ N_T
\]

\[
M_T = (T_{\#1} + T_{\#4}) \cdot Z_{E_0} + (T_{\#2} + T_{\#3}) \cdot Z_{E_1}
\]

\[
N_T = (T_{\#1} + T_{\#4}) \cdot Y_{E_0} + (T_{\#2} - T_{\#3}) \cdot Y_{E_1}
\]

The effective engine moment arm values are found on page 1.1-3.

The thrust reverser effects on the lift, drag and pitching moment coefficients are presented in Section 12.5. These increments are to be added to the equations for $C_L$, $C_D$ and $C_{m_c.g.}$ on pages 2.0-1, 3.0-1 and 4.0-1 respectively.

Sign conventions for the controls and aerodynamic coefficients are shown on page 1.3-6, while maximum control deflections are listed on page 1.3-7.

To aid in scaling, a list of maximum values is given on page 1.3-8, and a summary of nomenclature begins on page 1.3-9.
x, y, z - BODY AXES (FRL)

x_w, y_w, z_w - WIND AXES

x_s, y_s, z_s - STABILITY AXES

AXES ORIGIN AT THE CENTER OF GRAVITY
POSITIVE STABILIZER DEFLECTION ~ L.E. UP
FOR INDIVIDUAL AILERONS, $+\varepsilon_a$ ~ T.E. DOWN
FOR AILERONS ON BOTH WINGS, $+\varepsilon_a$ ~ L.H. WING T.E. DN.
R.H. WING T.E. UP

RIGHTWING SPOILER DEFLECTION IS POSITIVE.

SIGN CONVENTION
(Stability Axes)

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THE BOEING COMPANY
BENTON, WASHINGTON

PAGE 1-3-6
### Maximum Control Surface Deflection and Rates

<table>
<thead>
<tr>
<th>Control Surface</th>
<th>Symbol</th>
<th>Maximum Displacement (deg)</th>
<th>Normal Operation (Full Boost) Rate (deg/sec)</th>
<th>One Hydraulic System Failure Rate (deg/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevators</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inboard</td>
<td>εEI</td>
<td>+17</td>
<td>37 down</td>
<td>30 down</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-23</td>
<td>37 up</td>
<td>26 up</td>
</tr>
<tr>
<td>Outboard</td>
<td>εEO</td>
<td>+17</td>
<td>37 down</td>
<td>30 down</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-23</td>
<td>37 up</td>
<td>26 up</td>
</tr>
<tr>
<td>Stabilizer</td>
<td>ΔF.R.L.</td>
<td>+ 0.5</td>
<td>0.5 → 0.2</td>
<td>0.25 → 0.1</td>
</tr>
<tr>
<td>Pilot's Thumb</td>
<td></td>
<td>-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switch</td>
<td></td>
<td>+ 3</td>
<td>0.5 → 0.2</td>
<td>0.25 → 0.1</td>
</tr>
<tr>
<td>Control Stand</td>
<td></td>
<td>-12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Levers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ailerons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inboard</td>
<td>εAI</td>
<td>+20</td>
<td>40 down</td>
<td>27 down</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-20</td>
<td>45 up</td>
<td>35 up</td>
</tr>
<tr>
<td>Outboard</td>
<td>εAO</td>
<td>+15</td>
<td>45 down</td>
<td>22 down</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-25</td>
<td>55 up</td>
<td>45 up</td>
</tr>
<tr>
<td>Spoilers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panels 1, 2, 3, 4</td>
<td>εSP</td>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panels 9, 10, 11, 12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panels 5, 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panels 6, 7 (Speedbrakes only)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rudder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper</td>
<td>εRU</td>
<td>±25</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Lower</td>
<td>εRL</td>
<td>±25</td>
<td>50</td>
<td>40</td>
</tr>
</tbody>
</table>

**Note:** The deflection rates shown above are average values applicable to all flight conditions. The actual non-linear deflection rate response characteristics are presented in D6-13336, "Flight Control Systems Data For The 747 Flight Simulator".

**Footnote:** NASA simulation used a control wheel rate limit of 100 deg/sec in place of individual control rate limits.
# MAXIMUM VALUES

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Maximum Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_x$</td>
<td>30</td>
<td>ft/sec²</td>
</tr>
<tr>
<td>$a_y$</td>
<td>25</td>
<td>ft/sec²</td>
</tr>
<tr>
<td>$a_z$</td>
<td>120</td>
<td>ft/sec²</td>
</tr>
<tr>
<td>$\ddot{\theta}$</td>
<td>50</td>
<td>deg/sec²</td>
</tr>
<tr>
<td>$\ddot{\phi}$</td>
<td>130</td>
<td>deg/sec²</td>
</tr>
<tr>
<td>$\ddot{\psi}$</td>
<td>30</td>
<td>deg/sec²</td>
</tr>
<tr>
<td>$\dot{\theta}$</td>
<td>60</td>
<td>deg/sec</td>
</tr>
<tr>
<td>$\dot{\phi}$</td>
<td>75</td>
<td>deg/sec</td>
</tr>
<tr>
<td>$\dot{\psi}$</td>
<td>30</td>
<td>deg/sec</td>
</tr>
<tr>
<td>$\dot{\alpha}$</td>
<td>40</td>
<td>deg/sec</td>
</tr>
<tr>
<td>$\dot{\phi}$</td>
<td>30</td>
<td>deg/sec</td>
</tr>
<tr>
<td>Altitude</td>
<td>45000</td>
<td>ft</td>
</tr>
<tr>
<td>Rate of Climb</td>
<td>15000</td>
<td>ft/min</td>
</tr>
<tr>
<td>Rate of Descent</td>
<td>15000</td>
<td>ft/min</td>
</tr>
<tr>
<td>Center of Gravity Range</td>
<td>0-40</td>
<td>%MAC</td>
</tr>
</tbody>
</table>

**NOTE:** For complete center of gravity information consult D6-13585, "Mass Properties - 747 Flight Simulator".
<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_i$</td>
<td>Acceleration along the &quot;i&quot; axis (ft/sec$^2$)</td>
</tr>
<tr>
<td>$b$</td>
<td>Wing span (ft)</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Airplane drag coefficient. $C_D = \frac{D}{qS}$, where a positive drag force acts along the negative $x_s$ axis.</td>
</tr>
<tr>
<td>$C_L$</td>
<td>Airplane lift coefficient. $C_L = \frac{L}{qS}$, where a positive lift force acts along the negative $z_s$ axis.</td>
</tr>
<tr>
<td>$C_Y$</td>
<td>Airplane side force coefficient. $C_Y = \frac{Y}{qS}$, where a positive side force acts along the positive $y_s$ axis.</td>
</tr>
<tr>
<td>$C_l$</td>
<td>Airplane rolling moment coefficient about the reference axis, $x_s$. $C_l = \frac{L}{qSb}$</td>
</tr>
<tr>
<td>$C_m$</td>
<td>Airplane pitching moment coefficient about the reference axis, $y_s$. $C_m = \frac{M}{qS\ell}$</td>
</tr>
<tr>
<td>$C_n$</td>
<td>Airplane yawing moment coefficient about the reference axis, $z_s$. $C_n = \frac{N}{qSb}$</td>
</tr>
<tr>
<td>C.G.</td>
<td>Airplane center of gravity position as a fraction of the wing mean aerodynamic chord.</td>
</tr>
<tr>
<td>C.M.A.C.</td>
<td>Wing mean aerodynamic chord (ft).</td>
</tr>
<tr>
<td>$F_p$</td>
<td>Rudder pedal force, positive for a left rudder pedal force (lb).</td>
</tr>
<tr>
<td>$F_s$</td>
<td>Control column force, positive for a column pull force (lb).</td>
</tr>
<tr>
<td>$F_w$</td>
<td>Control wheel force, positive for a clockwise wheel moment (lb).</td>
</tr>
<tr>
<td>SYMBOL</td>
<td>DEFINITION</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>HM</td>
<td>Hinge moment (lb-ft).</td>
</tr>
<tr>
<td>h_p</td>
<td>Pressure altitude (ft).</td>
</tr>
<tr>
<td>I_{ij}</td>
<td>Airplane mass moment of inertia about the reference axes i, j (slug-ft²).</td>
</tr>
<tr>
<td>L,M,N</td>
<td>Rolling, pitching and yawing moments about a reference axes system.</td>
</tr>
<tr>
<td>M</td>
<td>Mach number.</td>
</tr>
<tr>
<td>n_{z}</td>
<td>Airplane normal load factor along the z-axis.</td>
</tr>
<tr>
<td>$p,q,r$</td>
<td>Roll, pitch and yaw rates about a reference axes system (radians/sec).</td>
</tr>
<tr>
<td>$q$</td>
<td>Dynamic pressure (lb/ft²).</td>
</tr>
<tr>
<td>$q_c$</td>
<td>Impact pressure (lb/ft²).</td>
</tr>
<tr>
<td>$S$</td>
<td>Wing area (ft²).</td>
</tr>
<tr>
<td>$T$</td>
<td>Engine thrust (lb).</td>
</tr>
<tr>
<td>V</td>
<td>True airspeed (ft/sec).</td>
</tr>
<tr>
<td>$V_c$</td>
<td>Calibrated airspeed (knots).</td>
</tr>
<tr>
<td>$V_e$</td>
<td>Equivalent airspeed (knots).</td>
</tr>
</tbody>
</table>

$$n_z = \frac{-Z_S \cos \alpha - X_S \sin \alpha + 0.0436T}{mg}$$

$$q = \frac{1}{2} \rho V^2 = \frac{V_e^2}{295.4}$$

$$q_c = P_{TOTAL} - P_{STATIC} = 2116.2166 \delta [(1 + 2M^2)^{3.5} - 1]$$

$$S = \text{Wing area (ft}^2).$$

$$V = \text{True airspeed (ft/sec).}$$

$$V_c = 1479.1026 \sqrt{\frac{q_c}{2116.2166 + 1}^{2/3} - 1}$$

$$V_e = \sigma^{1/2} \cdot V / 1.689$$
<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>Airplane gross weight (lb).</td>
</tr>
<tr>
<td>X,Y,Z</td>
<td>Axial force, side force, and normal force along a reference system.</td>
</tr>
<tr>
<td>X,Y,Z</td>
<td>Body axes system described in Section 1.3.</td>
</tr>
<tr>
<td>Xs, ys, zs</td>
<td>Stability axes system described in Section 1.3.</td>
</tr>
<tr>
<td>Xw, Yw, Zw</td>
<td>Wind axes system described in Section 1.3.</td>
</tr>
<tr>
<td>YeI</td>
<td>Effective inboard engine yawing arm (ft).</td>
</tr>
<tr>
<td>YeO</td>
<td>Effective outboard engine yawing arm (ft).</td>
</tr>
<tr>
<td>ZeI</td>
<td>Effective inboard engine pitching arm (ft).</td>
</tr>
<tr>
<td>ZeO</td>
<td>Effective outboard engine pitching arm (ft).</td>
</tr>
<tr>
<td>α, αf,r,l</td>
<td>Airplane angle of attack relative to the fuselage reference line (degrees).</td>
</tr>
<tr>
<td>αw,d,p</td>
<td>Airplane angle of attack relative to the wing design plane (degrees).</td>
</tr>
<tr>
<td>β</td>
<td>Airplane sideslip angle (degrees).</td>
</tr>
<tr>
<td>δ</td>
<td>Air pressure ratio.</td>
</tr>
<tr>
<td>δa</td>
<td>Aileron deflection angle (degrees).</td>
</tr>
<tr>
<td>δai</td>
<td>Inboard aileron deflection angle (degrees).</td>
</tr>
<tr>
<td>δao</td>
<td>Outboard aileron deflection angle (degrees).</td>
</tr>
<tr>
<td>δc</td>
<td>Control column deflection angle, positive for rearward column movement (degrees).</td>
</tr>
<tr>
<td>δe</td>
<td>Elevator deflection angle (degrees).</td>
</tr>
<tr>
<td>δei</td>
<td>Inboard elevator deflection angle (degrees).</td>
</tr>
<tr>
<td>δeo</td>
<td>Outboard elevator deflection angle (degrees).</td>
</tr>
<tr>
<td>δf</td>
<td>Flap setting</td>
</tr>
<tr>
<td>SYMBOL</td>
<td>DEFINITION</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>δ_p</td>
<td>Rudder pedal deflection angle, positive for positive rudder deflection (degrees).</td>
</tr>
<tr>
<td>δ_r</td>
<td>Rudder deflection angle (degrees).</td>
</tr>
<tr>
<td>δ_r_l</td>
<td>Lower rudder deflection angle (degrees).</td>
</tr>
<tr>
<td>δ_r_u</td>
<td>Upper rudder deflection angle (degrees).</td>
</tr>
<tr>
<td>δ_s_p</td>
<td>Spoiler deflection angle (degrees).</td>
</tr>
<tr>
<td>δ_w</td>
<td>Control wheel deflection angle, positive for a clockwise wheel movement (degrees).</td>
</tr>
<tr>
<td>α_f_r_l</td>
<td>Horizontal stabilizer angle relative to the fuselage reference line (degrees).</td>
</tr>
<tr>
<td>θ</td>
<td>Airplane Euler pitch angle.</td>
</tr>
<tr>
<td>φ</td>
<td>Airplane Euler roll angle.</td>
</tr>
<tr>
<td>ψ</td>
<td>Airplane Euler yaw angle.</td>
</tr>
<tr>
<td>ρ</td>
<td>Air mass density (slugs/ft³).</td>
</tr>
<tr>
<td>σ</td>
<td>Air density ratio</td>
</tr>
</tbody>
</table>

**SUBSCRIPT**

| F.R.L. | Fuselage reference line (any body water line). |
| W.D.P. | Wing design plane. |

As used with $V_E$ and $M$ placards:

| FE | Operational flaps extended placard. |
| LO | Landing gear operating placard. |
| LE | Landing gear extended placard. (Note: The landing gear cannot be extended above the LO limit, but flight to LE limits is possible). |
SUBSCRIPT

MO = Maximum operating limit.

DF = Design dive flight placard.

The time derivative operation normally denoted by $\frac{d}{dt}$ is replaced in this document by the dot derivative notation, $\frac{d(\_)}{dt} = (\ ')$ AND $\frac{d^2(\_)}{dt^2} = (\ ' ')$. 
LIFT FORCE COEFFICIENT

The dimensionless aerodynamic lift force coefficient is given in terms of its significant components by the equation below.

At a given $\alpha_{W,D,R}$,

$$C_L = C_{LBASIC} + (AC_L)_{\alpha_{W,D,R}=0^\circ} + \Delta \left( \frac{dC_L}{d\alpha} \right) \cdot \alpha_{W,D,R}$$

$$+ \frac{dC_L}{d\alpha} \cdot \left( \frac{\alpha \cdot \bar{E}}{2V} \right) + \frac{dC_L}{d\alpha} \cdot \left( \frac{\bar{E} \cdot \bar{E}}{2V} \right) + \frac{dC_L}{dn} \cdot n \bar{z}$$

$$+ K_\alpha \cdot \frac{dC_L}{d\alpha} \cdot \alpha_{R.L} + K_\alpha \cdot \frac{dC_L}{de} \cdot \delta_{E,L} + K_\alpha \cdot \frac{dC_L}{de} \cdot \delta_{E,O}$$

$$+ \Delta C_L \text{ SPOILERS} + \Delta C_L \text{ OUTBOARD AILERONS} + \Delta C_L \text{ LANDING GEAR}$$

$$+ \Delta C_L \text{ GROUND EFFECT} + \left[ \Delta C_L \text{ FLAP FAILURE} \right]$$

where,

$$C_{LBASIC}$$ = Basic lift coefficient for the rigid airplane at $\alpha_{R.L} = 0^\circ$, in free air and with the landing gear retracted. For low speed, $C_{LBASIC}$ is plotted on page 2.0-7. For flaps up, $C_{LBASIC}$ is plotted on page 2.0-8.

$$(AC_L)_{\alpha_{W,D,R}=0^\circ}$$ = Change in basic lift coefficient at $\alpha_{W,D,R} = 0^\circ$ due to aeroelasticity. For low speed, $(AC_L)_{\alpha_{W,D,R}=0^\circ}$

[ ] NOT IN NASA SIMULATION
is plotted on page 2.0-9. For flaps up, \( \Delta (dC_L)_{\alpha_{W.D.R.}} = 0^\circ \)
is plotted on page 2.0-10.

\( \Delta (dC_L)_{\alpha_{W.D.R.}} \) = Change in basic lift coefficient due to the aeroelastic effect on the rigid airplane basic lift coefficient curve slope. For low speed, \( \Delta \left( \frac{dC_L}{d\alpha} \right) \) is plotted on page 2.0-11. For flaps up, \( \Delta \left( \frac{dC_L}{d\alpha} \right) \) is plotted on page 2.0-12.

\[ \frac{dC_L}{d\alpha} \left( \frac{\alpha E}{\alpha V} \right) \] = Change in basic lift coefficient due to rate of change of angle of attack. \( \frac{dC_L}{d\alpha} \) is plotted on page 2.0-13.

\[ \frac{dC_L}{d\alpha} \left( \frac{\alpha E}{\alpha V} \right) \] = Change in basic lift coefficient due to pitch rate.

\[ \frac{dC_L}{d\dot{\alpha}} = K\dot{\alpha} \cdot \frac{dC_L}{d\dot{\alpha}} \]

where \( \frac{dC_L}{d\dot{\alpha}} \) and the center of gravity factor, \( K_{c} \) are plotted on page 2.0-14.

\[ \frac{dC_L}{dn_z} \] = Change in basic lift coefficient due to aeroelastic inertia relief caused by normal load factor, \( n_z \).

For low speed, \( \frac{dC_L}{dn_z} \) is plotted on page 2.0-15.

For flaps up, \( \frac{dC_L}{dn_z} \) is plotted on page 2.0-16.

\[ K_{c} \cdot \frac{dC_L}{d\alpha} \cdot \alpha_{R.L.} \] = Change in basic lift coefficient due to change in stabilizer angle from \( \alpha_{F.R.L.} = 0^\circ \). \( \frac{dC_L}{d\alpha} \) is plotted on page 2.0-17. The effectiveness factor for the
2.0 stabilizer (and elevators), $K_{\alpha}$ is plotted on page 4.0-19.

$$K_{\alpha} \cdot \frac{dC_L}{d\delta_{E_{in}}} = \text{Change in basic lift coefficient due to change in inboard elevator angle from } \delta_{E_{in}} = 0^\circ.$$  $\frac{dC_L}{d\delta_{E_{in}}}$ is plotted on page 2.0-18.

$$K_{\alpha} \cdot \frac{dC_L}{d\delta_{E_{out}}} = \text{Change in basic lift coefficient due to change in outboard elevator angle from } \delta_{E_{out}} = 0^\circ.$$  $\frac{dC_L}{d\delta_{E_{out}}}$ is plotted on page 2.0-19.

The normal system stick free (rigged) elevator deflection is $+20^\circ$ from the faired position.

$\Delta C_L^{\text{spoilers}} = \text{Change in basic lift coefficient due to spoiler or speedbrake deflection.}$  It should be noted that "spoilers" extended on one wing are used for lateral control, while symmetrically extended spoilers are used for "speed brakes."

$$\Delta C_L^{\text{spoilers}} = \sum \frac{(K_{\delta_{SP}})(\Delta C_L^{\text{SP}})_{45}}{} \cdot \frac{(L_{R})_{SP}}{\frac{L_{R}}{L_{R,SP}}} \cdot F_{2\delta_{E_{SP}}}$$

where $\Delta C_L^{\text{SP,45}}$ is the change in basic lift coefficient due to deflecting the operating spoiler panels to $45^\circ$. The operating spoiler panels are determined from the hydraulic systems schematic on page 1.2-7. $\Delta C_L^{\text{SP,45}}$ is plotted for spoilers and ground spoilers on page 2.0-21 and page 2.0-22.
respectively. The spoiler effectiveness factor, 
\((K_{S\text{SP}})_{L}\) is plotted on page 2.0-20. The Mach number effect, 
\((C_{L\text{SP}})_{M}/(C_{L\text{SP}})_{M=0}\) is plotted on page 2.0-23. The aeroelastic effect, 
\((\frac{LE}{LR})_{SP}\) is plotted on pages 2.0-24, 2.0-25, and 2.0-26. The ground 
effect factor, \(F_{\text{GE}}\) is obtained from page 5.0-29.

\[\Delta C_{L_{\text{OUTBOARD AILERONS}}} = \text{Change in basic lift coefficient due to outboard}
\text{aileron deflection.}\]

\[\Delta C_{L_{\text{OUTBOARD AILERONS}}} = \sum_{\text{LEFT AND RIGHT OUTBOARD AILERONS}} K_{SAO} \cdot \Delta C_{L_{AO}} \cdot F_{\text{GE}}\]

where \(\Delta C_{L_{AO}}\) is the change in basic lift coefficient 
due to deflecting one outboard aileron up to 25° or 
the opposite outboard aileron down to 15°. \(\Delta C_{L_{AO}}\) 
is plotted on page 2.0-27. The outboard aileron 
effectiveness factor, \(K_{SAO}\) is plotted on page 5.0-26. The ground effect factor, \(F_{\text{GE}}\) is obtained 
from page 5.0-29.

\[\Delta C_{L_{\text{LANDING GEAR}}} = \text{Change in basic lift coefficient due to main and nose}
\text{landing gear extension.}\]

\[\Delta C_{L_{\text{LANDING GEAR}}} = K_{GEAR} \cdot \Delta C_{L_{GEAR}} \cdot \frac{(C_{L_{GEAR}})_{M}}{(C_{L_{GEAR}})_{M=0}}\]

where \(\Delta C_{L_{GEAR}}\) is plotted on page 2.0-29. The Mach 
number effect, \((C_{L_{GEAR}})_{M}/(C_{L_{GEAR}})_{M=0}\) is plotted on page 2.0-30. The landing gear effectiveness factor, \(K_{GEAR}\) 
is plotted on page 2.0-28.
\[ \Delta C_{L_{\text{FLAP FAILURE}}} = \left[ (\Delta C_L)_{\alpha_{W.D.P.} = 0^\circ}^{\alpha_{W.D.P.}} \right]_{\text{FLAP FAILURE}} + \Delta \left( \frac{dC_L}{d\alpha} \right)_{\text{FLAP FAILURE}} \cdot \alpha_{W.D.P.} \]

where \( [ (\Delta C_L)_{\alpha_{W.D.P.} = 0^\circ}^{\alpha_{W.D.P.}} ]_{\text{FLAP FAILURE}} \) is the change in basic lift coefficient at \( \alpha_{W.D.P.} = 0^\circ \) due to symmetric inboard or outboard flap failure. \( \Delta \left( \frac{dC_L}{d\alpha} \right)_{\text{FLAP FAILURE}} \cdot \alpha_{W.D.P.} \) is the change in basic lift coefficient due to the effect of symmetric inboard or outboard flap failure on the rigid airplane basic lift coefficient curve slope.

\( \Delta \left( \frac{dC_L}{d\alpha} \right)_{\text{FLAP FAILURE}} \) is plotted on page 2.0-34.

The above data is also applicable for asymmetric (monitor limited) inboard or outboard flap failure, e.g., one inboard flap failed and the opposite inboard flap at the monitor limited extension or retraction position.
\( \Delta C_L_{\text{FLAP FAILURE}} \) is to be added to total \( C_L \) computed for the inboard flap position. Note that inboard flap position should be used for all functions of flap in this document.

The angle of attack for stick shaker actuation is plotted on page 2.0-35. The angle of attack for initial buffet is plotted on page 2.0-36. Certification stall speeds are plotted on page 2.0-37. The initial buffet boundary and trimmed \( C_{L,\text{MAX}} \) values are plotted on page 2.0-38.
<table>
<thead>
<tr>
<th>LIFT COEFFICIENT OF FLAPS ON (AC)</th>
<th>W/FLAPS</th>
<th>W/O FLAPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1.5</td>
<td>1.5</td>
<td>0.0</td>
</tr>
<tr>
<td>2.0</td>
<td>2.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Note: Use for all altitudes.
LOW SPEED

NOTE: USE FOR ALL ALTITUDES.

2. \( \Delta C_L = \Delta \left( \frac{dC_L}{d\alpha} \right) \cdot \text{W/O/F} \)

\(\Delta \left( \frac{dC_L}{d\alpha} \right) \text{ PER DEGREE}\)

\(\Delta \left( \frac{dC_L}{d\alpha} \right) \text{ PER DEGREE}\)

EQUIVALENT AIRSPEED, \(V_e \approx 475 \text{ KT}\)

FLAPS
20
15
10
5
25
30

LIFT COEFFICIENT

EFFECT OF FLAPS ON \(\Delta \left( \frac{dC_L}{d\alpha} \right)\)

THE BOEING COMPANY
LOW SPEED

Note: Use for all altitudes.

\[ \frac{dC_L}{dn_2} = \frac{dC_L}{dn_2} \cdot n_2 \] (\( n_2 = 1 \) for steady level flight)

LIFT COEFFICIENT
EFFECT OF FLAPS ON \( \frac{dC_L}{dn_2} \)

THE BOEING COMPANY

REV. D
2. $\Delta C_L = K_{\Delta \alpha} \cdot \frac{dC_L}{d\alpha}$
NOTE:

1. USE FOR ALL FLAP SETTINGS

2. BOTH INBOARD ELEVATORS DEFLECTED

3. FOR ONE INBOARD ELEVATOR DEFLECTED, USE HALF THE VALUE SHOWN

4. \( \Delta C_L = K_d \cdot \frac{dC_L}{d\delta_{E2}} \)
LIFT COEFFICIENT

EFFECT OF OUTBOARD ELEVATORS

THE BOEING COMPANY

USE: CLDE\(\phi\) = -0.2538 CMDE\(\phi\)
LIFT COEFFICIENT EFFECT OF SPOILERS (6 AND 7)

NOTE: DATA SHOWN FOR BOTH PANELS OPERATING
PANELS LIMITED TO 20 DEG MAX DEFLECTION

CALC: KUPC15  12/14/67  REVISED  DATE
CHECK: FOSTER  1/24/67  KUPC15  822/69
APR  LOW  2/14/70
APR
INK: ODEGARD  12/14/67

THE BOEING COMPANY

REV. D  747
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LIFT COEFFICIENT DUE TO SPOILERS (12 OR 1)

NOTE: USE FOR ALL FLAP SETTINGS
LIFT COEFFICIENT

EFFECT OF OUTBOARD AILERON

THE BOEING COMPANY
LOW SPEED

NOTE 1 FREE AIR

2. FOR LANDING GEAR FAILURE, REPLACE $\Delta C_{L\text{-Gear}}$ BY

$\Delta C_{L\text{-Gear Failure}} = K_{L\text{-Gear}} \cdot \Delta C_{L\text{-Gear}}$

<table>
<thead>
<tr>
<th>GEAR SELECTION</th>
<th>GEAR FAILURE</th>
<th>$K_{L\text{-Gear}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOWN</td>
<td>WING GEARS FAIL TO EXTEND</td>
<td>0.1</td>
</tr>
<tr>
<td>UP</td>
<td>WING GEARS FAIL TO RETRACT</td>
<td>0.9</td>
</tr>
<tr>
<td>✓</td>
<td>ONE WING GEAR FAILS TO RETRACT</td>
<td>0.45</td>
</tr>
<tr>
<td>✓</td>
<td>ONE BODY GEAR FAILS TO RETRACT</td>
<td>0.4</td>
</tr>
<tr>
<td>✓</td>
<td>ONE BODY GEAR DOOR FAILS TO RETRACT</td>
<td>0.3</td>
</tr>
<tr>
<td>✓</td>
<td>NOSE GEAR FAILS TO RETRACT</td>
<td>0</td>
</tr>
</tbody>
</table>

$LIFT$ $COEFFICIENT$

$EFFECT$ $OF$ $LANDING$ $GEAR$

THE BOEING COMPANY
NOTE

1. GEAR ON GROUND

2. $K_{GE} = 1.0

NORMAL TAXI ATTITUDE

TAIL SKID AND EXTENDED GEAR TOUCHING

$\Delta C_{L_{GE}}$

FLAPS 25

0 1 2 3 4

$\Delta W/B$ DEGREES

SEE SECTION 19 FOR REVISED DATA
NOTE 1. DATA APPLICABLE FOR SYMMETRIC OR ASYMMETRIC (MONITOR LIMITED) FLAP FAILURE.

These data not included in NASA simulation.

\[ \left( \Delta C_L \right)_{W.D.R = 0^*} \] FLAP FAILURE

INBOARD FLAP POSITION, \( \delta_{F1} \):
- 5
- 10
- 15
- 20
- 25
- 30

OUTBOARD FLAP POSITION, \( \delta_{F0} \):

| CALC  | LOW  | 53-69 | REVISI | DATE
|-------|------|-------|--------|------
| CHECK | LOW  | 2.1770|        |      |
| APR   | LOW  | 6.2570|        |      |
| INK   | ODEGARD | 53-69 |        |      |

LIFT COEFFICIENT
EFFECT OF FLAPS ON
\[ \left( \Delta C_L \right)_{W.D.R = 0^*} \] FLAP FAILURE

THE BOEING COMPANY
NOTE: DATA APPLICABLE FOR SYMMETRIC OR ASYMMETRIC (MONITOR LIMITED) FLAP FAILURE.

These data not included in NASA simulation.

\[
\frac{\Delta (dC_L)}{d\alpha} \text{ FLAP FAILURE}
\]

INBOARD FLAP POSITION, \(\delta_{F0} = 0.1\)

OUTBOARD FLAP POSITION, \(\delta_{F0}\)

<table>
<thead>
<tr>
<th>CALC</th>
<th>LOW</th>
<th>5.3.69</th>
<th>REvised</th>
<th>DATE</th>
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<tbody>
<tr>
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<td>LOW</td>
<td>2.17.70</td>
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<tr>
<td>APR</td>
<td>LOW</td>
<td>6.25.70</td>
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</tr>
<tr>
<td>INK ODEGARD</td>
<td>5.3.69</td>
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</tr>
</tbody>
</table>

LIFT COEFFICIENT EFFECT OF FLAPS ON 
\[
\Delta (dC_L / d\alpha) \text{ FLAP FAILURE}
\]

THE BOEING COMPANY
ANGLE OF ATTACK
FOR STICK SHAKER ACTUATION
THE BOEING COMPANY

0° STICK SHAKER

NOTE LOW SPEED

X W.D.O. - DEGREES

FLAP SETTING, $\alpha$

0 5 10 15 20 25 30

19-68 6-4-69 1-28-70

CALC LOW REVIS ED DATE
CHECK FOSTER 1-24-68 LOW 1-19-68
APR
APR
INK ODEGARD 1-19-68

SEE SECTION 19
FOR REVISED DATA

D-30643
Vol. II
PAGE 2.0-35
SEE SECTION 19
FOR REVISED DATA
3.0 DRAG FORCE COEFFICIENT

The dimensionless aerodynamic drag force coefficient is given in terms of its significant components by the equation below:

At a given $\alpha_{W.D.P.}$,

$$C_D = K \left[ C_{0,\text{BASIC}} + \frac{dC_D}{d\alpha} \cdot \Delta_{F.R.L.} \right] + [1-K][C_D]_M$$

$$+ \Delta C_{D,\text{SPOILERS}} + \Delta C_{D,\text{LANDING GEAR}} + \Delta C_{D,\text{GROUND EFFECT}}$$

$$+ \Delta C_{D,\text{SIDESLIP}} + \Delta C_{D,\text{RUDDERS}} + \left[ \Delta C_{D,\text{FLAP FAILURE}} \right]$$

where,

$C_{0,\text{BASIC}}$ = Basic drag coefficient for the rigid airplane at $\Delta_{F.R.L.} = 0^\circ$, in free air and with the landing gear retracted. $C_{0,\text{BASIC}}$ is plotted on page 3.0-5.

$K$ = 0 for flaps up, $K = 1$ for flaps 1, 5, 10, 20, 25 and 30.

$\frac{dC_D}{d\alpha} \cdot \Delta_{F.R.L.}$ = Change in basic drag coefficient due to change in stabilizer angle from $\Delta_{F.R.L.} = 0^\circ$. $\frac{dC_D}{d\alpha}$ is plotted on page 3.0-8 and page 3.0-7.

$[C_D]_M$ = Drag coefficient at Mach number, $M$. $[C_D]_M$ is plotted on page 3.0-8 and 3.0-9. $C_L^*$ is given by the first air terms of the lift force coefficient equation on page 2.0-1.

NOT IN NASA SIMULATION.
3.0 \( \Delta C_{D_{\text{SPOILERS}}} \) = Change in drag coefficient due to spoiler or speedbrake deflection.

\[
\Delta C_{D_{\text{SPOILERS}}} = \Delta C_{D_{SP}} \left[ 1 + F_{D} \cdot K_{GE}^B \right] \\
+ 0.05 \cdot F_{D} \cdot K_{GE}^B \cdot \frac{1}{45n} \cdot \sum \delta_{SP}
\]

where \( \Delta C_{D_{SP}} \) is the change in drag coefficient due to spoiler or speedbrake deflection in free air.

\[
\Delta C_{D_{SP}} = \sum \left[ (\Delta C_{D_{SP}})_{\alpha_{W.D.R.}=4^\circ} + \frac{d (\Delta C_{D_{SP}})}{d\alpha} (\alpha_{W.D.R.}-4^\circ) \right] \frac{(C_{D_{SP}})_M}{(C_{D_{SP}})_{M=0}}
\]

where \( (\Delta C_{D_{SP}})_{\alpha_{W.D.R.}=4^\circ} \) is the change in drag coefficient at \( \alpha_{W.D.R.}=4^\circ \) due to deflecting the operating spoiler panels. \( (\Delta C_{D_{SP}})_{\alpha_{W.D.R.}=4^\circ} \) is plotted for spoilers on page 3.0-10 and is tabulated for ground spoilers on page 3.0-12. \( \frac{d (\Delta C_{D_{SP}})}{d\alpha} \) is the rate of change with angle of attack of drag coefficient due to deflecting the operating spoiler panels. \( \frac{d (\Delta C_{D_{SP}})}{d\alpha} \) is plotted for spoilers on page 3.0-11 and is tabulated for ground spoilers on page 3.0-12. The Mach number effect, \( \frac{(C_{D_{SP}})_M}{(C_{D_{SP}})_{M=0}} \), is plotted on page 3.0-13. The ground effect lateral control factor, \( F_{D} \), is plotted on page 3.0-14. The ground effect height factor, \( K_{GE}^B \), is plotted on page 2.0-31. \( n \) is the number of operating spoiler panels. \( \delta_{SP} \) is the spoiler panel deflection.
angle (degrees).

\[ \Delta C_{DL} = \text{Change in drag coefficient due to main and nose landing gear extension.} \]

\[ \Delta C_{DL} = K_{GEAR} \cdot \Delta C_{DEAR} \cdot \frac{(C_{DEAR})_M}{(C_{DEAR})_{M=0}} \]

where \( \Delta C_{DEAR} \) is plotted on page 3.0-15. The Mach number effect, \( \frac{(C_{DEAR})_M}{(C_{DEAR})_{M=0}} \), is plotted on page 3.0-16. The landing gear effectiveness factor, \( K_{GEAR} \), is plotted on page 2.0-28.

\[ \Delta C_{DG} = \text{Change in drag coefficient due to ground effect.} \]

\[ \Delta C_{DG} = K_{GE} \cdot \Delta C_{DE} \]

where \( \Delta C_{DE} \) is plotted on page 3.0-16. The ground effect height factor, \( K_{GE} \), is plotted on page 3.0-17.

\[ \Delta C_{DS} = \text{Change in drag coefficient due to angle of sideslip, } \beta. \]

\( \Delta C_{DS} \) is plotted on page 3.0-19.

\[ \Delta C_{DR} = \text{Change in drag coefficient due to rudder deflection.} \]

\[ \Delta C_{DR} = \Delta C_{DRU} + \Delta C_{DRL} \]

where \( \Delta C_{DRU} \) and \( \Delta C_{DRL} \) are the changes in drag coefficient due to deflection of the upper rudder and the lower rudder respectively. \( \Delta C_{DRU} \) and \( \Delta C_{DRL} \) are obtained from page 3.0-19.
3.0 \( \Delta C_{D_{\text{FLAP FAILURE}}} \)

(Cont'd)

Change in basic drag coefficient due to flap extension or retraction from the flap position at which symmetric failure of each flap or group of flaps occurred.

For symmetric inflow, or outflow, flap failure,

\[
\Delta C_{D_{\text{FLAP FAILURE}}} = \left[ (\Delta C_D)_{\alpha_{W.D.P.} = 0^\circ} \right]_{\text{FLAP FAILURE}} + \Delta \left( \frac{dC_D}{d\alpha} \right)_{\text{FLAP FAILURE}} \alpha_{W.D.P.}
\]

where \( (\Delta C_D)_{\alpha_{W.D.P.} = 0^\circ} \)_{\text{FLAP FAILURE}} is the change in basic drag coefficient at \( \alpha_{W.D.P.} = 0^\circ \) due to symmetric inflow or outflow flap failure. \( \Delta \left( \frac{dC_D}{d\alpha} \right)_{\text{FLAP FAILURE}} \)_{\alpha_{W.D.P.}} is plotted on page 3.0-11.

The above data is also available for asymmetric (monitor limited) inflow or outflow flap failure.

\[
\Delta C_{D_{\text{FLAP FAILURE}}} \text{ is plotted on page 3.0-11.}
\]
EFFECT OF MACH NUMBER
M ≤ 0.7

THE BOEING COMPANY

DRAG COEFFICIENT

CALC: BYSTROM 2-13-70
CHECK
APR
APR
INK: ODEGARD 2-17-70

PAGE 30-8

REV. D
NOTE

DATA SHOWN FOR INDIVIDUAL PANELS 2 OR 5

1. FOR PANEL 12 OR 1, MULTIPLY BY 0.50
2. PANELS A4 & 5 LIMITED TO 20 DEG. MAX DEFLECTION

SPOLIER PANEL GROUP 2, 3, 6 OR 2, 3, 4

NOTE

TOTAL EFFECT OF SPOLIER GROUP 9, 10, 11 (OR 2, 3, 4) SHOWN

1. WITH HYDRAULIC SYSTEM NO. 2 OFF, MULTIPLY BY 0.50
2. WITH HYDRAULIC SYSTEM NO. 3 OFF, MULTIPLY BY 0.10
3. FOR SPOLIER GROUP 9, 10 (OR 3, 4), MULTIPLY BY 0.05

DRAG COEFFICIENT

EFFECT OF SPOILERS
**DRAG COEFFICIENT**

**EFFECT OF ANGLE OF ATTACK ON SPOILERS**

**THE BOEING COMPANY**

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<tr>
<th>CALC</th>
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<th>1/2/68</th>
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**NOTE**

DATA SHOWN FOR INDIVIDUAL PANELS 2 OR 5
FOR PANEL 2 OR 1, MULTIPLY BY 0.50
PANELS 8 & 9 LIMITED TO 20 DEG.
MAX. DEFLECTION

FLAPS

TOTAL EFFECT OF SPOILER GROUP 5, 0, 11 (OR 7, 3, 4) SHOWN
WITH HYDRAULIC SYSTEM NO. 2 OFF, MULTIPLY BY 0.70
WITH HYDRAULIC SYSTEM NO. 3 OFF, MULTIPLY BY 0.70
FOR SPOILER GROUP 9, 10 (OR 3, 4), MULTIPLY BY 0.65
### SPOILER PANELS 6 AND 7

**Note:** Data shown for both panels operating at 20°.

#### Flap Setting vs. Drag Coefficient

<table>
<thead>
<tr>
<th>Flap Setting</th>
<th>$(AC_{D_{SP}})<em>{x</em>{W.D.P.}}$</th>
<th>$\frac{d(AC_{D_{SP}})}{dx}$</th>
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<tbody>
<tr>
<td>Up</td>
<td>0.0008</td>
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<tr>
<td>1</td>
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<tr>
<td>5</td>
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**CALC**: KUPCIS 1/3/68  
**CHECK**: FOSTER 12/4/68  
**REvised**:  
**DATE**:  

**DRAG COEFFICIENT**  
**EFFECT OF SPOILERS (6 AND 7)**

**THE BOEING COMPANY**

**747**  
**DG-30048**  
**Vol. II**  
**PAGE**: 3.0-12  
**REV. C**
DRAG COEFFICIENT
GROUND EFFECT LATERAL CONTROL FACTOR, F_d

THE BOEING COMPANY
NOTE 1  FREE AIR

2. FOR LANDING GEAR FAILURE, REPLACE $\alpha_C$ BY

$\alpha_C = K_{\text{gear}} \cdot \alpha_C$

<table>
<thead>
<tr>
<th>GEAR SELECTION</th>
<th>GEAR FAILURE</th>
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<tr>
<td>DOWN</td>
<td>WING GEARS FAIL TO EXTEND</td>
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<td>UP</td>
<td>WING GEARS FAIL TO RETRACT</td>
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<tr>
<td></td>
<td>ONE WING GEAR FAILS TO RETRACT</td>
<td>0.3</td>
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<td>ONE BODY GEAR FAILS TO RETRACT</td>
<td>0.1</td>
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<td>NOSE GEAR FAILS TO RETRACT</td>
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DRAG COEFFICIENT EFFECT OF LANDING GEAR

THE BOEING COMPANY
DRAG COEFFICIENT
EFFECT OF MACH NUMBER ON $\Delta C_{D_{\text{rear}}}$

THE BOEING COMPANY

LOW 11-9-67
REvised DATE

CHECK FOSTER 11-24-68
APR
INK ODEGARD 11-9-67

AD 461 C R4

D6-30643 Vol. II
PAGE 3.0-16
GROSS HEIGHT ABOVE GROUND, FEET

A

K

DE-336
Vol. I

THE BOEING COMPANY

PAGE 3.0-1
NOTE 1  GEAR ON GROUND

NOTE 2  \( K_{GE} = 1.0 \)

\[ \Delta C_{D,GE} \]

NORMAL TAXI ATTITUDE

TAIL SKID AND EXTENDED GEAR TOUCHING

\( \text{W.D.P.} \sim \text{DEGREES} \)

FLAPS

10

8

6

4

2

0

-2

-4

-6

-8

-10

-12

-14

SEE SECTION 19 FOR REVISED DATA

CALC: CURNUTT 12/12/67  CHECK: FOSTER 1/24/68  REvised: CURNUTT 3/5/70

DRAG COEFFICIENT
GROUND EFFECT
THE BOEING COMPANY

PAGE 3.0-18
NOTE 1. \( AC_{D,LU} = (0.4) AC_{D, TOTAL} \)

2. \( AC_{D, KL} = (0.6) AC_{D, TOTAL} \)

3. REVERSE SIGN ON \( \delta \) FOR NEGATIVE RUDDER DEFLECTION

4. USE FOR ALL ANGLES OF ATTACK

5. USE FOR ALL FLAP POSITIONS

DRAG COEFFICIENT
EFFECT OF SIDESLIP
AND RUDDER

THE BOEING COMPANY
NOTE: DATA APPLICABLE FOR SYMMETRIC OR ASYMMETRIC (MONITOR LIMITED) FLAP FAILURE.

THESE DATA NOT INCLUDED IN NASA SIMULATION.

\[ \left( \Delta C_D \right)_{x, w.d.r. = 0} \text{ FLAP FAILURE} \]

\[
\begin{align*}
\text{INBOARD FLAP POSITION, } \delta_F &= 0.0 \\
\text{OUTBOARD FLAP POSITION, } \delta_{FO} &
\end{align*}
\]

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THE BOEING COMPANY

DE-30643
Vol. 11
Page 3.0-20
NOTE: DATA APPLICABLE FOR SYMMETRIC OR ASYMMETRIC (MONITOR LIMITED) FLAP FAILURE

THESE DATA NOT INCLUDED IN NASA SIMULATION.

\[ \frac{\Delta (dC_D)}{dx} \text{ FLAP FAILURE} \]

INBOARD FLAP POSITION, \( \delta_f = 5 \)

OUTBOARD FLAP POSITION, \( \delta_f = \)

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<td>[ \Delta (dC_D/d\alpha) ] FLAP FAILURE</td>
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</table>

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DO-30643
Vol. II

PAGE 3.0-21
4.0 PITCHING MOMENT COEFFICIENT

The dimensionless aerodynamic pitching moment coefficient is given in terms of its significant components by the equation below.

At a given \( \alpha_{w.d.p.} \),

\[
C_{m,c.o.} = C_{m,25}^{basic} + (\Delta C_{m,25})_{\alpha_{w.d.p.}=0^\circ} + \Delta \left( \frac{dC_{m,25}}{d\alpha} \right) \cdot \alpha_{w.d.p.} \\
+ C_L(C.G.-25) + \frac{dC_m}{d\alpha} \cdot (c_2) + \frac{dC_{m,25}}{d\delta} \cdot (2\dot{\gamma}) + \frac{dC_{m,25}}{d\dot{\eta}} \cdot \eta_2 \\
+ K_{\alpha} \cdot \frac{dC_{m,25}}{d\alpha} \cdot \delta_{f.l.} + K_{\alpha} \cdot \frac{dC_{m,25}}{d\delta} \cdot \delta_{e,1} + K_{\alpha} \cdot \frac{dC_{m,25}}{d\delta} \cdot \delta_{e,0} \\
+ \Delta C_{m,25}^{spoilers} + \Delta C_{m,25}^{inboard + \Delta C_{m,25}^{outboard + \Delta C_{m,25}^{landing + \Delta C_{m,25}^{gear}} \hspace{1cm} \Delta C_{m,25}^{sideslip} + \Delta C_{m,25}^{rudders}} \hspace{1cm} \Delta C_{m,25}^{flap failure}
\]

where,

\( C_{m,25}^{basic} \) = Basic pitching moment coefficient for the rigid airplane at \( \delta_{f.l.} = 0^\circ \), in free air, with the landing gear retracted, and with the C.G. = 25% M.A.C.

For low speed, \( C_{m,25}^{basic} \) is plotted on pages 4.0-8 and 4.0-9. For flaps up, \( C_{m,25}^{basic} \) is plotted on page 4.0-10.

\( \Delta C_{m,25}^{\alpha_{w.d.p.}=0^\circ} \) = Change in basic pitching moment coefficient at \( \alpha_{w.d.p.} = 0^\circ \) due to aeroelasticity. For low speed,
4.0
(Cont'd)

\[ (\Delta C_{m_{zs}})_{\kappa_{W.R.P.} = 0^\circ} \] is plotted on page 4.0-11.

For flaps up, \[ (\Delta C_{m_{zs}})_{\kappa_{W.R.P.} = 0^\circ} \] is plotted on page 4.0-12.

\[ \Delta \left( \frac{dC_{m_{zs}}}{d\alpha} \right)_{\kappa_{W.R.P.}} \] is plotted on page 4.0-13.

For flaps up, \[ \Delta \left( \frac{dC_{m_{zs}}}{d\alpha} \right) \] is plotted on page 4.0-14.

\[ C_{L}(CG-25) \] = Change in pitching moment coefficient due to center of gravity variation from 25% M.A.C. The total lift coefficient, \( C_L \), is defined in Section 2.0.

\[ \frac{dC_m}{d\alpha} \] = Change in basic pitching moment coefficient due to rate of change of angle of attack.

\[ \frac{dC_m}{d\alpha} = K_{\alpha} \cdot \frac{dC_{m_{zs}}}{d\alpha} \]

where \[ \frac{dC_{m_{zs}}}{d\alpha} \] and the center of gravity factor, \( K_{\alpha} \), are plotted on page 4.0-15.

\[ \frac{dC_{m_{zs}}}{d\dot{q}} \] = Change in basic pitching moment coefficient due to pitch rate. \[ \frac{dC_{m_{zs}}}{d\dot{q}} \] is plotted on page 4.0-16.

\[ \frac{dC_{m_{zs}}}{dn_{\kappa}} \] = Change in basic pitching moment coefficient due to aeroelastic inertia relief caused by normal load factor, \( n_{\kappa} \). For low speed, \[ \frac{dC_{m_{zs}}}{dn_{\kappa}} \] is plotted on page 4.0-17. For flaps up, \[ \frac{dC_{m_{zs}}}{dn_{\kappa}} \] is plotted.
4.0 on page 4.0-18.

(Cont'd) \[ K_{\alpha} \cdot \frac{dC_{m,25}}{d\delta_{E_2}} \Delta_{F,RL} = \] Change in basic pitching moment coefficient due to change in stabilizer angle from \( \Delta_{F,RL} = 0^\circ \).

\[ \frac{dC_{m,25}}{d\delta_{E_2}} \] is plotted on page 4.0-20. The effectiveness factor for the stabilizer (and elevators), \( K_{\alpha} \), is plotted on page 4.0-19.

\[ K_{\alpha} \cdot \frac{dC_{m,25}}{d\delta_{E_1}} \Delta_{E_1} = \] Change in basic pitching moment coefficient due to change in inboard elevator angle from \( \delta_{E_1} = 0^\circ \).

\[ \frac{dC_{m,25}}{d\delta_{E_1}} \] is plotted on page 4.0-21.

\[ K_{\alpha} \cdot \frac{dC_{m,25}}{d\delta_{E_0}} \Delta_{E_0} = \] Change in basic pitching moment coefficient due to change in outboard elevator angle from \( \delta_{E_0} = 0^\circ \).

\[ \frac{dC_{m,25}}{d\delta_{E_0}} \] is plotted on page 4.0-22.

The normal system stick free (rigged) elevator deflection is +2° from the faired position.

\[ \Delta C_{m,25} \text{ SPOILERS} = \] Change in basic pitching moment coefficient due to spoiler or speed brake deflection.

\[ \Delta C_{m,25} \text{ SPOILERS} = \sum \left( (\Delta C_{m,25})_{SP} \cdot \frac{(C_{m,25})_{SP}}{m} \cdot \frac{(C_{m,25})_{SP}^M}{M} \cdot \frac{(M_E)}{M(E)} \cdot \frac{F_m}{G_E} \right) \]

where \( (\Delta C_{m,25})_{SP} \) is the change in basic pitching moment coefficient due to deflecting the operating spoiler panels to 45°. \( (\Delta C_{m,25})_{SP} \) is plotted for spoilers and ground spoilers on page 4.0-24 and
The spoiler effectiveness factor, \((K_{SP})_m\) is plotted on page 4.0-23.

The Mach number effect, \((C_{m_{25SP}})_{M}/(C_{m_{25SP}})_{M=0}\) is plotted on page 4.0-26. The aeroelastic effect, \((M_{e}/M_{R})_{SP}\) is plotted on pages 4.0-27, 4.0-28, and 4.0-29.

The ground effect factor, \(F_{m_{GE}}\) is obtained as follows:

\[
F_{m_{GE}} = [1 + (F_m \cdot K_{GE})]
\]

where \(F_m\) is plotted on page 4.0-32. The ground effect height factor, \(K_{GE}\) is plotted on page 2.0-31.

\[
\Delta C_{m_{25\text{inboard ailerons}}} = \text{Change in basic pitching moment coefficient due to inboard aileron deflection.}
\]

\[
\Delta C_{m_{25\text{inboard ailerons}}} = K_{SA}(\Delta C_{m_{25AI}})_{20} \cdot \frac{(C_{m_{25AI}})_{M}}{(C_{m_{25AI}})_{M=0}} \cdot F_{m_{GE}}
\]

where \((\Delta C_{m_{25AI}})_{20}\) is the change in basic pitching moment coefficient due to deflecting one inboard aileron up to 20°. \((\Delta C_{m_{25AI}})_{20}\) is plotted on page 4.0-30. The inboard aileron effectiveness factor, \(K_{SA}\) is to be obtained for the up inboard aileron deflection and is plotted on page 5.0-22.

The Mach number effect, \((C_{m_{25AI}})_{M}/(C_{m_{25AI}})_{M=0}\) is plotted on page 4.0-30. The ground effect factor, \(F_{m_{GE}}\) is obtained from page 4.0-32.

\[
\Delta C_{m_{25\text{outboard ailerons}}} = \text{Change in basic pitching moment coefficient due to}
\]

\[
\Delta C_{m_{25\text{outboard ailerons}}} = \text{Change in basic pitching moment coefficient due to}
\]
outboard aileron deflection.

\[ \Delta C_{m,25}^{\text{OUTBOARD}} = \sum_{\text{UP AND DOWN OUTBOARD AILEYONS}} K_{\delta A_0} \cdot \Delta C_{m,25A_0} \cdot F_{mg G} \]

where \( \Delta C_{m,25A_0} \) is the change in basic pitching moment coefficient due to deflecting one outboard aileron up to 25° or the opposite outboard aileron down to 15°. \( \Delta C_{m,25A_0} \) is plotted on page 4.0-31. The outboard aileron effectiveness factor, \( K_{\delta A_0} \), is plotted on page 5.0-26. The ground effect factor, \( F_{mgG} \), is obtained from page 4.0-32.

\[ \Delta C_{m,25\text{LANDING GEAR}} = \text{Change in basic pitching moment coefficient due to main and nose landing gear extension.} \]

\[ \Delta C_{m,25\text{LANDING GEAR}} = K_{\text{GEAR}} \cdot \Delta C_{m,25\text{GEAR}} \cdot \frac{(C_{m,25 \text{GEAR}})_{M=0}}{(C_{m,25 \text{GEAR}})_{M=0}} \]

where \( \Delta C_{m,25 \text{GEAR}} \) is plotted on page 4.0-33. The Mach number effect, \( (C_{m,25 \text{GEAR}})_{M=0}/(C_{m,25 \text{GEAR}})_{M=0} \), is plotted on page 4.0-34. The landing gear effectiveness factor, \( K_{\text{GEAR}} \), is plotted on page 2.0-28.

\[ \Delta C_{m,25\text{GROUND EFFECT}} = \text{Change in basic pitching moment coefficient due to ground effect.} \]

\[ \Delta C_{m,25\text{GROUND EFFECT}} = K_{G} \cdot \Delta C_{m,25\text{GE}} \]

where \( \Delta C_{m,25\text{GE}} \) is plotted on page 4.0-35.
The ground effect weight factor, $k_{GE}$, is plotted on page 4-8-31.

$\Delta C_{m,25_{Sideslip}}$ = Change in basic pitching moment coefficient due to angle of attack $\beta$. $\Delta C_{m,25_{Sideslip}}$ is plotted on page 4-8-36.

$\Delta C_{m,25_{Rudders}}$ = Change in basic pitching moment coefficient due to deflection of rudder.

$\Delta C_{m,25_{Rudders}} = \Delta C_{m,25_{RU}} + \Delta C_{m,25_{RL}}$

where $\Delta C_{m,25_{RU}}$ and $\Delta C_{m,25_{RL}}$ are the changes in basic pitching moment coefficients due to deflection of upper and lower rudders respectively.

$\Delta C_{m,25_{RU}}$ and $\Delta C_{m,25_{RL}}$ are obtained from page 4-8-36.

$\Delta C_{m,25_{Flap Failure}}$ = Change in basic pitching moment coefficient due to flap deflection or retraction from the flap position at which the flap failure occurs. Both inboard or both outboard flaps can fail.

- Symmetric inboard outboard flap failure,

$\Delta C_{m,25_{Flap Failure}} = \left[ (\Delta C_{m,25})_{\alpha_{W.D.P.} = 0^\circ} \right]_{\text{Flap Failure}} + \Delta \left( \frac{dC_{m,25}}{d\alpha} \right)_{\text{Flap Failure}} \cdot \alpha_{W.D.P.}$

where $\left[ (\Delta C_{m,25})_{\alpha_{W.D.P.} = 0^\circ} \right]_{\text{Flap Failure}}$ is the change in basic pitching moment coefficient at $\alpha_{W.D.P.} = 0^\circ$. 
due to symmetric inboard or outboard flap failure.

\[ [(\Delta C_{m_{25}})\alpha_{W,D,P} = 0^\circ]_{\text{FLAP FAILURE}} \]

is plotted on page 4.0-34. \( \Delta \left( \frac{dC_{m_{25}}}{d\alpha} \right)_{\text{FLAP FAILURE}} \) is the change in basic pitching moment coefficient due to the effect of symmetric inboard or outboard flap failure on the rigid airplane basic pitching moment coefficient curve slope.

\( \Delta \left( \frac{dC_{m_{25}}}{d\alpha} \right)_{\text{FLAP FAILURE}} \) is plotted on page 4.0-38.

The above data is also applicable for asymmetric (monitor limited) inboard or outboard flap failure.

\( \Delta C_{m_{25}}_{\text{FLAP FAILURE}} \) is to be added to total \( C_{m_{c,q}} \) computed for the inboard flap position.
EFFECT OF ANGLE OF ATTACK ON
BASIC $C_m_{25}$ (FLAPS UP, 1, 5, 10)

THE BOEING COMPANY
PITCHING MOMENT COEFFICIENT EFFECT OF ANGLE OF ATTACK ON BASIC $C_{m_{25}}$ (FLAPS 20, 25, 30)

THE BOEING COMPANY
NOTE. USE FOR ALL ALTITUDES

\[ \Delta C_{m,25} = \frac{dC_{m,25}}{dn_2} n_2 \quad (n_2 = 1 \text{ for steady level flight}) \]

FLAP
30
20, 25
10, 15, 20

EQUIVALENT AIRSPEED, \( V_e \) - KNOTS

PITCHING MOMENT COEFFICIENT EFFECT OF FLAPS ON \( \frac{dC_{m,25}}{dn_2} \)

THE BOEING COMPANY
PITCHING MOMENT COEFFICIENT
AEREOELASTIC EFFECT ON
STABILIZER EFFECTIVENESS

THE BOEING COMPANY

CALC LOW 10-11-67 REVISED DATE
CHECK FOSTER 1-24-68 BRYANT 8-17-69
APR APR
INK ODEGARD 10-11-67

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VOL. 11
PAGE 4.0-20
NOTE

1. USE FOR ALL FLAP SETTINGS

2. FOR ONE INBOARD ELEVATOR DEFLECTED, USE SHADE THE VALUE SHOWN

\[ \Delta C_{M,ES} = K_{M,ES} \cdot \Delta \delta_{ES} \]

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PITCHING MOMENT COEFFICIENT
AEROELASTIC EFFECT ON INBOARD ELEVATOR EFFECTIVENESS

THE BOEING COMPANY

Page 4-21

AD 481 C:R4
NOTE

USE FOR ALL FLAP SETTINGS.

FOR ONE OUTBOARD ELEVATOR DEFLECTED, USE HALF THE VALUE SHOWN.

\[ \Delta C_{m, a} = K_a \cdot \frac{\Delta C_{m, e}}{\Delta \alpha} \]

PITCHING MOMENT COEFFICIENT

AEROELASTIC EFFECT ON OUTBOARD ELEVATOR EFFECTIVENESS

THE BOEING COMPANY

CALC  LOW  10-10-47  REVISED  DATE
CHECK  FOSTER  1-24-48  FOSTER  9-25-49
APR
APR
INK  ODEGARD  10-10-47

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Vol. II

PAGE 4-0-22
NOTE: Lin for all spoiler panels.

Panel C, D, E, and F limited to 20° max deflection.

(K + kv) in

\( s_{ai} \) in degrees

---

CALC: KUPCIS 12/14/67  REVISED: DATE
CHECK: FOSTER 12/14/67  KUPCIS 6/2/69
APR: KUPCIS 8/27/69
APR: LOW 2/14/70
INK: ODEGARD 12/14/67

PITCHING MOMENT COEFFICIENT EFFECTIVENESS FACTOR SPOILERS

THE BOEING COMPANY

D6-30643 Vol. II 747
PAGE 4.0-23  REV. D
NOTE 1. DATA SHOWN FOR INDIVIDUAL PANELS 6 OR 5
2. FOR PANEL 12 OR 1, REVERSE SIGN
3. PANELS 6 & 15 LIMITER TO 20 DEG. MAX. DEFORMATION

SPOILER PANEL GROUP: 6, 10, 11, OR 2, 3, 4

NOTE 1. TOTAL EFFECT OF SPOILER GROUP 6, 10, 11 (OR 2, 3, 4) SHOWN
2. FOR SPOILER GROUP 6, 10, (OR 2, 3, 4), MULTIPLY BY 0.17
3. WITH HYDRAULIC SYSTEM NO. 1 OFF, MULTIPLY BY 0.33
4. WITH HYDRAULIC SYSTEM NO. 2 OFF, MULTIPLY BY 0.17

PITCHING MOMENT COEFFICIENT
EFFECT OF SPOILERS
THE BOEING COMPANY

CALC KUPCIS 12-16-67 REVISED DATE
CHECK FOSTER 1-24-68 KUPCIS 6-2-69
APR KUPCIS 2-14-70
APR
INK KINSMA 2-24-70

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DG-30643
Vol. II
PAGE 40-24
NOTE: DATA SHOWN FOR BOTH PANEL'S OPERATING

PANELS LIMITED TO 25° MAX DEFORMATION.

PITCHING MOMENT COEFFICIENT
EFFECT OF SPOILERS (6 AND 7)

THE BOEING COMPANY
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**PITCHING MOMENT COEFFICIENT**

**EFFECT OF MACH NUMBER ON SPOILERS**

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THE BOEING COMPANY

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Vol. II

PAGE 4.0-26
NOTE: \[ F_{m_{\text{GE}}} = 1 + F_m \cdot K_{\text{GE}}^2 \]

WHERE \( K_{\text{GE}}^2 \) IS SHOWN ON PAGE 20-31.
NOTE 1: FREE AIR

2 FOR LANDING GEAR FAILURE, REPLACE $\Delta C_{M,GEAR}$ BY

$$\Delta C_{M,GEAR} = K_{M,GEAR} \cdot \Delta C_{M,GEAR}$$

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<th>GEAR FAILURE</th>
<th>$K_{M,GEAR}$</th>
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<td>0.2</td>
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<td>ONE BODY GEAR FAILS TO RETRACT</td>
<td>-0.4</td>
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<td>ONE BODY GEAR DOOR FAILS TO RETRACT</td>
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<tr>
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<td>NOSE GEAR FAILS TO RETRACT</td>
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$\Delta C_{M,GEAR}$

$\alpha_{W/AC}$ ~ DEG.

CALC: LOW 9-20-67
CHECK: FOSTER 1-24-68
APR: BYSTROM 2-23-70
INK: ODEGARD 3-2-70

THE BOEING COMPANY

PITCHING MOMENT COEFFICIENT
EFFECT OF LANDING GEAR

DE-30643
Vol. II
747
4.0-33
REV. D
NOTE: 1. GEAR ON GROUND
2. $K_{GE} = 1.0$

**PITCHING MOMENT COEFFICIENT**

**GROUND EFFECT**

**THE BOEING COMPANY**

**CALC:** CURNUTT 12-12-67
**CHECK:** FOSTER 1-24-68 CURNUTT 3-6-70
**APR:**

**INK:** KINSMAN 3-6-70

SEE SECTION 19 FOR REVISED DATA
NOTE: DATA APPLICABLE FOR SYMMETRIC OR ASYMMETRIC (MONITOR LIMITED) FLAP FAILURE.

THESE DATA NOT INCLUDED IN NASA SIMULATION.

\[
\left(\Delta C_{m_{25}}\right)_{\alpha_{W.D.P.} = 0^\circ} \text{ FLAP FAILURE,}
\]

INBOARD FLAP POSITION, \( \delta_i = 30^\circ \)

OUTBOARD FLAP POSITION, \( \delta_o \)

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PITCHING MOMENT COEFFICIENT

EFFECT OF FLAPS ON

\[
\left(\Delta C_{m_{25}}\right)_{\alpha_{W.D.P.} = 0^\circ} \text{ FLAP FAILURE}
\]

THE BOEING COMPANY
NOTE: DATA APPLICABLE FOR SYMMETRIC OR ASYMMETRIC (MONITOR LIMITED) FLAP FAILURE

CLOSED DATA NOT INCLUDED IN EACH SIMULATION

\[
\frac{\Delta \left( \frac{dC_{m,25}}{d\alpha} \right)}{\text{PER DEG.}} \text{ FLAP FAILURE}
\]

INBOARD FLAP POSITION, 0° = 30°

OUTBOARD FLAP POSITION, 0° = 10°

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PITCHING MOMENT COEFFICIENT EFFECT OF FLAPS ON
\[
\Delta \left( \frac{dC_{m,25}}{d\alpha} \right) \text{ FLAP FAILURE}
\]

THE BOEING COMPANY

PAGE 40-38
5.0 ROLLING MOMENT COEFFICIENT

The dimensionless aerodynamic rolling moment coefficient is given in terms of its significant components by the equation below.

At a given $\alpha_{N.D.P.}$,

$$C_1 = \frac{dC_1}{d\beta} \cdot \beta + \frac{dC_1}{d\beta} \cdot \frac{P_{sb}}{zV} + \frac{dC_1}{d\beta} \cdot \frac{r_{sb}}{zV}$$

$$+ \Delta C_1_{SPOILERS} + \Delta C_1_{INBOARD AILERONS} + \Delta C_1_{OUTBOARD AILERONS}$$

$$+ \Delta C_1_{RUDDERS} + \left[ \Delta C_1_{FLAP FAILURE} + \Delta C_1_{L.E. FAILURE} \right]^*$$

where,

$$\frac{dC_1}{d\beta} \cdot \beta = \text{Rolling moment coefficient due to angle of sideslip, } \beta .$$

The complete expression for $\frac{dC_1}{d\beta}$ is given as follows:

$$\frac{dC_1}{d\beta} = \left[ \frac{dC_1}{d\beta} \cdot \frac{C_{1\beta}}{(C_{1\beta})_A} \cdot \frac{C_{1\beta}}{(C_{1\beta})_R} + K_{GEAR} \cdot \Delta \left( \frac{dC_1}{d\beta} \right)_{LANDING GEAR} \right] \cdot R_{GE}$$

where $\left( \frac{dC_1}{d\beta} \right)$ is the basic rate of change of rolling moment coefficient due to angle of sideslip. For low speed, $\left( \frac{dC_1}{d\beta} \right)$ is plotted on page 5.0-7. For flaps up, $\left( \frac{dC_1}{d\beta} \right)$ is plotted on page 5.0-8. $\frac{(C_{1\beta})_A}{(C_{1\beta})_{A=0}}$ is plotted on page 5.0-9.

* NOT IN NASA SIMULATION
5.0

(Cont'd)

The aeroelastic effect, \( \frac{[C_{10}]}{[C_{10}]} \), is plotted on page 5.0-10. The effect of main and nose gear extension, \( \Delta \left( \frac{dC_A}{d\beta} \right)_{\text{LANDING GEAR}} \), is given by:

\[
\Delta \left( \frac{dC_A}{d\beta} \right)_{\text{LANDING GEAR}} = -0.0003 \text{ PER DEGREE}
\]

The landing gear effectiveness factor, \( K_{\text{GEAR}} \), is plotted on page 2.0-28. The ground effect factor, \( F_{\text{GEO}} \), is obtained as follows:

\[
F_{\text{GEO}} = [1 + F_{\text{GE}} \cdot K_{\text{GE}}]
\]

where the ground effect sideslip factor, \( F_{\text{GE}} \), is plotted on page 5.0-11. The ground effect height factor, \( K_{\text{GE}} \), is plotted on page 2.0-31.

\[
\frac{dC_A}{d\beta} \cdot \frac{r_{sb}}{2V} = \text{Rolling moment coefficient due to roll rate about the stability axis, } x_{\beta}.
\]

The complete expression for \( \frac{dC_A}{d\beta} \) is given as follows:

\[
\frac{dC_A}{d\beta} = \left( \frac{dC_A}{d\beta} \right)_{C_{2\beta}} \cdot \left( \frac{C_{2\beta}}{C_{2\beta}} \right)_{M=0}
\]

where \( \left( \frac{dC_A}{d\beta} \right) \) is plotted on page 5.0-12. The aeroelastic effect, \( \left( \frac{C_{2\beta}}{C_{2\beta}} \right)_{M=0} \), is plotted on page 5.0-13.

\[
\frac{dC_A}{df} \cdot \frac{r_{sb}}{2V} = \text{Rolling moment coefficient due to yaw rate about the stability axis, } z_{\beta}.
\]

The complete expression for \( \frac{dC_A}{df} \) is given as follows:
\[ \frac{dC_B}{dF} = \left( \frac{dC_B}{dF} \right) \left( \frac{C_{L,F}}{C_{L,A}} \right)_{M=0} \]

where \( \left( \frac{dC_B}{dF} \right) \) is plotted on page 5.0-14. The aeroelastic effect, \( \left( \frac{C_{L,F}}{C_{L,A}} \right)_{M=0} \), is plotted on page 5.0-15.

\[ \Delta C_{L, \text{SPOILERS}} = \text{Rolling moment coefficient due to spoiler deflection.} \]

\[ \Delta C_{L, \text{SPOILERS}} = \sum_{\text{OPERATING SPOILER PANELS}} \left( K_{C_{L,SP}} \right) \left( \Delta C_{L,SP} \right)_{45} \left( \frac{C_{L,SP}}{C_{L,A}} \right)_{M=0} \left( \frac{R_E}{R_{R/SP}} \right) \cdot F_{L,GE} \]

where \( \left( \Delta C_{L,SP} \right)_{45} \) is the rolling moment coefficient due to deflecting the operating spoiler panels to 45°.

\( \left( \Delta C_{L,SP} \right)_{45} \) is plotted on page 5.0-17. The spoiler effectiveness factor, \( \left( K_{C_{L,SP}} \right) \), is plotted on page 5.0-16. The Mach number effect, \( \left( \frac{C_{L,SP}}{C_{L,A}} \right)_{M=0} \), is plotted on page 5.0-18. The aeroelastic effect, \( \left( \frac{R_E}{R_{R/SP}} \right) \), is plotted on pages 5.0-19, 5.0-20, and 5.0-21. The ground effect factor, \( F_{L,GE} \), is obtained as follows:

\[ F_{L,GE} = \left[ 1 + F_L \cdot K_{L,GE} \right] \]

where the ground effect lateral control factor, \( F_L \), is plotted on page 5.0-29. The ground effect height factor, \( K_{L,GE} \), is plotted on page 2.0-31.

\[ \Delta C_{L, \text{INBOARD AILERONS}} = \text{Rolling moment coefficient due to inboard aileron deflection.} \]
(Cont'd)

\[ \Delta C_{\text{INBOARD AILERONS}} = \sum K_{S_{\text{AI}}} \cdot (\Delta C_{L_{\text{AI}}} \theta_{20}) \cdot \left( \frac{C_{L_{\text{AI}}}}{C_{L_{\text{AI}}}} \right) \frac{R_e}{R_R \cdot C_{L_{\text{AI}}}} \cdot F_{\text{GE}} \]

where \( (\Delta C_{L_{\text{AI}}} \theta_{20}) \) is the rolling moment coefficient due to deflecting one inboard aileron up to 20° or the opposite inboard aileron down to 20°. \( (\Delta C_{L_{\text{AI}}} \theta_{20}) \) is plotted on page 5.0-23. The inboard aileron effectiveness factor, \( K_{S_{\text{AI}}} \), is plotted on page 5.0-22. The Mach number effect, \( \left( \frac{C_{L_{\text{AI}}}}{C_{L_{\text{AI}}}} \right) \frac{R_e}{R_R \cdot C_{L_{\text{AI}}}} \), is plotted on page 5.0-24. The aeroelastic effect, \( \left( \frac{R_e}{R_R \cdot C_{L_{\text{AI}}}} \right) \), is plotted on page 5.0-25. The ground effect factor, \( F_{\text{GE}} \), is obtained from page 5.0-29.

\[ \Delta C_{\text{OUTBOARD AILERONS}} = \sum K_{S_{\text{AO}}} \cdot (\Delta C_{L_{\text{AO}}} \theta_{20}) \cdot \left( \frac{R_e}{R_R \cdot C_{L_{\text{AO}}}} \right) \cdot F_{\text{GE}} \]

where \( (\Delta C_{L_{\text{AO}}} \theta_{20}) \) is the rolling moment coefficient due to deflecting one outboard aileron up to 25° or the opposite outboard aileron down to 15°. \( (\Delta C_{L_{\text{AO}}} \theta_{20}) \) is plotted on page 5.0-27. The outboard aileron effectiveness factor, \( K_{S_{\text{AO}}} \), is plotted on page 5.0-26. The aeroelastic effect, \( \left( \frac{R_e}{R_R \cdot C_{L_{\text{AO}}}} \right) \), is plotted on page 5.0-28. The ground effect factor, \( F_{\text{GE}} \), is obtained from page 5.0-29.
5.0 \( \Delta C_{RUDDERS} \) = Rolling moment coefficient due to rudder deflection. 

(Cont'd)

\[
\Delta C_{RUDDERS} = K_{RU} (\Delta C_{RU})_{25} \left( \frac{C_{RU}}{C_{RU}} \right)_{M=0} + K_{RL} (\Delta C_{RL})_{25} \left( \frac{C_{RL}}{C_{RL}} \right)_{M=0}
\]

where \((\Delta C_{RU})_{25}\) and \((\Delta C_{RL})_{25}\) are the rolling moment coefficients due to full deflection of the upper rudder and the lower rudder respectively.

\((\Delta C_{RU})_{25}\) and \((\Delta C_{RL})_{25}\) are plotted on page 5.0-30. The upper rudder effectiveness factor, \(K_{RU}\), and the lower rudder effectiveness factor, \(K_{RL}\), are plotted on pages 6.0-17 and 6.0-18 respectively. The aeroelastic effects, \(\left( \frac{C_{RU}}{C_{RU}} \right)_{M=0}\) and \(\left( \frac{C_{RL}}{C_{RL}} \right)_{M=0}\), for the upper rudder and the lower rudder, are plotted on page 5.0-31 and page 5.0-32 respectively.

\(\Delta C_{FLAP FAILURE}\) = Rolling moment coefficient due to an asymmetric (monitor limited) inboard or outboard flap failure.

\(\Delta C_{FLAP FAILURE} = \Delta C_{FLAP FAILURE, INB} \) OR \(\Delta C_{FLAP FAILURE, OUTB}\)

where \(\Delta C_{FLAP FAILURE, INB}\) is the rolling moment coefficient due to an asymmetric (monitor limited) inboard flap failure. \(\Delta C_{FLAP FAILURE, INB}\) for flap extension or retraction is plotted on pages 5.0-33 and 5.0-34 respectively.

\(\Delta C_{FLAP FAILURE, OUTB}\) for flap extension or retraction is plotted on pages 5.0-35 and 5.0-36 respectively.
5.0 $\Delta C_{\text{LE, FAILURE}}$ = Rolling moment coefficient due to asymmetric leading edge flap failure. $\Delta C_{\text{LE, FAILURE}}$ is plotted on pages 5.0-37 and 5.0-38.
### ROLLING MOMENT COEFFICIENT

**EFFECT OF SIDESLIP**

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**Note:** Gear up, free air.

**Graph**

- Plot of rolling moment coefficient ($\frac{dC_l}{d\beta}$) vs. sideslip angle ($\beta$) for different flap settings.

---

**The Boeing Company**

**Page:** 5.0-7

**REVISION:** D

---

**AD 461 C-R4**
ROLLING MOMENT COEFFICIENT

SIDESLIP EFFECT ON \( \frac{dC_m}{d\beta} \)

THE BOEING COMPANY
\[ F_{\alpha, GE} = \left[ 1 + F_{\alpha, GE} \cdot k_{GE} \right] \]

Where \( k_{GE} \) is shown on page 2.0-31.
\[ \frac{dC}{d\phi} = \frac{b}{2V} \]

PER Radian

ROLLING MOMENT COEFFICIENT
EFFECT OF YAW RATE

THE BOEING COMPANY
ROLLING MOMENT COEFFICIENT
AEROELASTIC EFFECT ON ROLLING MOMENT
COEFFICIENT DUE TO ROLL RATE

THE BOEING COMPANY

CALC RICHARDSON 11-16-67
CHECK CURNUTT 11-16-67
APR CURNUTT 2-25-70
INK KINSMAN 3-4-70

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PAGE 5.0-13
ROLLING MOMENT COEFFICIENT
AERODYNAMIC EFFECT ON ROLLING MOMENT
COEFFICIENT DUE TO YAW RATE

THE BOEING COMPANY
**SPOILER PANEL B OR 12**

Note: Data shown for individual panels B or 12.

1. For panel 1 or 5, reverse sign.
2. Panels B & 5 limited to 20 deg. max. deflection.

\[
\left(\Delta C_{1SP}\right)_{45}
\]

**SPOILER PANEL GROUP 9, 10, 11**

Note: Total effect of spoiler group 9, 10, 11 shown.

1. For spoiler group 2-7-4 reverse sign.
2. With hydraulic system no. 2 off, multiply by 0.32.
3. With hydraulic system no. 3 off, multiply by 0.68.

\[
\left(\Delta C_{1SP}\right)_{45}
\]

---

**ROLLING MOMENT COEFFICIENT**

**EFFECT OF SPOILERS**

THE BOEING COMPANY

CALC: KUPCIS 11-29-47  REVISED  DATE
CHECK: FOSTER 1-24-48  KUPCIS 6-2-69
APR  KUPCIS 2-16-70
APR  KINSMAN 2-18-70

PAGE 5-0-17
NOTE

SYMMETRIC FOR UP AND DOWN AILERON

\[ K_{\text{eff}} \]

\[ \beta_{\text{A}} = \text{DEGREES} \]

\[ 0 \quad 5 \quad 10 \quad 15 \quad 20 \]

\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad 1.0 \]

EFFECTIVENESS FACTOR
INBOARD AILERONS

THE BOEING COMPANY

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NOTE

$\left( \Delta \alpha_{AI} \right)_{20}$ is shown for right aileron up only.

For full lateral control (right aileron up and left aileron down), use $2 \times \left( \Delta \alpha_{AI} \right)_{20}$.

---

**ROLLING MOMENT COEFFICIENT**

**EFFECT OF INBOARD AILERON**

THE BOEING COMPANY

*Graph showing rolling moment coefficient vs. angle of attack.*
ROLLING MOMENT COEFFICIENT
EFFECT OF MACH NUMBER
ON INBOARD AILERONS
THE BOEING COMPANY

747
DG-30643
Vol. II
PAGE 5.0-24
REV. D
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NOTE: USE FOR ALL FLAP SETTINGS

EFFECTIVENESS FACTOR
OUTBOARD AILERONS

THE BOEING COMPANY

PAGE 5.0-26
ROLLING MOMENT COEFFICIENT
EFFECT OF OUTBOARD AILERON

THE BOEING COMPANY
NOTE: USE FOR ALL FLAP SETTINGS

1. USE FOR ALL ALTITUDES

3. USE FOR UP OR DOWNAILERONS

ROLLING MOMENT COEFFICIENT AEROELASTIC EFFECT ON ROLLING MOMENT COEFFICIENT DUE TO OUTBOARDAILERONS

THE BOEING COMPANY
NOTE: $F_{FLAT} = \left[1 + F_a \cdot k_2 \right]$

Where $F_{FLAT}$ is shown on page 2.0.41.
ROLLING MOMENT COEFFICIENT
EFFECT OF RUDDERS

THE BOEING COMPANY
NOTE
1. RIGHT INBOARD FLAP AT MONITOR LIMITED EXTENSION POSITION
   CORRESPONDING TO LEFT INBOARD FLAP FAILURE POSITION

2. CHANGE SIGN FOR RIGHT INBOARD FLAP FAILURE

THESE DATA NOT INCLUDED IN NASA SIMULATION

ROLLING MOMENT COEFFICIENT
EFFECT OF ASYMMETRIC INBOARD FLAP FAILURE FOR FLAP EXTENSION

THE BOEING COMPANY

CALC LOW 5/26/69 REVISION DATE
CHECK LOW 2/7/70
APR LOW 6/29/70
INK ODEGARD 5/26/69

REV. E

PAGE 5.0-33
NOTE

1. RIGHT INBOARD FLAP AT MONITOR LIMITED RETRACTION POSITION
   CORRESPONDING TO LEFT INBOARD FLAP FAILURE POSITION

2. CHANGE SIGN FOR RIGHT INBOARD FLAP FAILURE

THESE DATA NOT INCLUDED
IN NASA SIMULATION
NOTE
RIGHT OUTBOARD FLAP AT MONITOR LIMITED RETRACTION POSITION

CORRESPONDING TO LEFT OUTBOARD FLAP FAILURE POSITION

2. CHANGE SIGN FOR RIGHT OUTBOARD FLAP FAILURE

THESE DATA NOT INCLUDED IN NASA SIMULATION

ROLLING MOMENT COEFFICIENT
EFFECT OF ASYMMETRIC OUTBOARD FLAP FAILURE
FOR FLAP RETRACTION

THE BOEING COMPANY

CALC  LOW  5-26-69  REVISED  DATE
CHECK  LOW  2-17-70
APR    LOW  6-25-70
INK ODEGARD  5-26-69
NOTE: CHANGE SUP. FOR FAILURE OF L.E. FLAP SEGMENTS 71, 73, 74, 75, 76.

THESE DATA NOT INCLUDED IN NASA SIMULATION.

ROLLING MOMENT COEFFICIENT EFFECT OF ASYMMETRIC L.E. FLAP SEGMENTS 1, 2, 3, 4, 5 OR 22, 23, 24, 25, 26

THE BOEING COMPANY

These data not included in NASA simulation.

ROLLING MOMENT COEFFICIENT
EFFECT OF ASYMMETRIC L.E. FLAP
SEGMENTS 4, 7, 8 OR 19, 20, 21

THE BOEING COMPANY
6.0 YAWING MOMENT COEFFICIENT

The dimensionless aerodynamic yawing moment coefficient is given in terms of its significant components by the equation below.

At a given \( \alpha_{w.d.r.} \),

\[
C_n_{c.e.} = \frac{dC_n}{d\beta} \beta + \frac{dC_n}{d\beta} \frac{\beta b}{2V} + \frac{dC_n}{d\beta} \frac{R_b}{2V} + \frac{dC_n}{d\phi} \frac{r_{b\phi}}{2V} + \Delta C_n_{spoilers} + \Delta C_n_{inboard ailerons} + \Delta C_n_{outboard ailerons} + \Delta C_n_{rudders} + \left[ \Delta C_n_{flap failure} + \Delta C_n_{l.e. failure} \right]
\]

where,

\[
\frac{dC_n}{d\beta} = \text{Yawing moment coefficient due to angle of sideslip, } \beta.
\]

The complete expression for \( \frac{dC_n}{d\beta} \) is given as follows:

\[
\frac{dC_n}{d\beta} = \frac{(dC_n)(C_{n,\phi})_M \cdot F_{n_{\rho GE}} + \frac{dC_Y}{d\beta} (c.g. -.25 \frac{E}{b})}{(C_{n,\phi})_{M=0}}
\]

where \( \frac{dC_n}{d\beta} \) is the basic rate of change of yawing moment coefficient due to angle of sideslip. For low speed, \( \frac{dC_n}{d\beta} \) is plotted on page 6.0-6. The aeroelastic effect, \( \frac{(C_n\phi)_M}{(C_n\phi)_{M=0}} \), is plotted on page 6.0-6. The ground effect factor, \( F_{n_{\rho GE}} \), is obtained as follows:

\[\text{[ ]* NOT IN NASA SIMULATION}\]
$F_{n_{SGE}} = \left[ 1 + F_{n_{b}} \cdot K_{SG}^{b} \right]$

where the ground effect sideslip factor, $F_{n_{b}}$, is plotted on page 6.0-7. The ground effect height factor, $K_{SG}^{b}$, is plotted on page 2.0-31. $\frac{dC_{V}}{dp}$ is obtained from page 7.0-1.

$\frac{dC_{n}}{d\Phi} \cdot \frac{d\Phi}{2V} = \text{Yawing moment coefficient due to rate of change of sideslip angle. The complete expression for } \frac{dC_{n}}{d\Phi}\text{ is given as follows:}$

$$\frac{dC_{n}}{d\Phi} = \left( \frac{dC_{n}}{d\Phi} \right) \frac{(C_{n} \hat{n})_{M}}{(C_{n} \hat{n})_{M=0}}$$

where $\left( \frac{dC_{n}}{d\Phi} \right)$ is plotted on page 6.0-8. The aeroelastic effect, $\left( \frac{(C_{n} \hat{n})_{M}}{(C_{n} \hat{n})_{M=0}} \right)$, is plotted on page 6.0-8.

$\frac{dC_{n}}{d\Phi} \cdot \frac{P \phi}{2V} = \text{Yawing moment coefficient due to roll rate about the stability axis, } x_{\Phi}. \frac{dC_{n}}{d\Phi} \text{ is plotted on page 6.0-9.}$

$\frac{dC_{n}}{d\Phi} \cdot \frac{r \phi}{2V} = \text{Yawing moment coefficient due to yaw rate about the stability axis, } z_{\Phi}. \text{ The complete expression for } \frac{dC_{n}}{d\Phi} \text{ is given as follows:}$

$$\frac{dC_{n}}{d\Phi} = K_{\phi} \cdot \left( \frac{dC_{n} z_{\phi}}{d\Phi} \right) \frac{(C_{n} \hat{n})_{M}}{(C_{n} \hat{n})_{M=0}}$$

where $\left( \frac{dC_{n} z_{\phi}}{d\Phi} \right)$ and the center of gravity factor, $K_{\phi}$,
are plotted on page 6.0-10. The aeroelastic effect, \( \frac{(CnF)M}{(CnP)M0} \), is plotted on page 6.0-10.

\[ \Delta Cn_{SPOILERS} = Yawing\ moment\ coefficient\ due\ to\ spoiler\ deflection. \]

\[
\Delta Cn_{SPOILERS} = \sum_{\text{OPERATING}
\text{SPOILER}
\text{PANELS}} (K\delta_{SP})_n \cdot (\Delta Cn_{SP})_{45} \cdot \frac{(CnF)M}{(CnP)M0} \cdot F_{nGE}
\]

where \( (\Delta Cn_{SP})_{45} \) is the yawing moment coefficient due to deflecting the operating spoiler panels to 45°. \( (\Delta Cn_{SP})_{45} \) is plotted on page 6.0-12.

The spoiler effectiveness factor, \( (K\delta_{SP})_n \), is plotted on page 6.0-11. The Mach number effect, \( \frac{(CnF)M}{(CnP)M0} \), is plotted on page 6.0-13. The ground effect factor, \( F_{nGE} \), is obtained as follows:

\[ F_{nGE} = \left[ 1 + F_n \cdot K_{GE}^B \right] \]

where the ground effect lateral control factor, \( F_n \), is plotted on page 6.0-14. The ground effect height factor, \( K_{GE}^B \), is plotted on page 2.0-31.

\[ \Delta Cn_{INBOARD}
\text{AILERONS} = Yawing\ moment\ coefficient\ due\ to\ inboard\ aileron\ deflection. \]

\[
\Delta Cn_{INBOARD}\ AILERONS = \sum_{\text{LEFT\ AND\ RIGHT}
\text{INBOARD}
\text{AILERONS}} K\delta_{AI} \cdot (\Delta Cn_{AI})_{20} \cdot \frac{(CnA)A}{(CnA)M0} \cdot F_{nGE}
\]

where \( (\Delta Cn_{AI})_{20} \) is the yawing moment coefficient due to deflecting one inboard aileron up to 20° or...
(Cont'd)

6.0

the opposite inboard aileron down to 20°. \((\Delta C_{n_{A^I}})_{20}\) is plotted on page 6.0-15. The inboard aileron effectiveness factor, \(K_{S_{A^I}}\), is plotted on page 5.0-22. The Mach number effect, \((\Delta C_{n_{A^I}})_{M}\) is plotted on page 6.0-15. The ground effect factor, \(F_{G\&L}\), is obtained from page 6.0-14.

\[ \Delta C_{n_{OUTBOARD AILERONS}} \]

\[ = \text{Yawing moment coefficient due to outboard aileron deflection.} \]

\[ \Delta C_{n_{OUTBOARD AILERONS}} = \sum_{\text{LEFT AND RIGHT OUTBOARD AILERONS}} K_{S_{AO}} \cdot \Delta C_{n_{AO}} \cdot F_{G\&L} \]

where \(\Delta C_{n_{AO}}\) is the yawing moment coefficient due to deflecting one outboard aileron up to 25° or the opposite outboard aileron down to 15°. \(\Delta C_{n_{AO}}\) is plotted on page 6.0-16. The outboard aileron effectiveness factor, \(K_{S_{AO}}\), is plotted on page 5.0-26. The ground effect factor, \(F_{G\&L}\), is obtained from page 6.0-14.

\[ \Delta C_{n_{RUDDERS}} \]

\[ = \text{Yawing moment coefficient due to rudder deflection.} \]

\[ \Delta C_{n_{RUDDERS}} = K_{S_{RU}} \cdot (\Delta C_{n_{RU}})_{25} \cdot \frac{(C_{n_{RU}})_{M=0}}{(C_{n_{RU}})_{M=0}} + K_{S_{RL}} \cdot (\Delta C_{n_{RL}})_{25} \cdot \frac{(C_{n_{RL}})_{M}}{(C_{n_{RL}})_{M}} \]

\[ + \Delta C_{Y_{RUDDERS}} \cdot (\text{C.G.-.25}) \cdot \frac{C}{b} \]

where \((\Delta C_{n_{RU}})_{25}\) and \((\Delta C_{n_{RL}})_{25}\) are the yawing moment coefficients due to full deflection of the upper rudder and the lower rudder respectively.
(Cont'd)  

\((\Delta C_{n_{RU}})_{25}\) and \((\Delta C_{n_{RL}})_{25}\) are plotted on page 6.0-19. The upper rudder effectiveness factor, \(K_{SRU}\), and the lower rudder effectiveness factor, \(K_{SRU}\), are plotted on page 6.0-17, and on page 6.0-18 respectively. The aeroelastic effects, \(\frac{(C_{n_{RU}})_{M}}{(C_{n_{RU}})_{M=0}}\) and \(\frac{(C_{n_{RL}})_{M}}{(C_{n_{RL}})_{M=0}}\), for the upper rudder and the lower rudder, are plotted on page 6.0-20 and page 6.0-21 respectively. It should be noted that for rudder deflection with one rudder inoperative, the appropriate rudder contribution should be multiplied by 1.12.  

\(\Delta C_{Y, RUDEERS}\) is obtained from page 7.0-3.

\[\Delta C_{n_{FLAP\ FAILURE}}\] = Yawing moment coefficient due to an asymmetric (monitor limited) inboard or outboard flap failure.

\[\Delta C_{n_{FLAP\ FAILURE}} = \Delta C_{n_{INB'D\ FAILURE}} \text{ OR } \Delta C_{n_{OUTB'D\ FAILURE}}\]

where \(\Delta C_{n_{INB'D\ FAILURE}}\) is the yawing moment coefficient due to an asymmetric (monitor limited) inboard flap failure. \(\Delta C_{n_{INB'D\ FAILURE}}\) for flap extension or retraction is plotted on pages 6.0-22 and 6.0-23 respectively.

\(\Delta C_{n_{OUTB'D\ FAILURE}}\) for flap extension or retraction is plotted on pages 6.0-24 and 6.0-25 respectively.

\[\Delta C_{n_{L.E.\ FAILURE}}\] = Yawing moment coefficient due to asymmetric leading edge flap failure. \(\Delta C_{n_{L.E.\ FAILURE}}\) is plotted on pages 6.0-26 and 6.0-27.
NOTE: 1. Scan up and down, free air.

\[ \frac{dC_n}{d\beta} \]

PER DEG

0.065

0.064

0.063

0.062

0.061

0.060

0.059

0.058

0.057

0.056

0.055

0.054

0.053

0.052

0.051

0.050

0.049

0.048

0.047

0.046

0.045

0.044

0.043

0.042

0.041

0.040

0.039

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0.037

0.036

0.035

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0.032

0.031

0.030

0.029

0.028

0.027

0.026

0.025

0.024

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0.021

0.020

0.019

0.018

0.017

0.016

0.015

0.014

0.013

0.012

0.011

0.010

0.009

0.008

0.007

0.006

0.005

0.004

0.003

0.002

0.001

0.000

X-W.D. - DEGREES

YAWING MOMENT COEFFICIENT
EFFECT OF SIDESLIP

THE BOEING COMPANY
\[ F_{n_{aex}} = 1 + K_{aex} K_{aex} \]

*NOTE: \( K_{aex} \) is shown on page 2.6-3.*
NOTE \( \frac{dC_n}{d\beta} = \frac{\dot{\alpha} \cdot \alpha}{V} \) per radian

2. USE FOR ALL FLAP SETTINGS

\[
\frac{C_{n\alpha}}{C_{n\beta} \cdot M = D}
\]

YAWING MOMENT COEFFICIENT \( \frac{\dot{\alpha}}{} \)
EFFECT OF \( \beta \)

THE BOEING COMPANY

CALC RICHARDSON 11-13-67 REVISED DATE
CHECK CURNUTT 11-14-67 LOW 6-14-69
APR LUDWIG 11-3-69
APR CURNUTT 2-29-70
INK ODEGARD 3-3-70
NOTE: \( \omega = \frac{P_B}{V}, \quad \beta = \text{rad/sec}, \quad V = \text{ft/sec} \) [TRUE AIRSPEED]

\[ \frac{dC_n}{d\beta} \]

PER RADIANS

YAWING MOMENT COEFFICIENT EFFECT OF ROLL RATE

THE BOEING COMPANY

CALC  RICHARDSON  11-14-67  REVISION  DATE
CHECK  CURNUTT  11-16-67  LUDWIG  11-5-69
APR  CURNUTT  2-25-70
APR
INK  ODEGARD  3-4-70

Page 6.0-9
EFFECT OF YAW RATE

$K_p = \frac{C_n}{\phi}$

$dC_n_{\phi = 25}$

df

PER Radian

$\frac{C_n f/M}{C_n A_{M=0}}$

YAWING MOMENT COEFFICIENT
EFFECT OF YAW RATE

THE BOEING COMPANY

CALC RICHARDSON 11-13-47
CHECK CURNUTT 11-16-47
APR CURNUTT 2-25-70
INK ODEGARD 3-2-70

REV. D

AD 461 C-R4
NOTE 1. USE FOR ALL SPOILER PANELS

2. PANELS 645 LIMITED TO 20 DEG MAX DEFLECTION

YAWING MOMENT COEFFICIENT EFFECTIVENESS FACTOR SPOILERS
THE BOEING COMPANY

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**Spoiler Panel B or 12**

**NOTE**
1. Data shown for individual panels B or 12.
2. For panel 1 or 5, reverse sign.
3. Panels B & S limited to 20 deg. max. deflection.

---

**Spoiler Panel Group 9, 10, 11**

**NOTE**
1. Total effect of spoiler group 9, 10, is shown.
2. For spoiler group 2, 3, 4, reverse sign.
3. With hydraulic system no. 2 off, multiply by 0.65.
4. With hydraulic system no. 3 off, multiply by 0.60.
NOTE: \( F_n = \left[ 1 + F_R - K_n \right] \)

WHERE \( K_n \) IS SHOWN ON PAGE 2.0-91

GROUND EFFECT
LATERAL CONTROL FACTOR, \( F_n \)

THE BOEING COMPANY

CALC: CURRUTT 12/18/67
CHECK: FOSTER 12/24/68
APR
APR
INK: ODEGARD 12/18/67

REV. D
NOTE 1: \[ (\Delta C_{n_{A_z}}) \text{ is shown for right aileron up only} \]

FOR FULL LATERAL CONTROL (RIGHT AILERON UP AND LEFT AILERON DOWN), USE \[ 2 \times (\Delta C_{n_{A_z}}) \text{ for } M < 1 \]

\[ (\Delta C_{r_{A_z}}) \text{ for } M > 1 \]
EFFECTIVENESS FACTOR
UPPER RUDDER

THE BOEING COMPANY
EFFECTIVENESS FACTOR
LOWER RUDDER
EFFECT OF RUDDERS

NOTE 1: FOR LOWER RUDDER INOPERATIVE, MULTIPLY BY 1.12

\[
\left( \frac{\Delta C_{\text{r}(L)}^{(N)}}{L} \right)_{25} = \text{value}
\]

\[
\left( \frac{\Delta C_{\text{r}(R)}^{(N)}}{L} \right)_{25} = \text{value}
\]

X_{HZA} - DEGREES

NOTE 2: FOR UPPER RUDDER INOPERATIVE, MULTIPLY BY 1.12

YAWING MOMENT COEFFICIENT
EFFECT OF RUDDERS

THE BOEING COMPANY
NOTE

YAWING MOMENT COEFFICIENT
AERODYNAMIC EFFECT ON YAWING MOMENT
COEFFICIENT DUE TO UPPER RUDDER

THE BOEING COMPANY

CALC WILCOXEN 12.20.67 CHECK RICHARDSON 12.21.67
CALC WILCOXEN 12.20.67 CHECK RICHARDSON 4.8.68
APR RICHARDSON LOW 6.14.69
APR RICHARDSON BECK 2.5.70
INK KINSMAN 2.5.70

PAGE 6.0-20

REV D

AD 401 C-R4
NOTE FOR ALL FLAP SETTIN

YAWING MOMENT COEFFICIENT
AEROELASTIC EFFECT ON YAWING MOMENT
COEFFICIENT DUE TO LOWER RUDDER

CALC WILCOXEN 12/20/67
CHECK RICHARDSON 12/21/67
APR 1968
APR
INK KINSMAN 2-5-70

THE BOEING COMPANY

PAGE 4.0-21
NOTE
RIGHT INBOARD FLAP AT MONITOR LIMITED RETRACTION POSITION
CORRESPONDING TO LEFT INBOARD FLAP FAILURE POSITION

2. CHANGE SIGN FOR RIGHT INBOARD FLAP FAILURE

THESE DATA NOT INCLUDED IN NASA SIMULATION.

CALC  LOW  5.5.669  REVISED  DATE
CHECK  LOW  2.17.70
APR    LOW  6.25.70
INK ODEGARD  5.26.69

YAWING MOMENT COEFFICIENT
EFFECT OF ASYMMETRIC INBOARD FLAP FAILURE
FOR FLAP RETRACTION

THE BOEING COMPANY
NOTE

RIGHT OUTBOARD FLAP AT MONITOR LIMITED EXTENSION POSITION
CORRESPONDING TO LEFT OUTBOARD FLAP FAILURE POSITION

2. CHANGE SIGN FOR RIGHT OUTBOARD FLAP FAILURE

THESE DATA NOT INCLUDED IN NASA SIMULATION.

YAWING MOMENT COEFFICIENT

EFFECT OF ASYMMETRIC OUTBOARD FLAP FAILURE FOR FLAP EXTENSION

THE BOEING COMPANY

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PAGE 6.0-24

DO-30643
Vol. II
NOTE:

1. RIGHT OUTBOARD FLAP AT MONITOR LIMITED RETRACTION POSITION CORRESPONDING TO LEFT OUTBOARD FLAP FAILURE POSITION

2. CHANGE SIGN FOR RIGHT OUTBOARD FLAP FAILURE

THESE DATA NOT INCLUDED IN NASA SIMULATION.

CALC | LOW | 5-26-69 | REVISED | DATE | 2-17-70 | 6-25-70
--- | --- | --- | --- | --- | ---
CHECK | LOW | | | | |
APR | LOW | | | | |
APR | | | | | |
INK | ODEGARD | 5-26-69 | | | |

YAWING MOMENT COEFFICIENT EFFECT OF ASYMMETRIC OUTBOARD FLAP FAILURE FOR FLAP RETRACTION

THE BOEING COMPANY

PAGE 6.0-25
NOTE 1. CHANGE SIGN FOR FAILURE OF L.E. FLAP SEGMENTS 22, 23, 24, 25, 26

THOSE DATA NOT INCLUDED IN NASA SIMULATION

LE. FLAP SEGMENTS 1, 2, 3, 4, 5 FAILED TO EXTEND

LE. FLAP SEGMENTS 1, 2, 3, 4, 5 FAILED TO RETRACT

Yawing Moment Coefficient

Effect of Asymmetric L.E. Flap

Segments 1, 2, 3, 4, 5 or 22, 23, 24, 25, 26
NOTE 1. CHANGE SIGN FOR FAILURE OF L.E. FLAP SEGMENTS 19, 20, 21.

PLATE DATA NOT INCLUDED IN V.M. SIMULATION.

\[ \Delta C_n \]
\[ \text{L.E. FLAP} \]
\[ \text{FAILURE} \]

L.E. FLAP SEGMENTS 6, 7, 8 FAILED TO EXTEND.
L.E. FLAP SEGMENTS 4, 7, 8 FAILED TO RETRACT.

\[ \text{\( \alpha_{\text{W.D.P.}} \)} \]
\[ \text{DEGREES} \]

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YAWING MOMENT COEFFICIENT
EFFECT OF ASYMMETRIC L.E. FLAP
SEGMENTS 6, 7, 8 OR 19, 20, 21

THE BOEING COMPANY

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DC-30643
Vol. II
PAGE 60-27
7.0 SIDE FORCE COEFFICIENT

The dimensionless aerodynamic side force coefficient is given in terms of its significant components by the equation below.

At a given $\alpha_{w.d.r.}$,

$$C_Y = \frac{dC_Y}{d\beta} \cdot \beta + \frac{dC_Y}{d\beta} \cdot P_{s\beta} \cdot \frac{c}{2V} + \frac{dC_Y}{d\beta} \cdot r_{s\beta} \cdot \frac{c}{2V}$$

$$+ \Delta C_{Y_{\text{sponiers}}} + \Delta C_{Y_{\text{rudders}}} + [\Delta C_{Y_{\text{flap failure}}}]$$

$$+ \Delta C_{Y_{\text{L.E. failure}}}]$$

where,

$$\frac{dC_Y}{d\beta} \cdot \beta = \text{Side force coefficient due to angle of sideslip, } \beta.$$  

The complete expression for $\frac{dC_Y}{d\beta}$ is given as follows:

$$\frac{dC_Y}{d\beta} = \left(\frac{dC_Y}{d\beta} \cdot \frac{(C_Y \beta)_M}{(C_Y \beta)_{M=0}} + K_{\text{GEAR}} \cdot \Delta \left(\frac{dC_Y}{d\beta}\right)_{\text{LANDING GEAR}}\right) F_{Y_{\text{GEAR}}},$$

where $\left(\frac{dC_Y}{d\beta}\right)$ is the basic rate of change of side force coefficient due to angle of sideslip. For low speed, $\left(\frac{dC_Y}{d\beta}\right)$ is plotted on page 7.0-5. The aeroelastic effect, $\frac{(C_Y \beta)_M}{(C_Y \beta)_{M=0}}$, is plotted on page 7.0-5. The effect of main and nose gear extension, $\Delta \left(\frac{dC_Y}{d\beta}\right)_{\text{LANDING GEAR}}$ is given by:

$$\Delta \left(\frac{dC_Y}{d\beta}\right)_{\text{LANDING GEAR}} = -0.002 \text{ PER DEGREE}$$

[ ]* NOT IN NASA SIMULATION
The landing gear effectiveness factor, $K_{GEAR}$, is plotted on page 2.0-28.

The ground effect factor, $F_{Y_{GE}}$, is obtained as follows:

$$F_{Y_{GE}} = \left[ 1 + F_{Y_{E}} \cdot K_{GE}^B \right]$$

where the ground effect sideslip factor, $F_{Y_{E}}$, is plotted on page 7.0-6. The ground effect height factor, $K_{GE}^B$, is plotted on page 2.0-31.

$$\frac{dC_Y}{d\beta} = \frac{F_{sb}}{2V}$$

is the side force coefficient due to roll rate about the stability axis, $x_s$. $\frac{dC_Y}{d\beta}$ is plotted on page 7.0-7.

$$\frac{dC_Y}{d\phi} = \frac{F_{sb}}{2V}$$

is the side force coefficient due to yaw rate about the stability axis, $z_s$. The complete expression for $\frac{dC_Y}{d\phi}$ is given as follows:

$$\frac{dC_Y}{d\phi} = \left( \frac{dC_Y}{d\phi} \right) \cdot \frac{(C_Y)_{M}}{(C_Y)_{M=0}}$$

where $\left( \frac{dC_Y}{d\phi} \right)$ is plotted on page 7.0-8. The aeroelastic effect, $\frac{(C_Y)_{M}}{(C_Y)_{M=0}}$, is plotted on page 7.0-9.

$$\Delta C_{Y_{SPOILERS}} = \text{Side force coefficient due to spoiler deflection.}$$

$$\Delta C_{Y_{SPOILERS}} = \sum_{\text{OPERATING SPOILER PANELS}} (K_{b_{SP}})_{\gamma} \cdot (\Delta C_{Y_{SP}})_{45} \cdot \frac{(C_{Y_{SP}})_{M}}{(C_{Y_{SP}})_{M=0}} \cdot F_{n_{GE}}$$

where $(\Delta C_{Y_{SP}})_{45}$ is the side force coefficient due to deflecting the operating spoiler panels to $45^\circ$.

$(\Delta C_{Y_{SP}})_{45}$ is plotted on page 7.0-11. The spoiler
effectiveness factor, \((K_{\text{effSP}})_{\gamma}\), is plotted on page 7.0-10. The Mach number effect, \(\frac{(C_{\text{YSP}})_M}{(C_{\text{YSP}})_{M=0}}\), is plotted on page 7.0-12. The ground effect factor, \(F_{\text{NE}}\), is obtained from page 6.0-14.

\[\Delta C_{Y\text{Rudders}} = \text{Side force coefficient due to rudder deflection.}\]

\[\Delta C_{Y\text{Rudders}} = K_{\delta\text{RU}} \cdot (\Delta C_{Y\text{RU}})_{25} \cdot \frac{(C_{Y\text{RU}})_M}{(C_{Y\text{RU}})_{M=0}} + K_{\delta\text{RL}} \cdot (\Delta C_{Y\text{RL}})_{25} \cdot \frac{(C_{Y\text{RL}})_M}{(C_{Y\text{RL}})_{M=0}}\]

where \((\Delta C_{Y\text{RU}})_{25}\) and \((\Delta C_{Y\text{RL}})_{25}\) are the side force coefficients due to full deflection of the upper rudder and the lower rudder respectively. \((\Delta C_{Y\text{RU}})_{25}\) and \((\Delta C_{Y\text{RL}})_{25}\) are plotted on page 7.0-13. The upper rudder effectiveness factor, \(K_{\delta\text{RU}}\), and the lower rudder effectiveness factor, \(K_{\delta\text{RL}}\), are plotted on pages 6.0-17 and 6.0-18 respectively. The aero-elastic effects, \(\frac{(C_{Y\text{RU}})_M}{(C_{Y\text{RU}})_{M=0}}\) and \(\frac{(C_{Y\text{RL}})_M}{(C_{Y\text{RL}})_{M=0}}\), for the upper rudder and the lower rudder, are plotted on pages 7.0-14 and 7.0-15 respectively.

\[\Delta C_{Y\text{Flap Failure}} = \text{Side force coefficient due to an asymmetric (monitor limited) inboard or outboard flap failure.}\]

\[\Delta C_{Y\text{Flap Failure}} = \Delta C_{Y\text{INBD Failure}} \text{ OR } \Delta C_{Y\text{OUTBD Failure}}\]

where \(\Delta C_{Y\text{INBD Failure}}\) is the side force coefficient due to an asymmetric (monitor limited) inboard flap failure. \(\Delta C_{Y\text{INBD Failure}}\) for flap extension or retraction is plotted on pages 7.0-16 and 7.0-17.
7.0 respectively.

(Cont'd) \( \Delta C_{Y_{\text{OUTER FAILURE}}} \) for flap extension or retraction is plotted on pages 7.0-18 and 7.0-19 respectively.

\( \Delta C_{Y_{\text{LE. FAILURE}}} \) = Side force coefficient due to asymmetric leading edge flap failure. \( \Delta C_{Y_{\text{LE. FAILURE}}} \) is plotted on pages 7.0-20 and 7.0-21.
NOTE

\[ k_{se} = \left[ 1 + k_{se} \right] \]

WHERE \( k_{se} \) IS SHOWN ON PAGE 2.0-31.
SIDE FORCE COEFFICIENT
AEROELASTIC EFFECT ON SIDE FORCE COEFFICIENT DUE TO YAW RATE
THE BOEING COMPANY

CALC RICHARDSON 4/15/67  
CHECK CURNUTT 4/14/67  
APR  
APR  
INK ODEGARD 11/14/67  

REV. B
NOTE 1 USE FOR ALL SPOILER PANELS

2 PANELS 0-5' LIMIT TO 20 DEG MAX DEFORMATION

(Spoiler Effectiveness Factor) vs. Deflection

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SIDE FORCE COEFFICIENT EFFECTIVENESS FACTOR SPOILERS

THE BOEING COMPANY
SPOILER PANEL B OR 12

NOTE
1. DATA SHOWN FOR INDIVIDUAL PANELS B OR 12
2. FOR PANEL 1 OR 5, REVERSE SIGN
3. PANELS B & 5 LIMITED TO 20 DEG. MAX. DEFLECTION

SPOILER PANEL GROUP 5, 10, 11

NOTE
1. TOTAL EFFECT OF SPOILER GROUP 5, 10, 11 SHOWN
2. FOR SPOILER GROUP 2, 3, 4, REVERSE SIGN
3. WITH HYDRAULIC SYSTEM NO. 2 OFF, MULTIPLY BY 0.60
4. WITH HYDRAULIC SYSTEM NO. 3 OFF, MULTIPLY BY 0.60

SIDE FORCE COEFFICIENT EFFECT OF SPOILERS

THE BOEING COMPANY
SIDE FORCE COEFFICIENT

AEROELASTIC EFFECT ON SIDE FORCE

COEFFICIENT DUE TO LOWER RUDDER

THE BOEING COMPANY

CALC: RICHARDSON 12-8-67
CHECK: FOSTER 1-24-68
APR: BECK 2-5-70
APR: KINSMAN 2-5-70

REVISED DATE
LOW 6-14-68

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PAGE 7.0-15
NOTE

RIGHT INBOARD FLAP AT MONITOR LIMITED RETRACTION POSITION
CORRESPONDING TO LEFT INBOARD FLAP FAILURE POSITION

2. CHANGE SIGN FOR RIGHT INBOARD FLAP FAILURE

SIDE FORCE COEFFICIENT

EFFECT OF ASYMMETRIC INBOARD FLAP FAILURE FOR FLAP RETRACTION

THE BOEING COMPANY

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CHECK APR APR INK ODEGARD 5-26-69 LOW 2-17-70 LOW 6-25-70 5-26-69

SIDE FORCE COEFFICIENT

EFFECT OF ASYMMETRIC INBOARD FLAP FAILURE FOR FLAP RETRACTION

THE BOEING COMPANY

747
NOTE

1. RIGHT OUTBOARD FLAP AT MONITOR LIMITED EXTENSION POSITION
   CORRESPONDING TO LEFT OUTBOARD FLAP FAILURE POSITION

2. CHANGE SIGN FOR RIGHT OUTBOARD FLAP FAILURE

These data not included in NGA SOLUCO.

SIDE FORCE COEFFICIENT
EFFECT OF ASYMMETRIC OUTBOARD FLAP FAILURE
FOR FLAP EXTENSION

THE BOEING COMPANY

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NOTE

RIGHT OUTBOARD FLAP AT MONITOR LIMITED RETRACTION POSITION

CORRESPONDING TO LEFT OUTBOARD FLAP FAILURE POSITION

2. CHANGE SIGN FOR RIGHT OUTBOARD FLAP FAILURE

SIDE FORCE COEFFICIENT

EFFECT OF ASYMMETRIC OUTBOARD FLAP FAILURE

FOR FLAP RETRACTION

THE BOEING COMPANY
NOTE 1. CHANGE SIGN FOR FAILURE OF L.E. FLAP SEGMENTS 19, 20, 21.

L.E.FLAP SEGMENTS 6, 7, 8 FAILED TO EXTEND
L.E.FLAP SEGMENTS 6, 7, 8 FAILED TO RETRACT

\[ \Delta C_y \]

\[ \text{L.E. FAILURE} \]

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SIDE FORCE COEFFICIENT

EFFECT OF ASYMMETRIC L.E. FLAP
SEGMENTS 6, 7, 8 OR 19, 20, 21

THE BOEING COMPANY
8.0 LONGITUDINAL CONTROL SYSTEM

A general description of the longitudinal system is presented in the Introduction on Pages 1.2-1 and 1.2-2 and in Volume I. A block diagram of the simulated elevator control system and stick force program is shown on Page 8.1-3. The data for each particular block can be found on the page numbers adjacent to the block.

8.1 Control Column Force and Elevator Deflection

The column travel in the 747 is $12.67^\circ$ pull and $-12.5^\circ$ push. The column travel in the FSAA is $+11^\circ$. The column deflection of the FSAA was scaled up by 1.15 ($= 12.67/11$) so that maximum column in the FSAA resulted in maximum column in the simulated 747.

The feel unit pressure, used in determining the feel unit torque, is

$$P_f = \frac{dF_s}{d\delta} \cdot (-120.9) \text{ lb/in}^2$$

where

$$\frac{dF_s}{d\delta} = \left[-0.0025 \cdot q_c + "Fs" \right] \Rightarrow "FQC"$$

$P_f =$ Feel unit pressure, lb/in$^2$

$\frac{dF_s}{d\delta} =$ Control column force gradient, lb/deg

"Fs" = Column force gradient at $q_c = 0$.
This is plotted on Page 8.1-7

"FQC" = Column force gradient $q_c$ limit.
This is plotted on Page 8.1-8
The stick force due to the column mass unbalance is:

\[ \text{FS}_\text{mass unbalance} = n_z [\vartheta_B + 5.4] \cdot (-.275) \text{ lb} \]

The FSAA control loader was programmed with a breakout force plus a constant gradient for zero computed stick force. The control loader preload characteristics recorded by an x-y plotter are shown on Page 8.1-9. The preload characteristics were subtracted from the computed stick force on the NASA digital computer. The control loader was commanded with an incremental stick force (computed stick force minus preload stick force).
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**Forward Quadrant Travel vs. Column Deflection**

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**FEEL UNIT TORQUE VS. AFT QUADRANT TRAVEL**

THE BOEING COMPANY
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Mechanical Advantage vs. Column Deflection

THE BOEING COMPANY

747

D6-30643
Vol. 11
Page 8.1-6
8.2 Elevator Control System

8.2.1 Elevator Limits - Boost On and Off

The maximum inboard and outboard elevator limits are shown on pages 8.2-2 and 8.2-3 for full and half boost operation, respectively.

An inboard or outboard elevator surface with both hydraulic systems off will trail at the float angles shown on pages 8.2-4 and 8.2-5, respectively.

8.2.2 Elevator Rigging

The elevator is downrigged at +2° from the faired position.

The outboard elevator angle is equal to the inboard elevator angle up to the blowdown angle of the outboard elevator.
LONGITUDINAL CONTROL
INBOARD ELEVATOR BLOWDOWN

THE BOEING COMPANY
NOTE: $K_{E,FLOAT} = \left( \frac{\delta_{E,FLOAT}}{\delta_{E,R.L} = 0} \right)^{\frac{1}{4}}$}

**FLAPS UP**

$\left( \frac{\delta_{E,FLOAT}}{\delta_{E,R.L} = 0} \right)^{\frac{1}{4}}$

**FLAPS DOWN**

$\left( \frac{\delta_{E,FLOAT}}{\delta_{E,R.L} = 0} \right)^{\frac{1}{4}}$

**EFFECT OF STABILIZER**

**MACH NUMBER, M**

**MACH NUMBER, M**

**LONGITUDINAL CONTROL**

**INBOARD ELEVATOR FLOAT ANGLES**

THE BOEING COMPANY

747

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Vol. II

PAGE 8.2-4
8.3 Stabilizer Trim System

8.3.1 Trim Rate

A block diagram of the simulated trim system is shown on Page 8.3-1. The stabilizer trim rate is programmed by impact pressure, $q_c$. Page 8.3-2 shows the pilot and autopilot trim rates.
9.0 LATERAL CONTROL SYSTEM

A general description of the system is presented in the Introduction on Pages 1.2-2, 1.2-3 and 1.2-4 and in Volume I. A block diagram of the NASA simulated lateral control system is shown on Page 9.1-2a. The data for each particular block can be found on the page number adjacent to the block. The computer requirements for the simulation were reduced by applying an equivalent rate limit to the wheel rather than to each spoiler panel. The outboard aileron lockout program utilized in the simulation was a function of flap screw travel, Page 9.2-8, rather than a function of time, as shown on Page 9.2-4.

9.1 Control Wheel Force and Angle

9.1.1 Control Wheel Force

\[ F_W = F_{WS} \pm F_{WFR} \]

where,

- \( F_W \) = Control wheel force, positive for a clockwise wheel moment (lb).

- \( F_{WS} \) = Control wheel force due to the spring and cam mechanism (lb). This is plotted on page 9.1-3.

- \( F_{WFR} \) = Friction force opposing control wheel motion (= 2.0 lb).
9.1.2 Control Wheel Angle

\[ \delta_W = \delta_{W_{REP}} + 0.35 F_W \]

where,

- \( \delta_W \) = Control wheel angle (degrees). The control wheel limits are \( \delta_W = \pm 88 \) degrees.
- \( \delta_{W_{REP}} \) = Reference control wheel angle (degrees). This does not include the effect of cable stretch and is the input to the aileron and spoiler programs plotted on pages 9.2-3 and 9.2-5 respectively.
- 0.35 = Cable stretch factor (deg/lb).

9.1.3 Lateral Trim

\( \delta_{W_{TRIM}} \) = Zero force datum wheel angle due to trim (degrees). This is plotted on page 9.1-4. The trim shifts the wheel force datum but does not change the wheel limits. The trim limits are \( \pm 6.27 \) units. The nominal trim rate is 2.5 degrees of control wheel per second.
NOTE
1. \( F_w = F_{w_5} + F_{w_{PR}} \)
2. \( F_{w_{PR}} = 2.0 \text{ lb} \)
3. SYMMETRIC FOR OPPOSITE WHEEL
4. CONTROL WHEEL LIMITS ARE \( \delta_w = \pm 86^\circ \)

THESE DATA NOT INCLUDED IN NASA SIMULATION SEE P. 14.1-52
NOTE 1  SYMMETRIC FOR OPPOSITE TRIM.

2  WHEEL FORCE DATUM SHIFTS WITH TRIM.

3  TRIM LIMITS = ± 6.27 UNITS.

4  TRIM RATE = 2.5° CONTROL WHEEL PER SECOND.

\[ \Delta \theta_{\text{trim}} \text{ DEG.} \]

\[ 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \]

LATERAL TRIM INDICATOR - UNITS

LATERAL CONTROL
LATERAL TRIM.

THE BOEING COMPANY

CALC MOOIWEER 12.4.67
CHECK HOLTZNER 12.4.67
APR KUPCIS 6-25-70
APR
INK ODEGARD 2-10-70

D6-30643
Vol. II

PAGE 9.1-4
9.2 Aileron-Spoiler-Wheel Program

9.2.1 Lateral Control Only

The inboard aileron wheel program is plotted on page 9.2-3.

For fully unlocked outboard ailerons, the outboard aileron wheel program is plotted on page 9.2-3. Full outboard aileron authority is available at all times for flaps 5, 10, 20, 25 and 30.

Outboard aileron unlocking is started at outboard flap jackscrew extension to 0% of jackscrew travel and full unlocking takes about 15 seconds. After this time, full outboard aileron authority is available. Outboard aileron locking is started at outboard flap jackscrew retraction to 0% of jackscrew travel and full locking takes about 15 seconds. After this time, no outboard aileron authority is available. For intermediate outboard aileron authority

\[ \delta_{\theta_0} = k_{\delta_{\theta_0}} \cdot \delta_{\theta_0, \text{ref}} \]

where,

- \( \delta_{\theta_0} \) = Outboard aileron angle (degrees). The outboard aileron mechanical limits are 25° T.E. up and 15° T.E. down.

- \( k_{\delta_{\theta_0}} \) = Intermediate outboard aileron gain factor. This is a function of flap screw travel and is plotted on Page 9.2-4.
9.2.1 \( \delta_{\text{A REF}} \) = Reference outboard aileron angle (degrees) commanded from the aileron - wheel program, Page 9.2-3.

In the NASA simulation outboard ailerons are locked out when flaps are fully retracted.

The spoiler-wheel program is plotted on page 9.2-5.

9.2.2 Lateral Control With Speed Brake Operation

The aileron wheel program remains the same for all speed brake handle positions.

For intermediate and normal inflight speed brake handle positions, the spoiler wheel program is plotted on page 9.2-6.

9.2.3 Speed Brake Operation

The speed brake program with no lateral control inputs is plotted on page 9.2-7. Panels 3, 4, 5, 6, 7, 8, 9, 10 are used as inflight speed brakes (intermediate and inflight speed brake handle positions). The remaining panels 1, 2, 11, 12 operate only as ground speed brakes (ground speed brake handle position). Spoiler panels 6 and 7, which operate symmetrically as speed brakes only, cannot be modulated. These surfaces are either fully extended or fully retracted depending on the position of the speed brake handle.
OUTBOARD AILERON = OUTBOARD AILERON COMMANDED BY WHEEL \times \frac{k_{5\alpha_0}}{k_{5\alpha_0}}

\left( S_{\alpha_0} = S_{\alpha_0}^{\text{REF}} \cdot \frac{k_{5\alpha_0}}{k_{5\alpha_0}} \right)

REFER TO P. 9.2-3 FOR THE AILERON-WHEEL PROGRAM

USE FOR UP AND DOWN AILERON

\frac{S_{\alpha_0}}{S_{\alpha_0}^{\text{REF}}} \text{ PST (FLAP SCREW TRAVEL)}

0 20 40 60 80 100

0 .2 .4 .6 .8 1.0

LATERAL CONTROL
INTERMEDIATE OUTBOARD
AILERON GAIN FACTOR

THE BOEING COMPANY

CALC
CHECK
APR
APR

REVISED DATE

3/25/79

NORDWALL

PAGE

9.2-4

74-7

D6-30643
VOL III
NOTE: FOR SPEED BRAKES IN THE GROUND DETENT, USE THE IN-FLIGHT DETENT CURVES FOR PANELS 3, 4, 5 & 8, 9, 10. FOR PANELS 11 & 12 USE THE CURVE FOR PANEL 3. FOR PANELS 11 & 12 USE THE CURVE FOR PANELS 9, 10. PANELS 4 & 7 REMAIN AT 20° FOR ALL WHEEL ANGLES.

INTERMEDIATE IN-FLIGHT SPEED BRAKE (SPEED BRAKE HANDLE = 16°)

SEE SECTION 19 FOR REVISED DATA

LATERAL CONTROL
SPOILER PROGRAM AT COMBINED LATERAL CONTROL - SPEED BRAKES

THE BOEING COMPANY
NOTE:  SPEED BRAKE HANDLE FRICTION FORCE = 20 LBS PULL, 0 LBS PULL

2. MAXIMUM AVAILABLE IN-FLIGHT SPEED BRAKE HANDLE POSITION = 30 DEG (IN-FLIGHT DETENT)

3. SPEED BRAKES BEYOND THE IN-FLIGHT DETENT ARE AVAILABLE ONLY ON THE GROUND

See Section 19 for revised data.
9.3 Control Surface Limits and Float Angles

The maximum inboard aileron and maximum outboard aileron angles for full boost and half boost are plotted on pages 9.3-2 and 9.3-3 respectively. The maximum spoiler angles are plotted on pages 9.3-4, 9.3-5 and 9.3-6.

Any inboard or outboard aileron surface with both hydraulic systems off, will trail at the float angles plotted on pages 9.3-7 and 9.3-8 respectively. The spoilers are held in a faired position, boost off, due to the hold down check valves.
NOTE

1. HYDRAULIC SYSTEMS 1 AND 2 ON LEFT AILERON

2. HYDRAULIC SYSTEMS 3 AND 4 ON RIGHT AILERON

3. FULL BOOST
   HALF BOOST

EQUIVALENT AIRSPEED, $V_e \sim$ KNOTS

120 140 160 180 200 220 240 260

LATERAL CONTROL

OUTBOARD AILERON BLOWDOWN

THE BOEING COMPANY
NOTE: $\frac{d\delta A_1}{dx}$ float = \left(\frac{\delta A_1}{\delta M} \right)_{\delta M = 0} + \frac{d\delta A_1}{dx} = \frac{\delta A_1}{\delta M} \cdot \delta M$

These data not included in NASA simulation.

FLAPS UP AND DOWN

FLAPS UP

LATITAL CONTROL
INBOARDAILERON FLOAT ANGLES

THE BOEING COMPANY
NOTE:
1. $\frac{d\delta_{s-A}}{dx}$
2. Interpolate Linearly For Intermediate Flap Settings.

THOSE DATA NOT INCLUDED.

LATERAL CONTROL
OUTBOARD AILERON FLOAT ANGLES

THE BOEING COMPANY
10.0 DIRECTIONAL CONTROL SYSTEM

A general description of the system is presented in the Introduction on Pages 1.2-4 and 1.2-5 and in Volume I. A block diagram of the simulated directional control system is shown on Page 10.1-2a. The data for each particular block can be found on the page number adjacent to the block.

10.1 Rudder Pedal Force and Angle

10.1.1 Rudder Pedal Force

\[ F_P = F_{PS} \pm F_{FR} \]

where,

\( F_P \) = Rudder pedal force, positive for a left rudder pedal force (lb).

\( F_{PS} \) = Rudder pedal force due to the spring and cam mechanism (lb). This is plotted on page 10.1-3.

\( F_{FR} \) = Friction force opposing rudder pedal motion (= 6.0 lb).

10.1.2 Rudder Pedal Angle

\[ \delta_P = \delta_{REF} + 0.023 F_P \]

where,
\[ \delta_p = \text{Rudder pedal angle (degrees). The rudder pedal limits are } \delta_p = \pm 14 \text{ degrees.} \]

\[ \delta_{p, \text{REF.}} = \text{Reference rudder pedal angle (degrees). This does not include the effect of cable stretch.} \]

\[ .023 = \text{Cable stretch factor (deg/lb).} \]

10.1.3 Rudder Trim

\[ \delta_{p, \text{TRIM}} = \text{Zero force datum rudder pedal angle due to trim (degrees). This is plotted on page 10.1-4. The trim shifts the rudder pedal force datum but does not change the rudder limits. The trim limits are } \pm 10 \text{ units.} \]

10.1.4 Rudder Limiter

\[ \delta_R = \frac{\delta_R}{\delta_{R, \text{MAX.}}} \cdot \delta_{R, \text{MAX.}}. \]

where,

\[ \frac{\delta_R}{\delta_{R, \text{MAX.}}} = \text{Rudder angle ratio. This is plotted on page 10.1-5.} \]

\[ \delta_{R, \text{MAX.}} = \text{Maximum available rudder angle (degrees). This is plotted on page 10.1-6.} \]
NOTE

1. \[ F_P = F_{P_0} + F_{P_{FR}} \]

2. \[ F_{P_{FR}} = 60 \text{ lb} \]

3. SYMMETRIC FOR OPPOSITE RUDDER

4. RUDDER PEDAL LIMITS ARE \[ S_P = \pm 14^\circ \]

These data not included in NASA simulation. See p. 14.1-53

---

**Graph:**

- **Y-axis:** \[ F_{P_0} \text{ (lb)} \]
- **X-axis:** Incremental Pedal Angle \((S_P_{REF} - S_P_{TRIM}) \text{ (deg)}\)

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**Directional Control Force Due to Spring and Cam Mechanism**

THE BOEING COMPANY

Page 10.13
NOTE

1. SYMMETRIC FOR OPPOSITE TRIM

2. RUDDER PEDAL FORCE DATUM SHIFTS WITH TRIM

3. TRIM LIMITS = ±10 UNITS (± 4.36 TRIM WHEEL TURNS)

4. COUNTERCLOCKWISE TRIM WHEEL ROTATION GIVES RIGHT RUDDER

5. TRIM WHEEL OPERATING TORQUE = 24 IN-LB
   [TRIM WHEEL RADIUS = 2.07 IN]

---

DIRECTIONAL CONTROL
RUDDER TRIM

THE BOEING COMPANY
NOTE 1. SYMMETRIC FOR OPPOSITE RUDDER.

REFERENCE RUDDER PEDAL ANGLE, $\theta_{r, ref}$, - DEG.

RUDDER PEDAL ANGLE, $\theta_r$ - DEG.

RUDDER PEDAL TRAVEL - INCHES.

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10.2 Rudder Blowdown

Rudder blowdown is not included in NASA Simulation.

The rudders are actuator force limited below the mechanically available rudder under some flight conditions. To determine these limits use the following equations:

\[ HM \cos \delta_{RU} = 855.2 \cdot C_{HRU} \cdot q \]
\[ HM \cos \delta_{RL} = 833.2 \cdot C_{HRL} \cdot q \]

where:

\[ HM = \pm 13,800 \text{ lb-ft. for each rudder with all hydraulic systems operative. This value is reduced by one-half if one of the two hydraulic systems on either rudder becomes inoperative.} \]

The hinge moment coefficient can be calculated for any flight condition using the data on pages 10.2-2, 10.2-3, and 10.2-4 with the following equation:

\[ C_{HR} = \frac{(C_{HR})_M}{(C_{HR})_{M=0}} \cdot (C_{HR})_{M=0} \]

Note that the hinge moments for rudders deflected separately are different from those with rudders deflected together. The rudders deflected separately curve is used only when one of the rudders is operating.
NOTE: REVERSE SIGNS FOR NEGATIVE RUDDER

USE FOR ALL FLAP SETTINGS

UPPER RUDDER

(\( C_{HR(u)} \)) \( M=0 \)

\[ \frac{C_{HR(u)}}{M=0} \]

Sideslip Angle, \( \beta \) ~ Deg

-15 -10 -5 0 5 10 15

LOWER RUDDER

(\( C_{HR(l)} \)) \( M=0 \)

\[ \frac{C_{HR(l)}}{M=0} \]

Sideslip Angle, \( \beta \) ~ Deg

-15 -10 -5 0 5 10 15

These data not included in NASA simulation.

CALC: FOSTER 10-21-67 REVISED DATE
CHECK: HOLTZNER 1-5-68 CURNUTT 10-20-68
APR: LAGREE 2-10-70
APR: BECK 6-25-70
INK: KINSMA 2-16-70

DIRECTIONAL CONTROL RUDDER HINGE MOMENTS SEGMENTS DEFLECTED TOGETHER

THE BOEING COMPANY

10-2-2
NOTE: 1. REVERSE SIGNS FOR NEGATIVE RUDDER
2. USE FOR ALL FLAP SETTINGS

UPPER RUDDER

\[ C_{HR} \] M = 0

LOWER RUDDER

\[ C_{HR} \] M = 0

SIDE SLIP ANGLE, \( \alpha \) = DEG

RIDER HINGE MOMENTS
SEGMENTS DEFLECTED SEPARATELY

THE BOEING COMPANY

747

PAGE 10.2-3
10.3 Yaw Damper/Turn Coordinator

Dutch roll oscillations on the 747 are attenuated by a series yaw damper which commands rudder proportional to yaw rate and bank angle. The yaw damper output signals are fed through shaping networks into the rudder actuator package, which drives the rudder. These rudder deflections do not result in any movement of the rudder pedals, nor do they affect normal operation of the rudder. The yaw damper is dualized in that both the upper and lower rudders have independent yaw damping systems. Deflection is limited to 3.6 degrees and the rate of deflection (for yaw damping) cannot exceed 15 degrees per second. A complete description of the yaw damper system is shown in the block diagram on page 10.3-2.

Turn coordination is achieved by deflecting the rudder, through the yaw damper actuator, proportional to roll rate. The input roll rate signal is actually a derived rate, as shown in the block diagram. The turn coordinator operates only when the flaps are down, having a gain of .69 degrees/degree per second.

An "easy-on" circuit has been incorporated with the flap switch to smooth transients in the bank attitude signals when the flap switch activates. (A warning light in the cockpit is provided to indicate improper operation of the flap switch).
747 YAW DAMPER TRANSFER FUNCTION & BLOCK DIAGRAM

SHAPING NETWORKS

WASHOUT

\[
\frac{4.044s}{(5+3.68)(5+3.68)}
\]

BODY AXIS YAW RATE

\[ \Psi_B \]

FLAP SWITCH

\[ \Psi \]

GAIN

\[ 1.25 \]

\[ 2.5 \]

\[ \Delta \delta_{R_{PILOT}} \]

\[ .05 \]

\[ \delta_R \]

\[ 1.56 \frac{(5+0.12)}{(5+0.1)(5+32)} \]

\[ 402 \frac{(5+20)}{(5+20)} \]

\[ \Delta \delta_{R_{MAX}} = 15 \text{ DEG/SEC} \]

\[ \Delta \delta_{R_{MAX}} = 3.6 \text{ DEG} \]

YAW DAMPER ACTUATOR

\[ \Delta \delta_{RC} \]

\[ \phi \]

EASY-ON/EASY-OFF SWITCHING NETWORK SMOOTHES TRANSIENTS DURING SWITCHING ONLY.

TRANSITION BETWEEN SWITCH POSITIONS IS A LINEAR FUNCTION OF TIME, REQUIRING 10 SECONDS.
HIGH LIFT SYSTEM

A general description of the system is presented in the Introduction on Pages 1.2-5 and 1.2-6 and in Volume I. A block diagram of the simulated high lift model is shown on Page 11.0-2. The data for each particular block can be found on the page number adjacent to the block.

A flap auto-retraction system is designed as part of the flap system. With the flap lever in the 30° detent and with aircraft speeds exceeding 169 knots, the flaps automatically drive back to the 25 position. The flaps automatically return to the original 30° setting when the airspeed is decreased to 164 knots.
FLAP SCREW TRAVEL RATE \( = \frac{d\text{FST}}{dt} = \pm 2.2 \text{ deg/sec} \)

HIGH LIFT MODEL
FLAP SCREW TRAVEL AND FLAP POSITION RELATIONSHIP

J 100
I 70
I 100

DETENT % FST
0 0
5 70
30 100

PSAA FLAP POSITION DETENT
X 747 FLAP POSITION DETENT

FLAP POSITION COMMANDED FROM CAB

%FLAP SCREW TRAVEL
0 20 40 60 80 100

% FST SF
0 0
70 5
100 30

FLAP POSITION
0 10 20 30

% FLAP SCREW TRAVEL
0 10 20

NORDWALL 7/27/74

THE BOEING COMPANY
12.0 PROPULSION SYSTEM

A general description of the system is presented in the Introduction on Pages 1.3-2 and 1.3-3 and in Volume I.

12.1 Engine Pressure Ratio

A block diagram of the engine pressure ratio simulation is shown on Page 12.1-2. The flight idle limit, occurring when the flap position is 25 or 30 and gear is down but not on the ground, was simulated by adding an incremental EPR of 0.015.

The NASA engine transient program, consisting of a transport delay and a lag, was modified to approximate the 747 engine dynamics shown on Pages 12.1-6 through 12.1-17.

The engine operating limitations are contained in Appendix A - Flight Manual.
NOTE: THE AREA BETWEEN THE LINES ACCOUNTS FOR THE CABLE STRETCH AND BACKLASH OF THE SYSTEM.
SNAP ACCELERATION
SEA LEVEL STATIC

\[ P_{t2}/P_{t1} \]

\( \Delta \text{TIME} \sim \text{SEC} \)

THROTTLE POSITION ~ DEG

D 20

1.00

1.10

1.20

1.30

50

40

30

20

10

0

0

10

20

30

40

REF: D6-13302
P 6.2-1

ENGINE TRANSIENT CHARACTERISTICS

THE BOEING COMPANY

747

D6-30643 VOL II

PAGE 12.1-6
SNAP ACCELERATIONS
SEA LEVEL STATIC JT9D-3

THROTTLE POSITION
~DEG

\[ \Delta \text{TIME} \sim \text{SEC} \]

\[ \text{P}_{1.0} \]

\[ \text{P}_{T1} \]

REF: D6-13302
P. 6-2-2

ENGINE TRANSIENT CHARACTERISTICS

THE BOEING COMPANY

CALC
CHECK
APR
APR
DRN 1/14/69
SNAP ACCELERATION - PARTIAL THROTTLE
SEA LEVEL STATIC  JT9D-3

THROTTLE POSITION ~ DEG

TIME ~ SEC

REF: D6-13302
P. 6.2-3

ENGINE TRANSIENT CHARACTERISTICS

THE BOEING COMPANY

CALC  CHECK  APR  APR  747

REVISION  DATE

D6-30643  VOL II

PAGE  12-1-8
SNAP ACCELERATION - PARTIAL THROTTLE
SEA LEVEL STATIC    JT9D-3

THROTTLE POSITION
~ DEG

\[ \Delta \text{TIME} \sim \text{SEC} \]

\[ P_{T2}/P_{T1} \]

REF: D6-13302
P 6.2-4

ENGINE TRANSIENT CHARACTERISTICS

THE BOEING COMPANY
SNAP DECEL-ACCEL
20000 FT M = .80 JT9D-3

POWER LEVEL
ANG. DISP. ~ DEG.

(THRUST LEVER = 33°)

(THRUST LEVER = 10°)

REF: D6-13302
P 6.2-9
MEDIUM DECEL - SNAP ACCEL
30,000 FT  M = .55  JT9D-3

POWER LEVER ANG. DISP. ~ DEG.

THRUXT LEVER = 27.5°

THRUXT LEVER = 0°

THRUXT LEVER = 28°

\[ \frac{P_{T_7}}{P_{T_1}} \]

\[ \Delta \text{TIME} \sim \text{SEC} \]

REF: D6-13302
P. 6.2-13
SNAP ACCEL - DECEL
30000 FT
M = 0.85
JT9D-3

POWER LEVER
ANG. DISP. ~ DEG.

THRUSET LEVER = 29°

THRUSET LEVER = 0

1/4
1/2
1.0
0.8
0.6

10
20
30

TIME ~ SEC.

R/P1

ENGINE TRANSIENT
CHARACTERISTICS

THE BOEING COMPANY
SLOW DECEL - MEDIUM ACCEL
30,000 FT M = 0.85
JT9D-3

POWER LEVER
ANG. DISP.
° DEG

100
80
60

1.4
1.2
1.0
0.8
0.6

REF: DG-1302
P. 6.2-17

ENGINE TRANSIENT
CHARACTERISTICS
747
DG-30643
VOL II
THE BOEING COMPANY
12.1-16

CALC
CHECK
APR
APR
DRN
11/10/67
12.2 Engine Thrust

A block diagram of the engine thrust simulation is shown on Page 12.2-2.

The reverse thrust characteristics used in the simulation were a function of ambient pressure and EPR, Page 12.2-5. This data was based on a Mach number of .2. Reverse thrust data as a function of Mach number is shown on Pages 12.2-6, 12.2-7 and 12.2-8.
REVERSE NET THRUST PER ENGINE
40 (Ft/s, lbm), 1000 lb

ENGINE PRESSURE RATIO, $P_{t2}/P_{t1}$

0 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7

MACH = 2

0.4

THESE DATA NOT INCLUDED IN NASA SIMULATION

REF. DG-13302
P. 2.2-1 4-2

REVERSE NET THRUST
PRIMARY + FAN REVERSER

CALC  REVISION  DATE
1 CHEC  
APR  
APR  APRIL 1970

THE BOEING COMPANY
JT9D-3 ENGINES

REVERSE NET THRUST
PRIMAR YT REVERSER

MACH .6
4
2
0

ENGINE PRESSURE RATIO ~ $\frac{P_{T7}}{P_T}$

CORRECTED NET THRUST ~ $\frac{(F_N / \delta_{AMB})_{REV}}{1000 \text{ lbs}}$

THE BOEING COMPANY

FOR FLIGHT SIMULATOR USE ONLY
12.3 Engine Cockpit Display Parameters

A block diagram for engine display parameters is shown on Page 12.3-2 and the block diagram for the NASA engine gauge simulation is shown on Page 12.3-3. The compressor RPM was scaled up by a factor of 8.8 to obtain the exhaust gas temperature in the simulation. The table on Page 12.3-4 shows the accuracy and the data points used in determining the scale factor.
APPROXIMATIONS FOR NASA ENGINE GAUGE DISPLAY
<table>
<thead>
<tr>
<th>EPR</th>
<th>M</th>
<th>$\theta_{T_2}$</th>
<th>$\sqrt{\theta_{T_2}}$</th>
<th>$\frac{N_i}{\sqrt{\theta_{T_i}}}$</th>
<th>$\frac{T_{T_2}}{\theta_{T_2}}$</th>
<th>$\frac{T_{T_2}}{\theta_{T_1}}$</th>
<th>SF = $\frac{T_{T_2} \text{C}}{N_i}$</th>
<th>$\theta_{T_2}$ = $1 + 2M^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
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<td>1.0</td>
<td>1.0</td>
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<td>892</td>
<td>1008</td>
<td>735</td>
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<tr>
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<td>0.5</td>
<td>1.05</td>
<td>1.025</td>
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<td>69.2</td>
<td>785</td>
<td>825</td>
<td>555</td>
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<tr>
<td>1.5</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>94.0</td>
<td>94.0</td>
<td>1097</td>
<td>1097</td>
<td>824</td>
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<td>1.061</td>
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<td>98.5</td>
<td>101.0</td>
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<td>892</td>
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<td>1.0</td>
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<td>83.5</td>
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<td>967</td>
<td>694</td>
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<tr>
<td>1.3</td>
<td>0.8</td>
<td>1.128</td>
<td>1.061</td>
<td>93.0</td>
<td>99.0</td>
<td>1041</td>
<td>1175</td>
<td>902</td>
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<tr>
<td>1.3</td>
<td>0.5</td>
<td>1.05</td>
<td>1.025</td>
<td>90.0</td>
<td>92.2</td>
<td>1013</td>
<td>1065</td>
<td>792</td>
</tr>
</tbody>
</table>

$\theta_{T_2} \approx \theta_{T_1}$

$SF = \frac{T_{T_2} \text{C}}{N_i} \approx 8.8 \frac{\text{C}}{N_i}$
12.4 Windmilling Drag

The windmilling drag characteristics on Page 12.4-2 were included in the simulation as a term in the engine equations.
For Flight Simulator only

JT9D-3 TURBOFAN ENGINE
WINDMILLING DRAG
REF: P&W A CURVE NO. 35819

CORRECTED WINDMILLING DRAG - LBS.

MACH NO.

WINDMILLING DRAG

JT9D 3 TURBOFAN ENGINE

THE BOEING COMPANY

PAGE 12.4-2
Thrust Reverser Effects on Aerodynamic Coefficients

The thrust reverser effects on the lift, drag and pitching moment coefficients are presented on Page 12.5-2. The approximations used in the simulation were made to conserve computer storage and justified because the thrust reversers are recommended to be in the idle reverse position by approximately 60 knots.
DETERMINATION OF OLEO STRUT COMPRESSION AND COMPRESSION RATE

\[ \Delta S_{T_i} = h - h_R + X_{Li} \sin \theta_B - Y_{Li} \sin \phi_B \cos \theta_B \]
\[ - Z_{Li} \cos \phi_B \cos \theta_B \]
\[ \Delta \dot{S}_{T_i} = h + X_{Li} \cos \theta_B \dot{\theta}_B + Y_{Li} \left( \sin \phi_B \sin \theta_B \dot{\theta}_B - \cos \phi_B \cos \theta_B \phi_B \dot{\phi}_B \right) + Z_{Li} \left( \sin \theta_B \cos \phi_B \dot{\theta}_B + \sin \phi_B \cos \theta_B \phi_B \dot{\phi}_B \right) \]

\[ \Delta S_{T2} \quad \Delta S_{T1} \quad \Delta S_{T3} \]
\[ \Delta \dot{S}_{T2} \quad \Delta \dot{S}_{T1} \quad \Delta \dot{S}_{T3} \]

NOTE: LANDING GEAR DOES NOT CONTACT THE RUNWAY UNLESS \( \Delta S_{T_i} < 0 \)

\( \Delta S_{T_i} \) IS NEGATIVE FOR STRUT COMPRESSION
LANDING GEAR

A general description of system and landing gear equations is included in Volume I of this report. A detailed derivation of the landing gear equations is contained in the Appendix to Volume I.

Block diagrams showing the method of calculating strut compression and force and wheel side and drag forces in the NASA simulation are shown on Pages 13.0-2 through 13.0-5. Refer to Volume I for the landing gear nomenclature.
**DETERMINATION OF OLEO STRUT FORCES**

\[ \Delta S_{Ti} \text{ and } F_{Gz_i} \text{ are negative for compression} \]
**NOTE:** STEERING ANGLE $\delta S$ IS USED FOR NOSE WHEEL EQUATIONS ONLY

---

**DETERMINATION OF WHEEL SIDE FORCE**

- $F_{NI}$
- $TIRE\ DEFLECTION\ K_{Ti}$
- $\delta Ti$
- $G_{Ti}$
- $F_{Si}$
- $\delta P$
- $\frac{\partial \delta S}{\partial \delta P}$

---

**EQUATIONS:**

1. $i = 1$ NOSE GEAR
2. $i = 2$ LEFT MAIN GEAR
3. $i = 3$ RIGHT MAIN GEAR

- $K_{T1} = \frac{-0.093}{2(1000)} \text{ IN/LB}$
- $K_{T2,3} = \frac{-0.077}{8(1000)} \text{ IN/LB}$

- $H_{T1} = (2)(73730)(.0042) = 619$
- $H_{T2,3} = 8(73730)(.0042) = 2477$

- $G_{T1} = 2(73730)(.026) = 3834$
- $G_{T2,3} = 8(73730)(.026) = 15336$

---

**Boeing NO. 6-30643 Vol. II**

**SECT** | **PAGE** 13.0 - 4
NASA DIGITAL COMPUTER

\[ F_{Bi} = 2 \left( \frac{0.263 \cdot W}{g} \cdot \delta_{Bi} \right) \]

\[ (F_{Bi})_{\text{MAX}} = 2 \left( 4.834 + 4.167 \cdot \mu_B \right) \cdot \frac{W}{g} \]

MAXIMUM DECELERATION = 5 FT/SEC² FOR MAXIMUM BRAKING ON EACH MAIN GEAR

\( \mu_B = 0.4 \) (DRY RUNWAY)
\( \mu_B = 0.1 \) (WET RUNWAY)

\( F_{\mu_i} \) IS ALWAYS NEGATIVE
NOTE: FORCE DUE TO DAMPING FOR LEFT OR RIGHT MAIN GEAR = FORCE BASED ON MAIN GEAR CURVE TIMES 2.

\[
\text{FORCE DUE TO DAMPING} = 2 \times C \times \left( \frac{\text{GEAR}}{\text{VEL}_1} \right) - \left( \frac{\text{GEAR}}{\text{VEL}_2} \right)
\]

LEFT OR RIGHT MAIN GEAR

NASA SIMULATION COMBINES WING AND BODY GEAR INTO AN EQUIVALENT MAIN GEAR.

REF: D6-30647 P. 294
NOTE: FORCE DUE TO STRUT DEFLECTION FOR LEFT OR RIGHT MAIN GEAR = FORCE BASED ON MAIN GEAR CURVE TIMES 2.

NASA SIMULATION COMBINES WING AND BODY GEAR INTO AN EQUIVALENT MAIN GEAR.

MAIN GEAR, WING OR BODY AIR+TIRES

TIRE + OLEO DEFLECTION ~ INCHES (COMPRESSION)

OIL LOAD ~ 1000LB

0 5 10 15 20 25 30

50 100 150 200 250

Nose Gear, Air+Tires

REF: DG-30437

CALC CHECK APPD APPD

REV LTR:

LANDING GEAR AIR CURVE 747
14.1.1 COCKPIT INSTRUMENTS

The cockpit instruments were statically checked to assure that the piloted checkout could be conducted with confidence. Rudimentary checks were made of the following instruments:

1. Altimeter
2. Rate-of-climb-indicator
3. Airspeed indicator
4. Attitude indicator
5. Turn and bank indicator
6. Mach meter
7. Flap position indicator
8. Stabilizer position indicator

The checks were conducted by putting the computer in "hold" and comparing the instrument readings with the computer values. These comparisons were made a number of times throughout the simulation checkout and all of the instruments were in good agreement with the computed values. The instruments operated smoothly during the dynamic checks and piloted evaluation.

A comparison of digital values and cockpit instrument readings were tabulated during the four engine climb performance test. The comparison between the computed and indicated pitch attitude shows the largest discrepancy. However, the pitch attitude is difficult to read to a fraction of a degree. The differences are within the tolerances specified in the table on Page 14.2-10.
The stabilizer position indicator in the FSAA was programmed using stabilizer referenced to the fuselage reference line, $\Delta_{\text{FRL}}$. All of the aerodynamic data are in terms of $\Delta_{\text{FRL}}$. The 747 stabilizer indicator and stabilizer information used in the flight manual and D6-30833-1 is in stabilizer "pilot's units", $\Delta_p$. The conversion is given by:

$$\Delta_p = 3^\circ - \Delta_{\text{FRL}}.$$
14.1.2 ATMOSPHERE MODEL

The atmosphere model, presented in Volume I of this report, was checked for a number of altitude and airspeed conditions. Values of $V_e$ for a number of altitudes were input to the computer. Output values of $M$, $V_c$, $V_t$, $q$, and $q_c$ were checked with the data in the table on Page 14.1-5.
### ATMOSPHERE CHECK

1. Standard Day, No Wind
2. Pilot's Airspeed $V_I$ is equal to $V_C$

<table>
<thead>
<tr>
<th>ALT. FT</th>
<th>$V_I$ KTS</th>
<th>$V_e$ KTS</th>
<th>$V_{TRUE}$ FT/SEC</th>
<th>MACH NO.</th>
<th>$\frac{q}{\text{LB/FT}^2}$</th>
<th>$\frac{q}{V_C}$ LB/FT^2</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>100</td>
<td>169</td>
<td>.151</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>0</td>
<td>200</td>
<td>200</td>
<td>337.5</td>
<td>.302</td>
<td>135.5</td>
<td>138.5</td>
</tr>
<tr>
<td>0</td>
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<td>300</td>
<td>500.5</td>
<td>.454</td>
<td>304.5</td>
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<tr>
<td>0</td>
<td>400</td>
<td>400</td>
<td>675</td>
<td>.605</td>
<td>541.5</td>
<td>593</td>
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</tbody>
</table>
14.1.3 ENGINE CHARACTERISTICS

Static forward and reverse thrust characteristics were checked by comparing the computer output data with a manual calculation of the same condition. The comparisons are shown in the examples on Pages 14.1-7 and -8.

The transient engine characteristics are shown on Pages 14.1-9 and -10. A sea level static condition was set up and throttle changes were commanded. The resulting transient characteristics for EPR approximates the engine transient data shown in Section 12.
# Static Thrust

**Altitude = 200 ft  M = 0.2  Standard Day**

## Maximum Forward Thrust

<table>
<thead>
<tr>
<th>Description</th>
<th>Manual Calculation</th>
<th>Digital Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward Thrust Lever Angle (Input)</td>
<td>61°</td>
<td>60.8°</td>
</tr>
<tr>
<td>Power Lever Angle</td>
<td>127°</td>
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<td>-0.0361</td>
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## Idle Forward Thrust

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### IDLE REVERSE THRUST

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### MAXIMUM REVERSE THRUST

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### STATIC THRUST

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BOEING

No. D6-306143
Vol. II

SECT | PAGE 14.1 - 6
SEA LEVEL, STANDARD DAY, STATIC
IDLE TO MAXIMUM THRUST
SNAP ACCELERATION - DECELERATION
SEA LEVEL, STANDARD DAY, STATIC
EPR AT T = 0 = 1.08
SNAP ACCELERATION - DECELERATION

ENGINE TRANSIENTS
14.1.4  LONGITUDINAL TRIM

The simulated airplane was statically trimmed at several variations of weight, c.g., altitude, speed, and flap positions. Computed values of $A$, $\Phi_B$, and $EPR/F_n$ were compared to Boeing simulator and flight test results. Comparisons to simulator results are tabulated on Pages 14.1-12 and -13 and plotted on Pages 14.1-14 thru -18. Comparisons to flight test and simulator results are plotted on Pages 14.1-19 thru -21.

The effects of configuration changes, landing gear up and down and speed brakes up and down, were computed and the results are tabulated on Page 14.1-22.

The effect of ground effect on trim is tabulated on Page 14.1-12. The trim data are based on the ground effect curves on Pages 2.0-31, -32, 3.0-17, -18 and 4.0-35.
<table>
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<th>V_{e}</th>
<th>M</th>
<th>L.W.D.P.</th>
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**GROUND EFFECT**

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<th>$\Theta_B$</th>
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564,000 LB
C.G. = 33% V_{z} = 142 KT
FLAPS 30 GEAR DOWN

LONGITUDINAL TRIM

REV LTR: 747
## Longitudinal Trim

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<th>M</th>
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<th>( \Theta_B ) ~ DEG</th>
<th>IEPR</th>
<th>( F_N ) ~ LB</th>
<th>( F_n ) ~ LB</th>
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### Computation Tolerance
- NASA values are from computer output.
- Boeing values are ± .5 units ± .5 deg. ± .01 ± 3% ± .25°.
LONGITUDINAL TRIM
ALT. = 20000 FT.

THE BOEING COMPANY
LONGITUDINAL TRIM
ALT. = 35000 FT.

THE BOEING COMPANY

500000 LB.
35000 FT.
FLAPS UP, GEAR UP.
LANDING APPROACH
FLAPS 30
142 KTS, 25% Cl, S.L.
G.W. = 564,000 LB
GEAR DOWN

Δp ~ UNITS

θ ~ FLIGHT PATH ANGLE ~ DEG.

TEPR

θθ ~ DEG.

EFFECT OF FLIGHT PATH ANGLE ON APPROACH TRIM CONDITIONS

THE BOEING COMPANY
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**SIMULATOR**
(06-20425, REV.D)

**Pilot Units**

**NASA**

---

**CALC**: BYSTROM 3.18.70
**CHECK**: CURNUTT 5-20-70

**LONGITUDINAL TRIM ~ 20,000 FT.**

**THE BOEING COMPANY**

**Page**: 747

**Vol. II**

**PAGE**: 14-1-19
FLAPS 30
GEAR DOWN

<table>
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<tr>
<th>SYM</th>
<th>A/P</th>
<th>FLT</th>
<th>CG-%MAC</th>
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NOTE
1. FLAGGED SYMBOLS ARE IDLE THRUST
2. FLT 7-1 (RA002) FROM DRAG TESTING WITH AUTOPILOT ON, Δp CORRECTED TO θw = 2°

---

NASA

\[ \Delta p \]

Pilot Units

---

SIMULATOR DATA (D6-20423, REV.D) FL.F.

---

IDLE THRUST (ZERO THROTTLE)
<table>
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<th>TEST</th>
<th>FLAP POSITION</th>
<th>GEAR</th>
<th>C. W. 1000 LB.</th>
<th>C. G. % MAC</th>
<th>ALTITUDE 1000 FT.</th>
<th>V1/M</th>
<th>SPEED BRAKES</th>
<th>ΔP ~ UNITS</th>
<th>Fg ~ LB.</th>
<th>θe ~ DEG.</th>
<th>θB ~ DEG.</th>
<th>Y</th>
<th>R/C ~ FT/MIN</th>
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**Computation Tolerance**

| ± .25 | ± 10% | ± .5 | ± .3 |
| ± .01 | ± 3% |
14.1.5 **ELEVATOR-STABILIZER TRADES**

The simulated airplane was initially trimmed for 1 g straight and level flight with zero column deflection. Values of $S_{col}$ were input and the airplane was retrimmed with stabilizer. The results are tabulated and plotted with Boeing simulation and flight test results on Page 14.1-24. This test provided a check on the column to elevator gearing, outboard elevator blowdown, and elevator and stabilizer effectiveness.
NOTE 1. FLAGGED SYMBOLS INDICATE OUTFLD. ELEV. BLOWN DOWN
2. $\Delta \alpha_p$ FROM TRIM COUNTER

- FLT. 73-5
  - $M = .74-.76$
  - G.W. = 628000 LB.
  - C.G. = 11.7% MAC
  - $\Delta \alpha_p\text{TRIM} = 5.25$ UNITS

- FLT. 73-11
  - $M = .74-.76$
  - G.W. = 604000 LB.
  - C.G. = 12.1% MAC
  - $\Delta \alpha_p\text{TRIM} = 5.12$ UNITS

SIMULATOR (D6-20423, REV. D DATA)
- $M = .75$
- G.W. = 628000 LB.
- C.G. = 11.7% MAC
- $\Delta \alpha_p\text{TRIM} = 5.4$ UNITS

FLAPS UP
GEAR UP

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<th>$\delta_{COL}$</th>
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<td>~ DEG.</td>
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<td>Boeing Target</td>
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<td>9.4</td>
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<td>10.8</td>
</tr>
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</table>

TOLERANCE $\pm 5^\circ \pm 1^\circ$

CALC
CHECK
APPD
APPD

REV LTR: JUNE 1970

STABILIZER - ELEVATOR TRADES
SIMULATOR - FLIGHT TEST COMPARISON
14.1.6 AIRPLANE DYNAMICS

Dynamic responses were run to check the Dutch roll, short period, and phugoid modes of the simulated airplane.

14.1.6.1 Dutch Roll

The Dutch roll was initiated by releasing the airplane from an initial condition of sideslip. Responses were made with yaw damper on and off. Comparisons of the time histories between the NASA and Boeing simulations are shown on Pages 14.1-26 thru -36.

14.1.6.2 Short Period and Phugoid

The short period and phugoid modes were exited by an elevator input after the airplane had been trimmed for straight and level flight. An incremental elevator was input for a prescribed time and then removed. Comparisons of the time histories between the NASA and Boeing simulations are shown on Pages 14.1-37 thru -49.
NASA

YAW DAMPER OFF

β

0

-5°

-10°

φ

0

-10°

GW = 564000 LB
V = 20 000 FT

C.G. = 25%

Ve = 325 KT

β₁c = 5°

(Δ NASA DAC LIMITED TO)

β = 4° FOR TEST

BOEING

NASA-BOEING DUTCH ROLL COMPARISON

BOEING

NO. 76-30643
Vol. 11
SECT
PAGE 14.1-26
NASA

YAW DAMPER OFF

\[ \beta \]

\[ \phi \]

GW: 564,000 LB
h = 20,000 FT
Ve = 225 KT
C.g. = 25%

\( \beta_{1c} = 6^\circ \)

(\( \beta = 4^\circ \) FOR TEST)

BOEING

\[ \beta \]

\[ \phi \]

NASA-BOEING DUTCH ROLL COMPARISON
NASA

yaw damper off

\[ \beta \]

\[ \phi \]

\[ GW = 564000 \text{ lb} \]
\[ h = 5000 \text{ ft} \]
\[ V_e = 250 \text{ KT} \]
\[ C.g. = 25\% \]

\[ \beta_{IC} = 5^\circ \]

\[ \Delta \text{ NASA DAC LIMITED TO } \beta = 4^\circ \text{ FOR TEST} \]

BOEING

\[ \beta \]

\[ \phi \]

NASA-BOEING DUTCH ROLL COMPARISON
GW: 564,000 LB
h: 200 FT  Vc = 142 KT
C. G.: 25%  δf = 30
\( \text{GW} = 564,000 \text{ LB} \)
\( h = 35,000 \text{ FT} \)
\( V_e = 275 \text{ KT} \)
\( \text{C.G.} = 25\% \)

---

**NASA - BOEING DUTCH ROLL COMPARISON**
NASA

**YAW DAMPER OFF**

GW = 710,000 LB
h = 200 FT
Ve = 180 KT
c.g. = 25%
δ[e] = 10

**YAW DAMPER ON**

NASA-BOEING DUTCH
ROLL COMPARISON
NASA

**NASA**

**YAW DAMPER OFF**

\[ \gamma = 4^\circ \]
\[ 5\text{ SEC} \]

\[ \beta \]
\[ 0 \]
\[ -4 \]
\[ 10^\circ \]
\[ \phi \]
\[ 0 \]
\[ -10 \]

\[ GW = 564,000 \text{ LB} \]
\[ h = 200 \text{ FT} \]
\[ V_e = 180 \text{ KT} \]
\[ c.g. = 25\% \]
\[ \delta_F = 30 \]

**BOEING**

**NASA-BOEING DUTCH ROLL COMPARISON**
NASA

YAW DAMPER ON

BOEING

GW = 564,000 LB
h = 200 FT
Ve = 180 KT
Cg. = 25%  δf = 30

NASA-BOEING DUTCH ROLL COMPARISON
NASA

YAW DAMPER ON

5 sec

BOEING

GW = 564,000 lb
h = 200 ft  Ve = 142 KT
c.g. = 25%  δf = 30

NASA-BOEING DUTCH ROLL COMPARISON
NASA

Yaw Damper Off

\[ \beta \]

\[ \phi \]

\[ \gamma \]

\[ \delta_{\alpha} \]

GW = 564,000 LB
h = 35,000 FT
Ve = 225 KT
C.g. = 25%

BOEING

Yaw Damper On

\[ \beta \]

\[ \phi \]

\[ \delta_{\alpha} \]

NASA - BOEING DUTCH ROLL COMPARISON
NASA

**NASA**

**YAW DAMPER OFF**

\[ \beta \]

\[ \phi \]

\[ \delta_{\phi} \]

GW = 564,000 lbs
h = 200 ft V_e = 142 KT
c.g. = 25% \( \delta_f = 30 \)
GEAR DOWN

**BOEING**

**NASA-BOEING DUTCH ROLL COMPARISON**
LONGITUDINAL DYNAMICS

$G = 710,000$ lb  $h = 5000$ ft
$V_I = 180$ KT  $c.g. = 25\%$
$\delta_f = 10$ GEAR $\theta_p$
$GW = 710,000$ LB  $h = 5000$ FT
$V_i = 210$ KT  $c.g. = 25\%$
$\delta_f = 10$ GEAR UP

**LONGITUDINAL DYNAMICS**
GW = 710,000 LB  h = 5000 FT
V_i = 180 KT  c.g. = 25%  
\delta_F = 10  GEAR UP

LONGITUDINAL DYNAMICS
GW = 710,000 LB   h = 5000 FT
Vf = 210 KT   c.g. = 25%
δf = 10   GEAR UP

LONGITUDINAL DYNAMICS
\( \alpha_e \)
\( \theta_e \)
\( \eta_e \)
\( V_{c\text{kt}} \)
\( \delta_e \)
\( q_{\text{g}} \)

\( a_W = 564,000 \text{ lb} \)
\( h = 5,000 \text{ ft} \)
\( V_I = 153 \text{ knot} \)
\( C.G. = 33\% \)
\( \delta_f = 30 \) Gear Down

LONGITUDINAL DYNAMICS
\( \gamma = 564,000 \text{ LB} \)  \( V_1 = 5000 \text{ FT} \)
\( V_1 = 153 \text{ KT} \)  \( \text{C.g.} = 33^\circ \)  \( \delta F = 30 \text{ GEAR DOWN} \)
$GW = 564,000 \text{ LB}$  $h = 5000 \text{ FT}$

$V_I = 153 \text{ KT}$  $C.g. = 15\%$

$\delta_F = 30$  GEAR DOWN

\text{LONGITUDINAL DYNAMICS}
$G_w = 564,000 \text{ LB} \quad h = 5000 \text{ FT}$

$V_I = 153 \text{ KT} \quad C.G. = 15\%$

$\delta_e = 30^\circ \text{ GEAR DOWN}$

$\Delta \delta_e = -17.05^\circ \text{ FOR 2 SEC}$

**LONGITUDINAL DYNAMICS**
\[ g_w = 564,000 \text{ lb} \quad h = 20,000 \text{ ft} \]
\[ M = 0.65 \quad c_g = 14\% \]
GW = 564,000 LB  h = 20,000 FT
M = .65  c.g. = 32.7%
GW = 564,000 LB  h = 35,000 FT  
M = .75  c.g. = 32%
\[ GW = 564,000 \text{ LB} \quad h = 35,000 \text{ FT} \]
\[ M = 0.87 \quad C.g. = 32\% \]

**LONGITUDINAL DYNAMICS**

**BOEING**

NO. Vol. II

SECT PAGE 14.1 - 48
BOEING

\[ \Delta \delta_{e} = 3^\circ \text{ for 2 sec.} \]
\[ (\Delta \delta_{e} = -3.3^\circ) \]

GW = 564,000 lb  h = 35,000 ft
M = 0.87  C.G. = 32\%
14.1.7 FLIGHT CONTROLS

14.1.7.1 Force and Displacement

The force and displacement curves for the wheel and rudder are shown on Pages 14.1-52 and 14.1-53. These curves were obtained from the control loader in the FSAA cab. The wheel force in the cab should be compared to the force characteristics on Page 9.1-3. The rudder force in the cab should be compared to the force characteristics on Page 10.1-3. Wheel and rudder forces were not calculated in the computer.

The column force was calculated in the computer and a modified force increment was input to the control loader to augment the constant stick force gradient initially set in the column control loader. Tests were made to verify the computed and cab column force.

A condition was set up in the computer to check the $S_{\text{col}}$ to $S_e$ relationship and the resulting forces for two c.g. positions. The tabulated comparisons between Boeing and NASA simulations are on Pages 14.1-54, 55. The data is plotted on Page 14.1-56. Column force and displacement data in the FSAA cab was also obtained for this condition.

The control column was deflected to a position and the computed values of stick force, $S_e$, and $S_{\text{col}}$ were obtained. Column stick force and $S_{\text{col}}$ were also obtained from the column control loader through a calibrated x-y plotter. The results are tabulated on Page 14.1-55 and plotted on Page 14.1-57.

Similar computed stick force data was obtained from the elevator stabilizer trade condition. The results are tabulated on Page 14.1-54 and plotted on Page 14.1-58.
Maneuvering column force data was obtained during the piloted checkout.
$F_1 = F_2 = 2.0$
$C_S = 1.5$
$F_{AE} = 4.0$
$R = 8.0$
$s = 7.5
# Longitudinal Control Forces

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<th>C. of M. 1000 ft.</th>
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| Computation Tolerance | ± 10% | ± 0° | ± 1° |

1. Computed values - includes 2.5 lb breakout force in pull direction and 3.0 lb in push direction.
2. Graphical results on page 14.1-57
3. Graphical results on page 14.1-56
600,000 LB  M = 0.8  h = 35,000 FT

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<th>δ_{EO}</th>
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<td>COMPUTED ~ DEG</td>
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<table>
<thead>
<tr>
<th>INPUT</th>
<th>δ_{COLUMN}</th>
<th>δ_{COLUMN}</th>
<th>δ_{EI}</th>
<th>δ_{EO}</th>
<th>FSAA</th>
<th>STICK</th>
<th>FORCE</th>
<th>COMPUTED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FSAF ~ DEG</td>
<td>COMPUTED ~ DEG</td>
<td>COMPUTED ~ DEG</td>
<td>COMPUTED ~ DEG</td>
<td>~ LB</td>
<td>~ LB</td>
<td>~ LB</td>
<td>~ LB</td>
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<tr>
<td>4.4</td>
<td>4.43</td>
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<td>-3.0</td>
<td>79</td>
<td>80.0</td>
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<td>-5.87</td>
<td>108</td>
<td>114.1</td>
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<td>-12.52</td>
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<td>9.33</td>
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<td>-77.3</td>
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<tr>
<td>-12.1</td>
<td>-12.1</td>
<td>17.0</td>
<td>9.33</td>
<td>-76</td>
<td>-78.0</td>
<td></td>
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<td></td>
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</tbody>
</table>

1. Includes 2.5 lb breakout force in pull direction and 3.0 lb in push direction.
2. \( \delta_{COLUMN} \) \& FSAA stick force obtained from X-Y plotter output of control loader.
3. Assume 7 in. of FSAA column deflection = 12.67 deg. of 747 column deflection.

Graphical results on page 14.1-56
14.1.7.2 RIGGING

The lateral control rigging was checked at high speed. The table on Page 14.1-60 shows a comparison of Boeing and NASA simulation results for various combinations of wheel and speed brake inputs.
<table>
<thead>
<tr>
<th>$\delta_A / \text{in.}$</th>
<th>$\delta_0 / \text{deg.}$</th>
<th>$\delta_{SP} / \text{deg.}$</th>
<th>$\delta_{SP} / \text{deg.}$</th>
<th>$\delta_{SP} / \text{deg.}$</th>
<th>$\delta_{SP} / \text{deg.}$</th>
<th>$\delta_{SP} / \text{deg.}$</th>
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</tr>
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<td>0</td>
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<td>0</td>
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<td>30</td>
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</tr>
<tr>
<td>INFLIGHT DETENT</td>
<td>INFLIGHT DETENT</td>
<td>INFLIGHT DETENT</td>
<td>INFLIGHT DETENT</td>
<td>INFLIGHT DETENT</td>
<td>INFLIGHT DETENT</td>
<td>INFLIGHT DETENT</td>
</tr>
</tbody>
</table>

**LATERAL CONTROL RUGGING**

**V.1 = 390 KTS**

**ALT. = 5000 FT**

**G = 0.10000000**

**CONFIRMATION TOLERANCE**

$\pm 1.0 \text{ deg.}$
14.1.7.3 BLOWDOWN

The blowdown for elevator and spoiler and the ratio changer limit value for rudder was verified at different times throughout the simulation checkout. The elevator stabilizer trade test provided a data point for elevator blowdown and the lateral rigging check provided spoiler blowdown data.

A further check on blowdown was a comparison of initial accelerations with full control inputs. The tabulation on Page 14.1-62 is a comparison of initial accelerations and control surface positions between Boeing and NASA simulations.
FLIGHT CONDITION: \( h = 20,000 \text{ FT} \) \( M = 0.800 \) \( C_g = 32.7\% \)
\( G_W = 564,000 \text{ LB} \) \( \delta_f = 0 \) \( GEAR \ UP \)
TRIM: \( \alpha = 1.61 \) \( \Delta_{RL} = -66 \) \( V_e = 358.5 \text{ KT} \)

<table>
<thead>
<tr>
<th>INPUT</th>
<th>Boeing</th>
<th>NASA</th>
<th>Boeing</th>
<th>NASA</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHEEL DEG</td>
<td>80.06</td>
<td>80.00</td>
<td>-80.0</td>
<td>-80.0</td>
</tr>
<tr>
<td>COLUMN DEG</td>
<td>12.67</td>
<td>12.67</td>
<td>-12.5</td>
<td>-12.5</td>
</tr>
<tr>
<td>RUDDER PEDAL DEG</td>
<td>12.2</td>
<td>12.2</td>
<td>-12.2</td>
<td>-12.2</td>
</tr>
<tr>
<td>( \beta ) DEG</td>
<td>4.994</td>
<td>5.0</td>
<td>4.995</td>
<td>5.0</td>
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</table>

<table>
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<th>NASA</th>
<th>Boeing</th>
<th>NASA</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_l )</td>
<td>0.1221</td>
<td>0.1268</td>
<td>0.2489</td>
<td>0.251</td>
</tr>
<tr>
<td>( C_d )</td>
<td>0.0221</td>
<td>0.0226</td>
<td>0.0237</td>
<td>0.0224</td>
</tr>
<tr>
<td>( C_m )</td>
<td>0.0032</td>
<td>0.0033</td>
<td>-0.0291</td>
<td>-0.0292</td>
</tr>
<tr>
<td>( C_n )</td>
<td>0.2700</td>
<td>0.2735</td>
<td>-0.1767</td>
<td>-0.1760</td>
</tr>
<tr>
<td>( C_y )</td>
<td>-0.0127</td>
<td>0.0126</td>
<td>0.0176</td>
<td>0.0175</td>
</tr>
<tr>
<td>( q_y )</td>
<td>-11.242</td>
<td>-11.348</td>
<td>-7.921</td>
<td>-7.943</td>
</tr>
<tr>
<td>( N_x )</td>
<td>0.522</td>
<td>0.549</td>
<td>1.060</td>
<td>1.083</td>
</tr>
<tr>
<td>( P )</td>
<td>6.735</td>
<td>6.823</td>
<td>-53.95</td>
<td>-54.09</td>
</tr>
<tr>
<td>( \dot{q}_g )</td>
<td>32.105</td>
<td>32.557</td>
<td>-19.80</td>
<td>-19.76</td>
</tr>
<tr>
<td>( \dot{v}_g )</td>
<td>7.632</td>
<td>7.603</td>
<td>9.512</td>
<td>9.470</td>
</tr>
</tbody>
</table>

INBOARD ELEVATOR DEG | -16.97 | -17.05 | 16.99 | 17.00 |
OUTBOARD ELEVATOR DEG | -2.04 | -2.06 | 6.03 | 6.02 |
STICK FORCE Lb 181.19 | 181.30 | 167.81 | 169.14 |
INBOARD AILERON DEG | 20.0 | 20.0 | 20.0 | 20.0 |
RUDDER DEG 2.86 | 2.85 | 2.86 | 2.85 |
SPOILER PANEL 1/12 DEG | 0/41.84 | 0/41.8 | 41.84/0 | 41.71/0 |
| 2/11 DEG | 0/28.29 | 0/28.17 | 28.30/0 | 28.22/0 |
| 3/10 DEG | 0/28.29 | 0/28.27 | 28.30/0 | 28.22/0 |
| 4/9 DEG | 0/28.29 | 0/28.27 | 28.30/0 | 28.24/0 |
| 5/8 DEG | 0/20.0 | 0/20.0 | 20.0/0 | 20.0/0 |

COMPARISON OF INITIAL VALUES (t=0) FOR VARIOUS CONTROL INPUTS
14.1.8 LANDING GEAR

The landing gear was static checked by allowing the airplane to settle on the ground and verifying the amount of strut compression. Dynamic responses were made by releasing the airplane from \( \Delta h \) and \( \Delta \theta \) initial conditions.

In consideration of the computer limitations and the overall simulation, the landing gear simulation was run at a computational frame time of 39 milliseconds. The time histories on Page 14.1-64 shows the response to a \( \Delta h \) initial condition for two different computation times. The increase in computation speed, frame time to 13 ms, results in a smoother response than the "normal" frame time of 39 ms. Neglecting the limit cycle, the response with the 39 ms frame time appears to have the same frequency and slightly increased damping over the 13 ms response.

The time histories on Page 14.1-65 shows the response to a \( \Delta \theta \) initial condition. The comments on the \( \Delta h \) response are applicable to the \( \Delta \theta \) responses.

The effects of slowing the computation speed, or increasing the frame time, are shown in the responses on Page 14.1-66. The amplitude of the limit cycle increased as the computation speed decreased.

The aircraft response due to landing gear deflections felt realistic to the Boeing test pilot in the moving base simulation. Even though a limit cycle existed in the computed response with a 39 ms frame time the amplitude of the computed limit cycle was low and the frequency was high enough (3 cps) that no objectionable characteristics were noted by the pilot.
LANDING GEAR RESPONSE

FRAME TIME = 39 MS (REAL TIME)
Δh_{IC} = 2.5" COMPRESSION

GW = 436 000 LB  c.g. = 25%
LANDING GEAR RESPONSE

FRAME TIME = 39 MS (REALTIME)

$\Delta \theta_{ic} = -0.2^\circ$

$G_W = 436000 \text{ lb}$  $c.g. = 25\%$

BOEING NO. D6-30643
SECT Vol. II
PAGE 14.1-65
\( \Delta \theta_{ic} = -0.2^\circ \)

GW = 436000 LB  \( \text{c.g.} = 25\% \)

LANDING GEAR RESPONSE
PILOTED CHECKOUT

The piloted checkout provided an overall assessment of the simulation as well as quantitative data. Jack Waddell, Boeing 747 project pilot, flew the motion simulator for a total of 5 hours in 3 sessions. He qualitatively evaluated the following characteristics:

1. Airplane handling characteristics
   a. Dutch roll mode
   b. Spiral mode
   c. Short period mode
   d. Phugoid mode
   e. Roll rate
   f. Climb performance
   g. Flap extension and retraction
   h. Speed brakes

2. Engine response

3. Ground effect

4. Control forces

5. Takeoff (3 and 4 engine)

6. Landing

7. Stall

8. Air minimum control speed

9. Buffet

10. Stick shaker

The ground effect characteristics were modified during the approach and landing evaluation. The ground effect data on Pages 2.0-31, -32,
3.0-17, -18, and 4.0-35 were modified by the following factors:

- .7 times the pitching moment increment
- .3 times the drag increment
- .9 times the lift increment

The above changes to the ground effect data were substantiated by additional piloted testing on the Boeing 747 simulation. The resulting Boeing revisions are included in Section 19.

The buffet and stick shaker amplitude and frequency characteristics were tailored to the satisfaction of the pilot. His overall comments substantiated the validity of the simulation.

Rapid roll inputs resulted in lateral acceleration which the pilot felt were greater than in the airplane. The pilots vertical location above the c.g. (10 feet) was reduced to an effective distance of 6 feet in the simulator drive equations. The pilot felt the resulting simulator motion comparable to the airplane. The lateral acceleration due to the pilot location above the c.g. is attributed to aircraft flexibility.

Quantitative data were obtained with NASA pilots. The following pages contain the results of the piloted tests.
14.2.1 TAKEOFF

Two takeoffs at different gross weights were performed to verify the takeoff acceleration. The simulation of basic drag characteristics, thrust lapse rate, ground effect in taxi attitudes, rolling coefficient of friction and inertia effects are indirectly checked by timing takeoff acceleration.

The time to obtain rotation and lift-off speeds were determined by the airspeed indicator and a stop watch. Comparisons between Boeing and NASA simulations are shown in the table on Page 14.2-4. The NASA simulated takeoff started with $V = 15$ kt (at $t = 0$) and takeoff thrust while the Boeing takeoff data started at $V = 0$ ($t = 0$) and takeoff thrust. To compare the two, the time to accelerate from 0 to 15 knots must be added to the NASA data. This time is equal to 15 kt divided by the average acceleration. The average acceleration was determined from the curves on Pages 14.2-7 and 14.2-8.

Time histories from the NASA takeoff are shown on Pages 14.2-5 and -6. Velocity versus time data from the NASA test are plotted with the Boeing results on Pages 14.2-7 and -8.
### Takeoff Acceleration

<table>
<thead>
<tr>
<th></th>
<th>Flap Position</th>
<th>Gear</th>
<th>C. of W.</th>
<th>C. of G.</th>
<th>Altitude</th>
<th>( \Delta P )</th>
<th>T/O</th>
<th>Rotation</th>
<th>Liftoff</th>
<th>H = 35 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boeing</td>
<td>10</td>
<td>DN</td>
<td>707.2</td>
<td>14.0 S.L.</td>
<td>8.4</td>
<td>1,420</td>
<td>151</td>
<td>47.5</td>
<td>168</td>
<td>50.0</td>
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<tr>
<td>NASA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>45(^\circ)</td>
<td>47.5(^\circ)</td>
<td></td>
</tr>
<tr>
<td>Boeing</td>
<td>20</td>
<td>DN</td>
<td>527.2</td>
<td>15.6</td>
<td>6.8</td>
<td>1,380</td>
<td>131</td>
<td>30.0</td>
<td>140</td>
<td>33.0</td>
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<tr>
<td>NASA</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>27(^\circ)</td>
<td>30(^\circ)</td>
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</table>

**Computation Tolerance**

<table>
<thead>
<tr>
<th></th>
<th>\pm 2 Sec</th>
<th>\pm 2 Sec</th>
<th>\pm 100 Ft</th>
</tr>
</thead>
</table>

1. Add 3.5 sec. to account for starting at 15 KT \( (V = 15 \text{ KT at } t = 0) \)
2. Add 3.0 sec to account for starting at 15 KT

**NASA-Boeing Take-Off Acceleration Comparison**
$GW = 527,200 \text{ lb} \quad \text{SEA LEVEL}$

$\delta_F = 20 \quad \text{c.g.} \quad 15.6\%$

$O_{FRL} = -3.8$

TAKE OFF
TAKEOFF ACCELERATION
FLAPS 20
G.W. = 527200 LB.
C.G. = 15.6% MAC
TEST 59-10 CERT.
COND. 1.06.051.015.0

NOTE 1. IEPR(t=0) = 1.380
2. Δp = 6.8 UNITS
3. FLT TEST SIM
   VR  128.6 KIAS  131
   VLOF 139.7   ✓  140
   t35° 37 SEC.  35

TAKEOFF ACCELERATION
FLAPS 20  527200 LB.
THE BOEING COMPANY
14.2.2 CLIMB PERFORMANCE

The purpose of this test was to verify the climb performance simulation. The pilot started the test near sea level and his task was to fly the air speed and EPR schedule prescribed for this condition, Page 14.2-10. At the check altitudes, the computer was put in "hold" and data was obtained from the cockpit instruments and the computer. The comparison between Boeing and NASA simulator results is tabulated on Page 14.2-10 and plotted on Page 14.2-11. The difficulty in performing this task is to have the airplane stabilized when putting the computer to "hold".
FOUR-ENGINE CLIMB PERFORMANCE

<table>
<thead>
<tr>
<th>CLIMB CONDITION</th>
<th>FLAP POSITION</th>
<th>GEAR</th>
<th>C.G. ~ 1000 LB.</th>
<th>C.G. ~ 8% MAC</th>
<th>ALTITUDE ~ 1000 FT.</th>
<th>Vl/M</th>
<th>IEPR</th>
<th>( \Theta_B ) ~ DEG.</th>
<th>R/C ~ FT/MIN.</th>
<th>Fh ~ LB/ENG</th>
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<tbody>
<tr>
<td>CLIMB TO ALT.</td>
<td>UP</td>
<td>UP</td>
<td>650</td>
<td>14</td>
<td>10</td>
<td>5</td>
<td>340</td>
<td>1.187</td>
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<td>4.4</td>
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<td></td>
<td>1.47</td>
<td>2.7</td>
<td>0</td>
</tr>
</tbody>
</table>

COMPUTATION TOLERANCE

\( \pm 0.01 \) \( \pm 0.5 \) DEG. \( \pm 5\% \)

NASA DATA WAS OBTAINED FROM COCKPIT INSTRUMENTS

↑ NASA DATA AT 21700 FT.
4 - ENGINE ENROUTE CLIMB

G.W. = 650000 LB.
C.G. = 14% MAC

NOTE
1. MAX. CLIMB THRUST (A/C AIRBLEED ON)
2. STANDARD DAY
3. NO FUEL BURNOFF
4. SEE TABLE (PAGE 5.2-3) FOR THRUST, IEPR, AND ATTITUDE INFORMATION

MAX. ALTITUDE

rate of climb ~ 100 FT/Min

TIME TO CLimb ~ MINUTES

hp ~ 1000 FT.
14.2.3 **INFLIGHT ACCELERATION AND DECELERATION**

The acceleration condition was performed by starting at $M = .65$ with maximum continuous thrust and accelerating to the maximum speed. Speed and time data were obtained from the cockpit. The comparison between Boeing and NASA simulations is shown on Page 14.2-13.

The deceleration check was performed with speed brakes and idle power, starting at $M = .85$. The NASA simulation results are plotted on Page 14.2-14. The differences in the NASA and Boeing data are the result of a difference in idle EPR. The Boeing test utilized a revised Mach and altitude correction to EPR which affected the idle thrust at high altitude and Mach number. The trend of the results, accounting for the higher idle thrust, appeared correct. The adjustment to the idle EPR was made in the NASA simulation after the checkout data were obtained.
### Diagram Description

The diagram illustrates the relationship between Mach number and various flight parameters, including time (in minutes), TEPR (Thrust Efficiency Ratio), and angle of attack ($\theta_8$). The data points are labeled with conditions such as G.W. = 450000 LB, ALT. = 35000 FT, and CG = 25% MAC (Center of Gravity).

**Without Speed Brakes**
- A line indicating the flight characteristics under these conditions is present.

**With Speed Brakes (Inflight Detent)**
- Another line showing the effects of speed brakes is visible.

**Note:**
1. J8-2092S REV. D Sim. Data
2. Idle thrust (Zero Throttle)

---

### Table: Level Flight Deceleration

<table>
<thead>
<tr>
<th>CALC</th>
<th>BRYANT</th>
<th>5-16-70</th>
<th>REVISED</th>
<th>DATE</th>
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</thead>
<tbody>
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<td>CHECK</td>
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</tr>
<tr>
<td>APR</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>APR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLENN</td>
<td>5-19-70</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Level Flight Deceleration**

- **FLAPS UP**
  - G.W. = 450000 LB
  - ALT. = 35000 FT

**The Boeing Company**
14.2.4 STEADY TURNS

This test was conducted to check the stick force and elevator required to hold a bank angle, or load factor. The pilot trimmed the airplane for straight and level flight and then rolled into a steady coordinated turn at a specified bank angle. The airplane was allowed to descend in order to maintain a constant airspeed. When the condition was stabilized, the computer was put in "hold" and the computed values of $F_s$, $\phi_B$, and $\delta_e$ were obtained. The results are tabulated with the Boeing simulation results on Page 14.2-16. The data are plotted, along with flight test results, on Pages 14.2-17 and -18. The data scatter is a result of the difficulty in having a stabilized condition when going to "hold". A calculated value of $\eta_s = 1/\cos \phi_B$ was used in plotting the data.
### STEADY COORDINATED TURNS

<table>
<thead>
<tr>
<th>FLAP POSITION</th>
<th>GEAR</th>
<th>C.N. ~ 1000 LB.</th>
<th>C.G. ~ % WAC</th>
<th>ALTITUDE ~ FT</th>
<th>VI/M ~ UNITS</th>
<th>∆P ~ DEG</th>
<th>BANK ANGLE, φB ~ DEG</th>
<th>Fg ~ LB.</th>
<th>δe ~ DEG</th>
<th>n2</th>
<th>n2</th>
<th>BOEING</th>
<th>NASA</th>
<th>BOEING</th>
<th>NASA</th>
<th>BOEING</th>
<th>NASA</th>
<th>BOEING</th>
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<tr>
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<td>1.3</td>
<td>1.15</td>
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<td>1.16</td>
<td>1.47/1.43</td>
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<td>1.74</td>
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<td>1.47/1.43</td>
<td>38/32.5</td>
<td>.3</td>
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<tr>
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<td>34</td>
<td>.86</td>
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<td>30, 50, 58*</td>
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<td>-3.2</td>
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<td>30, 40, 45</td>
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<td>1.17</td>
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<td>1.17</td>
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<td>-5.2</td>
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<td>-5.2</td>
<td>1.30</td>
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<td></td>
<td>19.5</td>
<td>-7.6</td>
<td>1.41</td>
<td>1.41</td>
<td>1.41</td>
<td>1.47/1.41</td>
<td>19.5</td>
<td>-7.6</td>
<td>1.41</td>
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</tr>
</tbody>
</table>

**COMPUTATION TOLERANCE**

± 10% ± 0.5 DEG

\[ n_2 = \frac{1}{\cos \phi_B} \]

* INITIAL BUFFET
**FLAPS UP**

**GEAR UP**

<table>
<thead>
<tr>
<th>NASA</th>
<th>SYM</th>
<th>A/P</th>
<th>FLT.</th>
<th>COND. NO.</th>
<th>C.G.</th>
<th>% MAC</th>
<th>G.W.~1000 LB</th>
<th>ALT.~ FT.</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>31-6</td>
<td>1.21.003.005.0-6.7</td>
<td>31</td>
<td>540</td>
<td>34000</td>
<td>.86</td>
<td></td>
</tr>
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<td>30-2</td>
<td>1.21.003.047.0-.9</td>
<td>14</td>
<td>560</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SIMULATOR (D6-20423, REV. D DATA)**

**NOTE**: 1. CONSTANT THROTTLE (P.L.F. @ $\frac{1}{\eta_z} = 1.0$)
2. SIMULATOR $F_s$ INCLUDES 2.5 LB. BREAKOUT FORCE

---

**BUFFET ONSET**

- $F_s \sim \text{L.B.}$
- $\cos^{-1} \left( \frac{1}{\eta_z} \right)$
- LOAD FACTOR, $\eta_z$
- $\beta_e \sim \text{DEG.}$

---

**STEADY COORDINATED TURN**

35000 FT.  
$M = .86$

---

**THE BOEING COMPANY**

---

CALC  BYSTROM  4-4-70  REVISION  DATE
CHECK  CURNUTT  5-18-70
APR
APR  ODEGARD  5-23-70

---

PAGE  14-2-17
NOTE: 1. CONSTANT THROTTLE (PLF @ N₂ = 1.0)

2. SIMULATOR Fₕ INCLUDES: 2.5 LB BREAKOUT FORCE
14.2.5 LONGITUDINAL STATIC STABILITY

The airplane was trimmed for straight and level flight. Without changing the stabilizer or throttle, the pilot slowly changed the speed using the elevator. The thrust discrepancy was allowed to generate a rate of climb or descent. Computed values of $S_e$, $F_s$, and $\Theta_B$ were recorded when the airplane was stabilized at the prescribed speed. The column was then released to see if the airplane would return to the trim speed. The results are plotted on Page 14.2-20.
\[ \Delta \theta_{FRL} = -1.26^\circ \]

**SIMULATOR (76-20423 REV. D DATA)**

**NOTE:**
1. SHADEN SYM 30L INDICATES TRIM POINT
2. FLAGGED SYMBOLS INDICATE RETURN TO TRIM
3. THRUST FOR LEVEL FLIGHT AT THE TRIM SPEED
4. MASS UNBALANCE EFFECTS INCLUDED IN BREAKOUT
14.2.6 STEADY SIDESLIPS

After a trimmed flight condition was set up, the pilot slowly applied rudder to hold a steady sideslip. A combination of lateral control and bank angle was used to maintain a straight and level flight path. When the airplane was stabilized, computed values of $\beta$, $\delta_R$, $\xi_w$, and $\phi_B$ were recorded. Comparisons between NASA and Boeing simulations and flight test are shown on Pages 14.2-22 and -23.
FLAPS 20

D6-20423 REV D SIM DATA
MAXIMUM RUDDER
(RATIO CHANGER LIMIT)

SYMmetric FOR POSITIVE
& NEGATIVE RUDDER

GEAR UP
G.W. 558,000 LB
h.P. 9850 FT
C.G. 31.9 % M.A.C
V(I) 143.4 KNOTS

○ NASA

□ FLIGHT 4-I, A/P RAI01
COND. 125.051.002
(β BASED ON MANUAL NOTES)

Fp ~ LB

80

60

40

20

0

β ~ DEG.

15

10

5

0

0

10

20

ΩR ~ DEG.

FRICTION BAND
(+ 6 LB.)

NOMINAL

50

40

30

20

10

0

0

10

20

WR ~ DEG.

ΦR ~ DEG.

15

10

5

0

0

10

20

ΩR ~ DEG.

60

40

20

0

STEADY SIDESLIP

V(I) 143.4 KNOTS
FLAPS 20

THE BOEING COMPANY

CALC BECK 5-18-70 REVISI2 DATE
CHECK APR APR
INK KINGSAN 5-12-70

PAGE 14-2-23
14.2.7 **ROLL RATES**

The pilot trimmed the airplane for straight and level flight and then rolled into a 30° bank. The yaw damper was on and the rudder pedals were not used. After the bank angle was established, a wheel input was rapidly applied and held until the airplane banked to 30° in the opposite direction. The time to bank through the 60° was obtained with a stop watch and the maximum roll rate and magnitude of wheel input were obtained from the computed time histories. The average roll rate was determined by dividing the change in bank angle, 60°, by the time required to bank 60°. The NASA simulator data is compared to Boeing results in the table on Page 14.2-25 and to the plotted data on Pages 14.2-26 thru -28.
<table>
<thead>
<tr>
<th>Flap Position</th>
<th>Gear</th>
<th>G-H 1000</th>
<th>Altitude 1000</th>
<th>V/I/M</th>
<th>Hyd. Sys.</th>
<th>Yaw Damper</th>
<th>$\gamma_W$ Trims $\times 30$</th>
<th>$t_{-30/30}$</th>
<th>$P_{avg}$</th>
<th>$P_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>UP</td>
<td>710</td>
<td>10</td>
<td>200</td>
<td>ON</td>
<td>-3.4</td>
<td>BOEING</td>
<td>NASA</td>
<td>BOEING</td>
<td>NASA</td>
</tr>
<tr>
<td>0</td>
<td>UP</td>
<td>550</td>
<td>35</td>
<td>.86</td>
<td>ON</td>
<td>- .8</td>
<td>25</td>
<td>32°</td>
<td>7.5</td>
<td>7</td>
</tr>
<tr>
<td>30</td>
<td>DN</td>
<td>564</td>
<td>S.L.</td>
<td>180</td>
<td>ON</td>
<td>-7.6</td>
<td>80</td>
<td>41°</td>
<td>8.6</td>
<td>4.1</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>80</td>
<td>12</td>
<td>7.1</td>
<td>5</td>
<td>5.5</td>
<td>3.8</td>
<td>5.0</td>
<td>6.7</td>
<td>7</td>
</tr>
</tbody>
</table>
NOTE:
1. TRIM AT -30° BANK AND ROLL THROUGH +30° BANK.
2. GEAR UP; YAW DAMPER ON.
3. Ixx = 14.3 x 10^6 SLUG-FT^2

**4. REDUCE ROLL RATES 1 DEG/SEC. FOR 710000 LB.
(Ixx = 20.3 x 10^6 SLUG-FT^2)

FLIGHT TEST

HYBRID SIMULATOR (D6-20423, REV. D)

(710000 LB)

NASA

ROLL RATE CAPABILITY
FLAPS 10

THE BOEING COMPANY
Note:
1. Trim at -30° bank and roll through ±30° bank.
2. VAW damper on.
3. $I_{xx} = 14.0 \times 10^6$ slug-ft.$^2$
4. Wheel effect applies to test conditions
   ($I_{xx} = 17.8 \times 10^6$ slug-ft.$^2$)

FLAPS UP
35,000 FT.
550,000 LB.

Roll Rate Capability
FLAPS UP ~ 35,000 FT.
<table>
<thead>
<tr>
<th>CALC</th>
<th>1KUCIS</th>
<th>4.3070</th>
<th>REVISION</th>
<th>DATE</th>
<th>ROLL RATE CAPABILITY</th>
<th>FLAPS 30</th>
<th>747</th>
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<td>THE BOEING COMPANY</td>
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<td>AD 4.050 C-65</td>
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<td>14.2-20</td>
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</tr>
</tbody>
</table>
14.2.8 AIR MINIMUM CONTROL SPEED

Minimum control speed in the air is defined as the lowest speed at which an airplane can maintain straight flight with a critical engine failed, rudder at full deflection, and bank angle at 5 degrees (dead engine high). The results from the NASA test are plotted on Page 14.2-30.
15.0  APPENDIX A - FLIGHT MANUAL

Selected pages from the performance section of the FAA approved airplane flight manual are contained in this section. This information will allow the simulation to be operated in compliance with the appropriate performance criteria and certification requirements of FAR Part 25 and Part 36.
THIS AIRPLANE MUST BE OPERATED IN COMPLIANCE WITH THE PRESCRIBED CERTIFICATE LIMITATIONS IN SECTION 1 HEREIN

Approved by:  Robert F. Frumon

Chief, Aircraft Engineering Division,
FAA, WESTERN REGION

Date  December 30, 1969

DD-13703

PUBLISHED BY THE BOEING COMPANY, COMMERCIAL AIRPLANE GROUP, RENTON, WASHINGTON U.S.A.
GENERAL

REGULATORY COMPLIANCE

The information in this section is presented for compliance with the appropriate performance criteria and certification requirements of FAR Part 25 and Part 36.

STANDARD PERFORMANCE CONDITIONS

All performance in this section is based on the following:

1. Approved engine thrust ratings less installation losses, airbleed and accessory losses.
2. Full temperature accountability within the operational limits, except for landing distance, which is based on standard day temperatures.
3. Trailing edge flaps positions as follows:

<table>
<thead>
<tr>
<th>Trailing Edge Flaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeoff</td>
</tr>
<tr>
<td>Transition Flap Setting</td>
</tr>
<tr>
<td>Enroute</td>
</tr>
<tr>
<td>Approach</td>
</tr>
<tr>
<td>Landing</td>
</tr>
<tr>
<td>10, 20</td>
</tr>
<tr>
<td>1, 5</td>
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<tr>
<td>0</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>25, 30</td>
</tr>
</tbody>
</table>

4. Leading edge devices in the appropriate position for trailing edge flap position.

VARIABLE FACTORS AFFECTING PERFORMANCE

Details of the variable factors affecting performance are given under performance configuration, but certain assumptions relating to all performance data are as follows:

ICING PROTECTION

The effect of anti-icing systems operation is shown on applicable charts.

HUMIDITY

Humidity has no appreciable effect on the thrust of the engines; therefore, it has not been considered in the performance data.

WIND

The wind velocity used in calculations is factored to assure compliance with the relevant operating regulations. All charts should be entered with actual tower-reported wind components.
GENERAL

DEFINITIONS

AIRSPEEDS

All airspeed and Mach values in this manual assume a zero instrument error.

All Indicated Airspeeds are based on normal static source position error.

Position error is the instrument indication error due to location of static ports.

Equivalent Airspeed, EAS - Airspeed indicator reading, as installed in the airplane, corrected for static source position error and compressibility.

Calibrated Airspeed, CAS - Airspeed indicator reading, as installed in the airplane, corrected for static source position error.

Indicated Airspeed, IAS - Airspeed indicator reading, as installed in the airplane, uncorrected for static source position error.

True Mach Number, M - Machmeter reading, as installed in the airplane, corrected for static source position error.

Critical Engine Failure Speed, V₁ - The speed at which, when an engine failure is recognized, the distance to continue the takeoff to a height of 35 feet will not exceed the usable takeoff distance; or, the distance to bring the airplane to a full stop will not exceed the accelerate-stop distance available. V₁ must not be less than the Ground Minimum Control Speed, VMCG, or greater than the rotation speed, VR, or greater than the maximum brake energy speed, VMBE.

Engine Failure Speed Ratio, V₁/VR - The ratio of the engine failure speed, V₁, for actual runway dimensions and conditions, to the rotation speed, VR.

Maximum Brake Energy Speed, VMBE - The maximum speed on the ground from which a stop can be accomplished within the energy capabilities of the brakes.
AIRPLANE FLIGHT MANUAL

GENERAL

DEFINITIONS

AIRSPEEDS (Continued)

Rotation Speed, \( VR \) - The speed at which rotation is initiated during the takeoff.

Takeoff Safety Speed, \( V_2 \) - The scheduled target speed to be attained at the 35 foot height with one engine inoperative.

Air Minimum Control Speed, \( VMCA \) - The minimum flight speed at which the airplane is controllable with a maximum of 5° bank when the critical engine suddenly becomes inoperative with the remaining engines at takeoff thrust.

Ground Minimum Control Speed, \( VMCG \) - The minimum speed on the ground at which the takeoff can be continued, utilizing aerodynamic controls alone, when the critical engine suddenly becomes inoperative with the remaining engines at takeoff thrust.

Landing Reference Speed, \( V_{REF} \) - The minimum speed at the 50 foot height in a normal landing. This speed is equal to 1.3 times the stall speed in the landing configuration.

Design Maneuvering Speed, \( VA \) - The maximum speed at which application of full available aileron, rudder or elevator will not overstress the airplane.
GENERAL

DEFINITIONS (Continued)

TEMPERATURE

ISA - International Standard Atmosphere, as accepted by the International Civil Aviation Organization.

OAT - Outside Air Temperature - the free air static (ambient) temperature.

SAT - Static Air Temperature - outside air (ambient) temperature as computed by the Air Data Computer and presented on the Static Air Temperature indicator.

TAT - Total Air Temperature - static air temperature plus adiabatic compression (ram) rise as indicated on the Total Air Temperature indicator.

WIND

Wind Velocity - The actual wind velocity at a 50 foot height reported from the tower and corrected by the wind component chart to a headwind or tailwind component parallel to the flight path.

HEIGHT

Gross Height - The geometric height attained at any point in the takeoff flight path using gross climb performance. Gross height is used for calculating actual pressure altitudes at which obstacle clearance procedures and wing flap retraction are initiated, and level-off-height scheduled.

Net Height - The geometric height attained at any point in the takeoff flight path using net climb performance. Net height is used to determine the net flight path which must clear any obstacles by at least 35 feet to comply with the regulations.

ICING

Icing Conditions - Icing may develop when visible moisture such as fog, rain, or wet snow is present with Static Air Temperature below 8°C (46°F).

TAKEOFF DATA

Balanced Field Length - The condition where V1 is selected to make the takeoff distance equal to the accelerate-stop distance.

Unbalanced Field Length - The condition where V1 is selected to make the takeoff distance and accelerate-stop distance unequal.
GENERAL

GRADIENT OF CLimb

Gross Gradient - The demonstrated ratio, expressed as a percentage, of:

\[
\text{Change in Height} \quad \frac{\text{Horizontal Distance Traveled}}{\text{Change in Height}}
\]

The gradients shown on the charts are true gradients, i.e., they are based on true, not pressure, rates of climb.

Net Gradient - The demonstrated gross gradient reduced by the increment as required by regulation.

BUFFET ONSET CHARACTERISTICS

The buffet boundary is a basic characteristic of the airplane that is defined by angle of attack and Mach numbers. Below approximately 0.85 M, the buffet is related to the wing maximum lift capability (therefore to true airplane stall). In the range above 0.85 M, buffet is related to the growth of shock waves on the wing.

At any flight condition, it is possible to determine the altitude, low-speed, high-speed, and maneuvering margins before buffet onset occurs. (See Cruise Maneuvering Capability chart.)

CROSSWIND VALUES (Takeoff and Landing)

The maximum demonstrated crosswind component is 30 knots reported wind at 50 foot height. This component is not considered to be limiting.

For performance scheduling, the full headwind component may be used provided that the corresponding crosswind component does not exceed 30 knots.

MINIMUM CONTROL SPEEDS:

The Air Minimum Control Speeds (VMCA), and the Ground Minimum Control Speeds (VMCG), of this airplane are shown on a chart in this Section, and on the takeoff Speeds charts where applicable.
PERFORMANCE CONDITIONS AND PROCEDURES

Takeoff field length performance shown in this section accounts for 115 percent of the all-engines operating distance, or the total distance considering an engine failure recognition at V1, whichever is greater. These distances are based on a smooth, dry, hard-surfaced runway.

The appropriate airplane configuration, outlined under Performance Configurations, was used.

The conditions and procedures used in establishing the performance data in this manual are presented under each phase of operation. Procedures are guidance material only.

TAKEOFF

Conditions

Prior to takeoff, a review was made of stabilizer and flap settings, takeoff speeds, and that sufficient field length was available for the gross weight and ambient conditions. Corrections were applied, when necessary, for significantly altered ambient conditions or loading.

Procedures

Thrust was set to 1.1 EPR prior to brake release, or as the airplane was aligned with the runway. With no wind, or a direct headwind, EPR was advanced prior to brake release. Thrust levers were adjusted as necessary to obtain target EPR values by approximately 40 to 80 knots on the takeoff roll.

Rudder pedals were used for directional control through the nose wheel and rudder.

Rotation to takeoff attitude was initiated at VR. A speed not less than V2 was obtained at a height of 35 feet. The landing gear was retracted after a positive rate of climb was established.

A smooth positive rotation was used to the initial climb attitude (approximately 13 to 22 degrees depending upon gross weight and thrust available). Minor attitude variations were made after liftoff to achieve the initial climb speed. Engine failure results in approximately 2 to 2-1/2 degrees lower attitude than normal climb.

NOTE: With center of gravity at or near the aft limit, avoid sudden brake release and maintain forward pressure on the control column to approximately 80 knots to increase nose wheel steering effectiveness.
PERFORMANCE CONDITIONS AND PROCEDURES

REFUSED TAKEOFF (Anti-Skid On)

Conditions

Calculated accelerate-stop distances account for demonstrated recognition and reaction times, plus arbitrary time delays.

Reverse thrust was not used.

Procedures

When an engine failure occurred, the takeoff was refused when the failure was recognized prior to V1.

If the takeoff was refused for any reason, prior to V1, the following procedure was accomplished as rapidly as possible:

Wheel Brakes - MAXIMUM BRAKING APPLIED
All Thrust Levers - IDLE
Speed Brakes - UP

CLIMB-OUT (3 or 4 Engines)

Conditions

Climb gradient and obstacle clearance flight path performance is based on the most critical engine inoperative at V1.

Procedures

Takeoff flap setting and V2 speed were maintained to at least the height selected for initiation of flap retraction.

Flaps were retracted according to the Flap Retraction Speed Schedule, in this section.

Enroute procedures were followed after climbing to at least 1500 feet above runway elevation, or after all takeoff flight path obstacles had been cleared.
PERFORMANCE CONDITIONS AND PROCEDURES

OBSTACLE CLEARANCE

Conditions

With all engines operating, a speed not greater than \( V_2 + 10 \) knots was maintained until either the scheduled flap retraction height, or the minimum gross height for obstacle clearance (whichever was lower), was reached.

When engine failure occurred prior to \( V_2 \), and the takeoff weight was obstacle limited, \( V_2 \) was maintained up to the gross height required for obstacle clearance.

If an engine failure occurred after \( V_2 \), speed at engine failure (\( V_2 + 10 \) knots maximum) was maintained up to the gross height required for obstacle clearance.

Procedures

When the height selected for initiation of flap retraction was limited due to distant-obstacle considerations, the procedure was to initiate flap retraction and accelerate to final takeoff climb speed while maintaining constant altitude and initial takeoff thrust setting.

Final takeoff climb was continued to 1500 feet above runway elevation, or to the minimum gross height required for obstacle clearance, at final takeoff climb speed and maximum continuous thrust.

NOTES: The airplane should be levelled off, and flaps retracted at the selected level-off height, only if the limiting obstacle is beyond the Third Segment and an engine failure has occurred.

The height selected for initiation of flap retraction may be limited by available performance as described under Takeoff Flight Path, this section. Vertical clearance of either close-in or distant obstacles in the intended flight path must be established by reference to the appropriate obstacle clearance charts.
PERFORMANCE CONDITIONS AND PROCEDURES

LANDING FIELD LENGTH

Conditions

All landing field lengths shown in this section are based on standard day temperatures on a smooth, level, hard-surfaced runway. Dry landing field lengths are demonstrated landing distances, from a 50 foot height at VREF, divided by a factor 0.6. Wet landing field lengths are determined by multiplying the dry landing field length by a factor of 1.15.

Procedures

Approach and landing were made with landing gear down, flaps in landing position, thrust reduced to flight-idle on all engines before touch-down, and automatically set to ground-idle on all engines after touch-down.

When the landing was made with anti-skid operating, full speed brakes and maximum wheel braking were applied 2 seconds or less after touch-down.

When the landing was made with anti-skid inoperative, speed brakes were raised immediately upon touch-down and steady, light braking was used if gross weight was approximately 500,000 lb (226,800 kg.) or less. Steady, light to moderate braking was used if landing weight was over 500,000 lbs (226,800 kg.). Brakes were modulated as necessary to prevent skidding.

NOTE: Landing field lengths are not based on use of reverse thrust.
FLAP RETRACTION SPEED SCHEDULE

Maximum level-off heights, Third Segment distances and Final Segment climb performance shown in this manual are based upon retracting the wing flaps during Third Segment acceleration using the schedule below. This schedule is recommended for all normal flap retraction operations.

During acceleration, select flap positions at the following initiation speeds:

TAKEOFF FLAPS POSITION 10 OR 20

<table>
<thead>
<tr>
<th>Initiation Speed, Knots</th>
<th>Select Flap Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>V2 + 20</td>
<td>10</td>
</tr>
<tr>
<td>V2 + 40</td>
<td>5</td>
</tr>
<tr>
<td>V2 + 60</td>
<td>1</td>
</tr>
<tr>
<td>V2 + 80</td>
<td>0</td>
</tr>
</tbody>
</table>

Final Segment Climb Speed: V2 + 80 Knots.

When flaps are being retracted at a constant altitude due to engine failure, with a critical final segment obstacle, begin climbing when V2 + 80 knots is achieved, maintaining takeoff thrust setting until flaps are completely retracted.
PERFORMANCE CONFIGURATION

The airplane configuration associated with the performance data in this manual is shown below. Performance conditions not shown below are on the appropriate charts.

<table>
<thead>
<tr>
<th>THRUST</th>
<th>FLAPS</th>
<th>GEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAKEOFF Takeoff on all engines to V1, and three engines subsequent to V1.</td>
<td>Takeoff setting. Noted on charts.</td>
<td>Down</td>
</tr>
<tr>
<td>1st SEGMENT CLimb Takeoff on operating engines (3).</td>
<td>Same as takeoff.</td>
<td>Down</td>
</tr>
<tr>
<td>2nd SEGMENT CLimb Same as 1st segment.</td>
<td>Same as takeoff.</td>
<td>Up</td>
</tr>
<tr>
<td>3rd SEGMENT Same as 1st segment.</td>
<td>Takeoff setting to flaps up, according to schedule.</td>
<td>Up</td>
</tr>
<tr>
<td>FINAL TAKEOFF CLimb Maximum continuous on operating engines (3).</td>
<td>Up</td>
<td>Up</td>
</tr>
<tr>
<td>ENROUTE CLimb Maximum continuous on operating engines (3 or 2).</td>
<td>Up</td>
<td>Up</td>
</tr>
<tr>
<td>APPROACH CLimb Takeoff on operating engines (3).</td>
<td>Approach setting. Noted on chart.</td>
<td>Up</td>
</tr>
<tr>
<td>LANDING CLimb Maximum available in 8 seconds on all engines.</td>
<td>Landing setting. Noted on chart.</td>
<td>Down</td>
</tr>
<tr>
<td>LANDING Ground idle on all engines after touchdown.</td>
<td>Landing setting. Noted on chart.</td>
<td>Down</td>
</tr>
</tbody>
</table>

Anti-skid is on for takeoff and landing with up to two brakes deactivated, unless anti-skid inoperative braking performance is used.

One or three Air Conditioning Packs are on for all takeoff thrust operations. R

All three Air Conditioning packs are on for final takeoff climb. For enroute climb the number of the Air Conditioning packs on is noted on the charts. R

Wing anti-icing is off during all flaps-extended operations.
NOISE CHARACTERISTICS

No determination has been made by the Federal Aviation Administration that the noise levels in this manual are, or should be, acceptable or unacceptable for operation at, into, or out of, an airport.

The noise levels tabulated below are the result of Federal Aviation Regulations, Part 36 certification tests:

<table>
<thead>
<tr>
<th>GROSS WEIGHT</th>
<th>FLAPS</th>
<th>NOISE LEVEL (EPNdB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pounds</td>
<td>Kilograms</td>
<td>Position</td>
</tr>
<tr>
<td>710,000</td>
<td>322,056</td>
<td>10</td>
</tr>
<tr>
<td>673,000</td>
<td>305,273</td>
<td>20</td>
</tr>
<tr>
<td>564,000</td>
<td>255,830</td>
<td>30</td>
</tr>
</tbody>
</table>

The traded noise level is 112.0 EPNdB.

Normal all engines takeoff procedures were used, with a climb-out at V2 + 10 knots at Takeoff Thrust with no thrust cut-back. The landing approach was made at VREF + 10 knots.
NOTE: NO EPR REDUCTION REQUIRED FOR NACELLE ANTI-ICE "ON" AT TEMPERATURES BELOW 8°C (46°F) WITH 1 A/C PACK OPERATING ADD 0.1 EPR.
SET STABILIZER FOR TAKEOFF CENTER
OF GRAVITY DETERMINED BY CALCULATED
OR GRAPHICAL METHOD, WITH GEAR DOWN
AND WITH TAKEOFF FLAPS.

\[ \Delta_p = 3 - \Delta_{FRL} \]
\[ \Delta_{FRL} = 3 - \Delta_p \]

![Diagram showing stabilizer trim units for takeoff](image)

CENTER OF GRAVITY — PERCENT MAC

AIRPLANE NOSE DOWN

AIRPLANE NOSE UP

STABILIZER TRIM UNITS FOR TAKEOFF

TAKING OFF GROSS WEIGHT: 4000 LB

400

300

200

100

0

FAA APPROVED 5-11-70
CONVERSION CHART FOR
IAS TO MACH NUMBER

NOTE: WITH UNHEATED PROBE
REDUCE TOTAL AIR
TEMPERATURE BY 0.5 °C

TOTAL AIR — STATIC AIR
HEATED ROSEMOATM PROBE

INDICATED AIRSPEED—KNOTS

MACH NUMBER

150 200 250 300 350 400

INDICATED PRESSURE ALTITUDE—1000 FT.
NOTE APPLICABLE FOR TAKEOFF AND LANDING ALTITUDES ONLY.
GEAR UP EXCEPT AS NOTED.

STALL SPEEDS

GROSS WEIGHT — 1000 LB.

FAA APPROVED 12-30-69
MAXIMUM ALLOWABLE TAKEOFF WEIGHT

NORMAL TAKEOFF WEIGHT ANALYSIS

CHART READING PROCEDURE

The following steps will be adequate for most takeoff situations. The dotted guide-lines on typical charts and the Illustrative Examples are for guidance purposes.

1. Select most probable takeoff flap setting.

2. Runway Length Corrections (All Engines) chart - Enter with actual runway length available. Make slope and wind corrections. Read corrected runway length.

3. Runway Length and V1 Adjustments chart - Enter with actual runway length available on both the Runway Length, and Accelerate-Stop Distance scales. Make slope and wind corrections from the respective reference lines. Where the two corrected distances intersect on the "web" portion of the chart, read V1/VR, and corrected runway length.

4. Maximum Takeoff Weight, Field Length Limits chart - Enter with the lesser of the corrected runway lengths from Step 2 or Step 3, airport pressure altitude, and temperature. Read gross weight.

5. Maximum Takeoff Weight, Climb Limits chart - Enter with airport pressure altitude and temperature. Read gross weight.

6. IF 200 MPH TIRES ARE INSTALLED, USE:
   Maximum Takeoff Weight, Tire Speed chart - Enter with airport pressure altitude and temperature. Make wind correction. Read gross weight.

NOTE: If obstacles are present, proceed with Steps 7 through 10.
MAXIMUM ALLOWABLE TAKEOFF WEIGHT

NORMAL TAKEOFF WEIGHT ANALYSIS

CHART READING PROCEDURE  (Continued)

7. Takeoff Climb chart - Enter with least gross weight determined by Steps 4, 5, 6, structural limits, or operational requirements, then proceed to temperature and airport pressure altitude. Read Second Segment gradient. Correct the gradient for wind, if applicable, using Gradient Corrections chart.

8. Obstacle Clearance (Close-in Obstacles) chart - Enter with obstacle distance from end of takeoff distance required. Correct the distance for wind. Proceed vertically to zero-wind gradient available, from Step 7.

(a) If this exceeds obstacle height, obstacle is cleared.
(b) If obstacle height is not exceeded, follow dashed field-length-trade guide lines to obstacle height. Read gradient required for obstacle clearance. This gradient accounts for the shorter takeoff distances required when gross weight is reduced. (See SLOPED RUNWAY EFFECT ON OBSTACLE CLEARANCE).

9. Obstacle Clearance (Distant Obstacles) chart - Enter with obstacle distance from end of takeoff distance required. Proceed vertically to wind-corrected gradient available, from Step 7.

(a) If this exceeds obstacle height, obstacle is cleared. However, now drop back down to obstacle height, then move left (horizontally) to wind-corrected gradient available. Read gross height.
(b) If obstacle is not cleared at wind-corrected gradient available, follow dashed field-length-trade lines to the obstacle height. Read gross height and gradient required for obstacle clearance. Correct the gradient required to zero-wind gradient, on the Gradient Corrections chart. (See OBSTACLE IN THIRD SEGMENT, and OBSTACLE IN FINAL SEGMENT.)
MAXIMUM ALLOWABLE TAKEOFF WEIGHT

NORMAL TAKEOFF WEIGHT ANALYSIS

CHART READING PROCEDURE  (Continued)

10. **Takeoff Climb chart** - Enter gradient scale with the largest zero-wind gradient required for obstacle clearance as determined from Step 8 or 9. Proceed to airport pressure altitude, and temperature. Read gross weight.

11. **Takeoff Speeds chart** - Enter with airport pressure altitude, temperature, and the least gross weight determined by Steps 4, 5, 6, 10, structural limits, or operating requirements. Read VR and V2. Read V1 at the V1/VR ratio from Step 3. The resulting V1 must exceed the minimum V1 (VMCG), (See V1 Less than VMCG), and the resulting VR must exceed the VMCA limit. (See VR Less than VMCA Limit).

12. **Maximum Brake Energy Limit Speed chart** - Enter with airport pressure altitude, temperature, and gross weight used in Step 11. Correct for runway slope, and wind. Read VMEE. This speed must exceed V1 of Step 10. (See V1 Greater than VMEE).

13. **Gross Height - Pressure Altitude Conversion chart** - Enter with gross height obtained from Step 9. Correct for temperature and altitude. Read pressure altitude increment. Add this value to the airport pressure altitude. Acceleration and flap retraction should not be scheduled below this altimeter reading.

14. Determine flap retraction and final climb speeds from the FLAP RETRACTION SPEED SCHEDULE.
MAXIMUM ALLOWABLE TAKEOFF WEIGHT

TAKEOFF WEIGHT ANALYSIS WITH IMPROVED CLIMB PERFORMANCE

The following steps describe the procedure for finding the maximum allowable takeoff weight when using Improved Climb Performance. Improved Obstacle Clearance with speed increase is considered under a separate paragraph heading. The term, "normal", refers to the weights and speeds based on no increase in takeoff speeds.

1. Steps 1 through 6 of the Normal Takeoff Analysis are unchanged.

2. Maximum Takeoff Weight and Speeds (Improved Climb Performance) chart - Enter the weight portion of this chart with normal field length and climb limited gross weights. Follow the guidelines until they intersect. At the intersection, read gross weight and speed increase. Repeat, using tire speed and climb limited gross weights if 200 MPH tires are installed. Use lesser weight and speed increase.

3. Takeoff Speeds chart - Enter this chart, as in Normal Analysis, with pressure altitude and temperature, and with the gross weight determined from Step 2 above. Read VR, V2, and V1 for the V1/VR ratio in Step 3 of Normal Analysis.

4. Maximum Takeoff Weight and Speeds (Improved Climb Performance) chart - Enter the speed correction portion with the VR, V2 and V1 speeds determined in Step 3 above. Follow the guidelines to the speed increase determined in Step 2 above. Read Corrected VR, V2, and V1. V1 must be less than VMCE. (See V1 Greater than VMCE).

5. Determine flap-retraction speeds based on the V2 speed derived from Step 3 above.
MAXIMUM ALLOWABLE TAKEOFF WEIGHT

SELECTION OF V1

When the calculated or scheduled takeoff weight is not field-length limited, V1 may be raised or lowered to suit operating conditions within the restrictions imposed by the available runway length, VMCG, VR, and VMBE. Even when takeoff weight is field-length limited, a small reduction in V1 is available if the 3-engine field length requirement is shorter than the all-engine requirement. This is generally true for this airplane.

The following additional steps are required in the Normal Takeoff Weight Analysis to determine the V1 limits:

1. Maximum Takeoff Weight (Field Length Limits) chart - Enter with airport pressure altitude, temperature, and actual scheduled takeoff weight. Read corrected runway length required.

2. Runway Length and V1 Adjustments chart - Enter, in upper right portion of the chart, with the corrected runway length obtained from Step 1. Where this runway length intersects the slope and wind corrected takeoff distance available line as determined in Step 3 of the Normal Analysis procedure, read minimum V1/VR. Where this runway length intersects the slope and wind corrected accelerate-stop distance line as determined in Step 3 of the Normal Analysis procedure, read maximum V1/VR.

If either intersect occurs off the limits of the chart, use minimum or maximum values shown on the chart.

3. Takeoff Speed chart - At the actual scheduled takeoff weight, and the V1/VR ratios determined in Step 2 above, read minimum V1 and maximum V1.

4. Choose a suitable, single value of V1 between the limits determined in Step 3 above. The speed selected must be greater than VMCG, and less than the VR and VMBE determined in Steps 11 and 12 of the Normal Analysis procedure.
MAXIMUM ALLOWABLE TAKEOFF WEIGHT

V1 LESS THAN VMCG

Usually this will only occur when the takeoff weight is not field-length limited:

Takeoff Speeds chart - Read V1 at the field-length limited gross weight obtained from Step 4 of Normal Analysis procedure, and at the V1/VR ratio obtained from Step 3 of Normal Analysis. Use a V1 between VMCG and the maximum V1 so determined, but not exceeding VR.

V1 GREATER THAN VMCG

If the minimum V1, as determined by Steps 1 through 3 under SELECTION OF V1, still exceeds the brake energy speed, the takeoff weight will have to be reduced:

Maximum Brake Energy Limit Speed chart - Determine ΔV1, as defined on the chart. Reduce gross weight as indicated and redetermine VR, V1 and V2 for the lower weight.

VR LESS THAN VMCA LIMIT

On this airplane, VMCG is greater than 1.05 VMCA; therefore, minimum VR is equal to VMCG. This implies that the available runway length must be sufficient to permit a V1 equal to VR. This condition will be satisfied if the slope and wind-corrected accelerate-stop distance exceeds 4500 feet on the Runway Length and V1 Adjustments chart.

OPERATION WITH ONE AIR CONDITIONING PACK ON

Performance limited takeoff weights and takeoff climb gradients available can be increased by scheduling takeoff with only one air conditioning pack on. Performance increments are shown on the Takeoff With 1 A/C Pack On chart; these increments are applied to the weights and gradients obtained in steps 4, 5 and 7 of the Normal Takeoff Weight Analysis procedure. The gradient increment must be subtracted from the gradient required for use in step 10 to find an obstacle limited weight.
MAXIMUM ALLOWABLE TAKEOFF WEIGHT

SLIPPERY RUNWAY

Wet or icy runway conditions have the same effect on takeoff field length requirements as an inoperative anti-skid system; namely, reduced braking effectiveness. This makes the one engine inoperative condition critical.

The operator must review the existing runway conditions, decide how much additional stopping distance is desired, then proceed with the following steps to determine the changes in the field length limited takeoff weight, and V1 speed:

1. Omit Step 2 of the Normal Takeoff Weight Analysis procedure.

2. Runway Length and V1 Adjustments chart - Determine V1/VR as usual, except that the accelerate-stop distance must be reduced by an arbitrary amount equal to the desired extra stopping margin before making corrections for slope and wind. At the intersection of the corrected takeoff distance available and corrected accelerate-stop distance lines in the "web" portion of the chart, read corrected runway length and V1/VR.

3. Maximum Takeoff Weight chart - Enter the appropriate chart with the corrected runway length from Step 2 above. Read gross weight.

NOTE: If the V1, determined by using the V1/VR ratio from Step 2 above, is greater than the minimum V1 as determined under SELECTION OF V1, no reduction in field length limited takeoff weight is necessary. In fact, the use of minimum V1 in this case will give a greater stopping distance margin.
MAXIMUM ALLOWABLE TAKEOFF WEIGHT

EXAMPLES

Example lines shown on the charts do not necessarily reflect these examples.

ILLUSTRATIVE EXAMPLE 1

Given: Airport Conditions

Runway Length Available = 12,000 ft.
Runway Slope = 0.5% (Uphill)
Airport Elevation (Pressure Altitude) = 2000 ft.
Obstacles: 120 ft. high at 3400 ft.
500 ft. high at 25,000 ft.

Atmospheric Conditions

Reported Wind (at 50 ft.) = 10 kt. (Headwind)
OAT = 20°C (68°F)

Airplane Conditions

Takeoff flap position 10
This example illustrates the general use of the charts, and the obstacle clearance charts in particular, and is restricted to normal speed operation.
See example 5 for improved obstacle clearance with speed increase method.
See chart reading procedure for chart titles and methods of use.

1. From Runway Length Corrections (All Engines) chart, corrected runway length = 12,070 ft.
2. From Runway Length and V1 Adjustments chart, corrected runway length = 12,570 ft. and V1/VR = .970
3. From Maximum Takeoff Weight (Field Length Limits) chart, using the lesser of the corrected runway length from Steps 1 and 2, field length limited takeoff weight = 683,000 lb.
4. From Maximum Takeoff Weight (Climb Limits) chart, climb limited takeoff weight = 649,000 lb.
5. From Maximum Takeoff Weight (Tire Speed Limits) chart, 200 MPH tire speed limited takeoff weight = 743,000 lb. Maximum Takeoff weight = 649,000 lb.
6. From Takeoff Climb chart, using field length limited weight of 683,000 lb, second segment gross gradient at 400 ft. = 2.30%
Using Gradient Corrections chart, gradient corrected for wind = 2.37%

(Continued)
ILLUSTRATIVE EXAMPLE 1  (Continued)

7. From Close-in Obstacle Clearance chart, second segment gross gradient required for close-in obstacle clearance = 4.50%. Obstacle is not cleared with gradient available (uncorrected for wind). Change in reference zero = 5100 - 3400 = 1700 ft. due to the decrease in field length required for the reduced takeoff weight.

In this distance, reference zero shifts 1700 x .005 = 8.5 ft. (vertical) due to runway slope.

The obstacle height is now 128.5 ft. at 5100 ft. from reference zero and the required gradient is 3.08%.

8. From Distance Obstacle Clearance chart determine gross gradient required and minimum gross height.

Gradient capability (from Step 6) = 3.08% (corrected for wind = 3.17%)
Corrected obstacle distance = 25,000 + 1700 = 26,700 ft.
Required gross gradient = 2.89% (less than gradient available).
Distance from reference zero to reach obstacle height of 500 ft. is 23,300 ft.
Minimum gross height for flap retraction is 770 ft.

9. From Takeoff Climb chart, obstacle limited weight = 638,500 lb. at a gross gradient of 3.08%.

10. From Distance Obstacle Clearance chart, maximum level-off height is 940 ft. Therefore extended final segment climb is unnecessary in this case.

11. From Gross Height - Pressure Altitude Conversion chart, the pressure altitude increment for a gross height of 770 ft. is 750 ft. Therefore, the minimum pressure altitude for level-off and flap retraction is 2750 ft.

12. From Takeoff Speeds chart for V1/VR = .970 and 638,500 lb.
    VR = 152.5 kt.  V1 = 147.5 kt.  V2 = 159 kt.

13. Determine flap retraction and final climb speeds.
PERFORMANCE
RUNWAY LENGTH CORRECTIONS
ALL ENGINES OPERATING
FLAP POS. 10 & 20

CORRECTED RUNWAY LENGTH

ACTUAL RUNWAY LENGTH

FAA APPROVED 12-30-69

BOEING 747 AIRPLANE FLIGHT MANUAL

BASSETT 12-7-69
747-100 JT9D-3

CHART APPLICABLE TO

APPROVED
DATE
B.: 1-8-69

NO. 26-30643
Vol. II

SECT
PAGE 15.0 - 35
NOTE

HIGHER WEIGHTS ARE ALLOWED WITH IMPROVED CLIMB PERFORMANCE. SEE TEXT.
NOTE: ENTER CHART WITH TAKEOFF CLIMB
GRADIENT CORRECTED FOR WIND AND
LEVEL-OFF HEIGHT ABOVE 400 FT.
## Gradient Corrections

<table>
<thead>
<tr>
<th>Bank Angle</th>
<th>Flap Pos. 0</th>
<th>Flap Pos. 10 &amp; 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>21</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>63</td>
</tr>
</tbody>
</table>

### Takeoff Climb

![Takeoff Climb Diagram](image)

**Chart Applicable to:** 747-100 JT9D-3

**FAA Approved:** 12-30-69
APPROACH AND LANDING

Charts on the following pages present approach and landing gradients, maximum landing weights as limited by approach and landing performance, landing field length requirements, and landing weights for the maximum brake energy at which wheel thermal plugs will remain intact.

The speed schedules shown on the Approach and Landing Climb charts are those at which the gradients were calculated in accordance with FAR 25.121(d) and 25.119, and have no operational significance. The minimum landing approach speeds are shown on the Landing Field Length and Speed charts.

The ICE CORRECTION on the charts accounts for maximum probable performance effects of ice remaining on the airplane surfaces without anti-ice protection. The correction applies when operating in icing conditions during any part of the flight, unless the forecast temperature at the destination airport is high enough (above 8°C or 46°F) to ensure that the ice will melt off prior to approach and landing.

The Maximum Landing Weight, Climb Limits, can be increased for one air conditioning pack on operation. This information is included to permit a showing of compliance with FAR 25.1001 (c) at the increased allowable takeoff weight.

This information may also be used to schedule higher allowable landing weights provided approach and landing procedures are modified to have only one air conditioning pack on prior to the point where a go-around might be initiated. See Normal Procedures.
REDUCE GRADIENT BY 0.5% FOR ICE ACCUMULATION
WHEN OPERATING IN ICING CONDITIONS DURING ANY PART
OF THE FLIGHT WITH FORECAST LANDING TEMPERATURE
BELOW 8°C.
LANDING CLIMB: GROSS
GRADIENT LIMIT = 5.2%

SPEED SCHEDULE

REDUCE GRADIENT BY 0.33% FOR ICE ACCUMULATION
WHEN OPERATING IN ICING CONDITIONS DURING ANY PART
OF THE FLIGHT WITH FORECAST LANDING TEMPERATURE
BELOW 8°C.

REDUCE GRADIENT BY 0.25% WHEN
ENGINE AIRBLEED IS USED FOR NACELLE
ANTI-ICE.

FAA APPROVED 12-30-69
NOTICE: USE ICE CORRECTION WHEN OPERATING IN ICING CONDITIONS DURING ANY PART OF THE FLIGHT WITH FORECAST LANDING TEMPERATURE BELOW 0°C.
NOTE: USE ICE CORRECTION WHEN OPERATING IN ICING CONDITIONS DURING ANY PART OF THE FLIGHT WITH FORECAST LANDING TEMPERATURE BELOW 6°C.
16.0 **APPENDIX B - BUFFET CHARACTERISTICS**

The buffet frequency was estimated for the conditions listed in the table on Page 16.0-2. These conditions include stall buffet for each flap detent and compressibility buffet for $V_D$ and $V_D$ conditions.

From this investigation it was concluded that:

- Average buffet frequency $= 3.0-3.5$ CPS
- Buffet amplitude range $= \pm 1.5g - \pm 6g$

For illustration, flight data is attached for the following five conditions.

<table>
<thead>
<tr>
<th>COND.</th>
<th>$V_c$ ~KT</th>
<th>ALTITUDE ~1000FT</th>
<th>G.W ~1000 LB</th>
<th>FLAPS/GEAR</th>
<th>C.G. ~%MAC</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_D$</td>
<td>—</td>
<td>32</td>
<td>464</td>
<td>UP/UP</td>
<td></td>
<td>27</td>
</tr>
<tr>
<td>$V_D$</td>
<td>447</td>
<td>15.5</td>
<td>490</td>
<td>UP/UP</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>CLEAN</td>
<td>190</td>
<td>18.7</td>
<td>552</td>
<td>UP/UP</td>
<td></td>
<td>32</td>
</tr>
<tr>
<td>STALL</td>
<td>128</td>
<td>12.0</td>
<td>536</td>
<td>10/UP</td>
<td></td>
<td>32</td>
</tr>
<tr>
<td>STALL</td>
<td>107</td>
<td>13.4</td>
<td>525</td>
<td>30/DOWN</td>
<td></td>
<td>33.3</td>
</tr>
</tbody>
</table>

For illustration, flight data is attached for the following five conditions.
<table>
<thead>
<tr>
<th>COND</th>
<th>Vc</th>
<th>ALTITUDE</th>
<th>G W</th>
<th>FLAPS / GEAR</th>
<th>C. G.</th>
<th>BUFFET FREQ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>~ KT</td>
<td>~1000 FT</td>
<td>~1000 LB</td>
<td>UP / UP</td>
<td>~ % MAC</td>
<td>~ CPS</td>
</tr>
<tr>
<td>M_0</td>
<td>32</td>
<td>464</td>
<td></td>
<td>UP / UP</td>
<td>27</td>
<td>2.9 - 3.1</td>
</tr>
<tr>
<td>V_0</td>
<td>447</td>
<td>490</td>
<td></td>
<td>UP / UP</td>
<td>25</td>
<td>3.1 - 3.3</td>
</tr>
<tr>
<td>CLEAN STALL</td>
<td>190</td>
<td>18.7</td>
<td>552</td>
<td>UP / UP</td>
<td>32</td>
<td>3.0 - 5.0</td>
</tr>
<tr>
<td>STALL</td>
<td>137</td>
<td>16.5</td>
<td>538</td>
<td>5 / UP</td>
<td>32</td>
<td>3.0 - 4^*</td>
</tr>
<tr>
<td>STALL</td>
<td>128</td>
<td>12.0</td>
<td>536</td>
<td>10 / UP</td>
<td>32</td>
<td>3.0 - 4^*</td>
</tr>
<tr>
<td>STALL</td>
<td>117</td>
<td>10.9</td>
<td>530</td>
<td>20 / UP</td>
<td>32.5</td>
<td>2.8 - 3.5</td>
</tr>
<tr>
<td>STALL</td>
<td>114</td>
<td>15.65</td>
<td>525</td>
<td>25 / DOWN</td>
<td>33</td>
<td>2.8 - 3.5</td>
</tr>
<tr>
<td>STALL</td>
<td>107</td>
<td>13.4</td>
<td>525</td>
<td>30 / DOWN</td>
<td>33.3</td>
<td>2.8 - 4^*</td>
</tr>
</tbody>
</table>

INITIAL BUFFET = ± 1.0 g → ± 50.75 g

REFERENCE: D6-30642 "747-100 SIMULATOR FLIGHT DECK VIBRATION ENVIRONMENT"
The block diagram on Page 17.0-2 is a simplified autothrottle block diagram for use in small perturbation 747 control simulation. This data is provided for information purposes and was not incorporated in the simulation.
This section contains a description of the automatic pilot, flight director, yaw damper, and autothrottle systems for the 747 aircraft. This data is provided for information purposes. The autopilot and autothrottle were not incorporated in the simulation.
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SUMMARY

This document provides a description of the Automatic Pilot, Flight Director, Yaw Damper, and Autothrottle Systems for the 747 aircraft. It contains block diagrams, pictorials, and tables to describe operation of each of these systems as they are planned for incorporation in the aircraft.

Two autopilots give the flight crew a choice of fail-safe systems, each of which can provide all manual and path modes except LAND. Both autopilot channels are used to give "fail passive" control at low altitudes during the automatic landing sequence. Two separate dual-channel automatic pilot pitch trim systems and two yaw dampers give a high level of system integrity.
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I. 747 INTEGRATED AUTOPILOT AND FLIGHT DIRECTOR

A. GENERAL

The Sperry SPZ-1 integrated autopilot flight director system was developed for the Boeing 747. The autopilot is used for path or manual control via the pitch wheel and turn knob.* Flight director commands are provided and may be used to monitor autopilot operation, or to be tracked with the autopilot manual mode, or to be tracked manually.*

The basic 747 is equipped with a dual autopilot system and a triple flight director system. Each pitch or roll computer contains all of the circuitry necessary to compute the respective pitch or roll autopilot and flight director commands. Each autopilot or flight director channel consists of two computers: one roll, and one pitch.

The general autopilot flight director system layout and interconnects used on the basic Boeing 747 are shown in Figure 1. A dual set of sensors provide navigational and performance signals to the autopilot flight director computers.

Only autopilot computers of channel A and B are connected to hydraulic servos. Computer C is used only for computing flight director commands and cannot be switched in as an autopilot. The number 1 sensor group serves both the A and C computers while sensor group 2 supplies information to the B computers.

Instrument switching allows either the pilot or co-pilot to select any one of the three flight director computer signals for display on his ADI.

The autopilot can be used as a single-channel system in the navigation, cruise, and manual modes of operation. Either channel A or B can be selected for these single-channel modes.

For automatic landing only, fail passive operation is obtained with the dual channel system. Both A and B autopilot channels must be engaged for this mode of operation.

The cockpit location of the controls and indicators for the autopilot/Flight Director, as well as the other systems of the IEFCS, are shown in Figure 1A.

*Maneuvering control for certain airlines will be via control wheel steering instead of turn and pitch knob.
B. SYSTEM INTRODUCTION

All components associated with each flight axis of each channel are packaged in separate computer units. The elements which comprise a basic autopilot/flight director system are:

1) One mode selector panel
2) One flight controller or optionally 3 force sensors.
3) Two flight mode annunciators
4) One monitor and logic unit
5) Three accessory boxes
6) Three roll computers
7) Three pitch computers
8) One automatic stabilizer trim unit

1. Mode Select Panel

The mode select panel contains the switches and logic for mode selection and control of all the autopilot/flight director computer channels. Figure 2 shows the mode select panel. The controls shown shaded in are for optional modes.

The engage switches are solenoid held in MAN and COMMAND with locking provisions at OFF. Each engage switch controls both the pitch and roll computer associated with that channel. Either channel A or B may be engaged in Manual or Command by choice of engage switches. Once one engage switch has been placed into the Manual or Command position, the other switch is locked off and cannot be moved from the OFF position except when LAND has been selected and a monitor check has been satisfactorily completed.

The course select switch may be placed in either the course 1 or course 2 position without regard to which channel of the autopilot has been selected. It is solenoid held in both positions. The switch drops to the dual position when the LAND mode has been selected. Course 1 position feeds the No. 1 VOR/LOC receiver output and course error signal to all three A/P - F/D roll computers and course 2 does likewise for the No. 2 VOR/LOC and No. 2 course error. In the dual position, LOC No. 1 and Course error No. 1 are fed to computers A and C while LOC No. 2 and course error No. 2 are fed to the B computer. Figure 3 is a pictorial diagram of the above switching functions and indicates the isolation and independence achieved for single and dual channel modes of autopilot operation.
Heading select is accomplished for all three channels through a single set knob which positions two synchros fed from two separate magnetic heading reference units to maintain heading isolation.

The lateral navigation modes (INS, HDG, VOR/LOC), as well as the landing approach control modes ILS and LAND, are selected by the main mode selector switch. This is a simple rotary type switch without holding or centering devices. A second selector switch, also rotary type, allows selection of the Turbulence mode, V/S (vertical speed), IAS hold, or Mach hold. This second switch is solenoid held in each mode select position. The V/S and IAS modes may be selected alone or during the arm phases of ALT. Select, ILS, and LAND. When used during the armed phases of another mode, the switch will drop to OFF when the mode goes into the capture phase.

The switch will not hold in Turb. if the autopilot is not engaged. Also, if the switch is moved to Turb while the altitude select is engaged, the altitude select switch will drop to OFF. Further, if Turb. is engaged and ALT hold is selected, the Turb. switch will drop to OFF.

The Back Beam switch is designed to mechanically preclude accidental turn on and is solenoid held in the ON position. It will hold only if VOR/LOC is selected on the mode selector switch. Also available on the mode select panel are the ON/OFF switches and pitch trim controls for flight directors.

The mode selection and mode compatibility interlocks related to the position of the switches on the Mode Select Panel are shown in Table 1 (Pitch channel) and Table 2 (Roll channel) for both the autopilot and the Flight Director.

2. Flight Controller

The Flight Controller which contains the autopilot pitch wheels and turn knob is shown in Figure 4. The pitch wheel and turn knob provide attitude commands proportional to their respective rotations. The outputs for channels A and B of the autopilot are electrically independent. The potentiometers used with the pitch wheels are unclutched electrically from the wheels during all pitch path modes.

For customers who order the control wheel steering option the flight controller is not used. Instead three force transducers shown in Figure 4a are provided to maneuver the aircraft via the normal control column and control wheel with autopilot engaged.
AUTOPilot-FLIGHT DIRECTOR MODE CHART - PITCH MODES

<table>
<thead>
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<th>PITCH MODES</th>
<th>ALL OFF</th>
<th>ALT OFF</th>
<th>ALT SELECT</th>
<th>IAS HOLD</th>
<th>MACH HOLD</th>
<th>VERT SPEED</th>
<th>ILS (GLIDE SLOPE)</th>
<th>LAND (GS &amp; FLARE)</th>
<th>G/A (FIXED ATTITUDE)</th>
<th>TURBULENCE</th>
</tr>
</thead>
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<tr>
<td>A/P ENGAGE</td>
<td>A/P FD</td>
<td>A/P FD</td>
<td>A/P FD</td>
<td>A/P FD</td>
<td>A/P FD</td>
<td>A/P FD</td>
<td>A/P FD</td>
<td>A/P FD</td>
<td>A/P FD</td>
<td>A/P FD</td>
</tr>
<tr>
<td>COMMAND</td>
<td>PW PTW</td>
<td>X X</td>
<td>X X</td>
<td>X X</td>
<td>X X</td>
<td>X X</td>
<td>PW OR PTW</td>
<td>PW OR PTW</td>
<td>NOT APPL</td>
<td>NOT APPL</td>
</tr>
<tr>
<td>MANUAL</td>
<td>PW PTW</td>
<td>X X</td>
<td>PW PTW</td>
<td>PW X</td>
<td>PW X</td>
<td>PW X</td>
<td>ALT HOLD PTW OR</td>
<td>ALT HOLD PTW OR</td>
<td>NOT APPL</td>
<td>PW PTW</td>
</tr>
<tr>
<td>OFF</td>
<td>0 PTW</td>
<td>0 X</td>
<td>0 PTW OR</td>
<td>0 X</td>
<td>0 X</td>
<td>0 X</td>
<td>0 PTW OR</td>
<td>0 PTW OR</td>
<td>TURB SWI</td>
<td>NOT HOLD</td>
</tr>
</tbody>
</table>

**NOT ENGAGED**

- **SELECTED COMPATIBLE MODE**, THAT IS: IAS HOLD, MACH HOLD, VERT SPEED, ILS ARMED OR LAND ARMED.

- **SELECTED COMPATIBLE MODE**, THAT IS: ALT HOLD, ALT SEL, IAS HOLD, OR VERT SPEED.

- **NOT CERTIFIED BEYOND CATEGORY II.**

- **AUTOPILOT ENGAGE SWITCH WILL NOT HOLD IN THIS POSITION.**

- **A/P WARNING LIGHT "FLASHING AMBER" UNLESS BOTH A/P ENGAGE SWITCHES ARE IN "COMMAND" POSITION.**

Table 1 Autopilot/Flight Director Mode Chart - Pitch Modes
# Autopilot-Flight Director Mode Chart - Roll Modes

<table>
<thead>
<tr>
<th>Roll Modes</th>
<th>INS</th>
<th>HDG (SELECT)</th>
<th>VOR/Loc</th>
<th>VOR/LOC Back Beam (Option)</th>
<th>ILS (LOC)</th>
<th>LAND (LOC)</th>
<th>G/A (Wing Level)</th>
<th>Turbulence (Not Available in ILS or Land Modes)</th>
</tr>
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<tr>
<td>A/P Engage Switch</td>
<td>ARMED</td>
<td>A/P FD</td>
<td>ARMED</td>
<td>A/P FD</td>
<td>ARMED</td>
<td>A/P FD</td>
<td>ARMED</td>
<td>A/P FD</td>
</tr>
<tr>
<td>COMMAND</td>
<td>HDG SEL</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>NOT APPL</td>
<td>HDG SEL</td>
<td>X</td>
</tr>
<tr>
<td>MANUAL</td>
<td>TK SEL</td>
<td>TK</td>
<td>TK</td>
<td>TK</td>
<td>TK</td>
<td>TK</td>
<td>TK</td>
<td>TK</td>
</tr>
<tr>
<td>OFF</td>
<td>0</td>
<td>HDG SEL</td>
<td>0</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0</td>
</tr>
</tbody>
</table>

**Legend:**
- O : Not Engaged
- X : Engaged or Operative
- TK : Turn Control Knob (or CWS)
- ▲ : Not Certified Beyond Category II
- ▶ : Autopilot Engage Switch Will Not Hold in This Position
- ▪ : A/P Warning Light "Flashing Amber" Unless Both A/P Engage Switches Are in "Command" Position

**Table 2** Autopilot/Flight Director Mode Chart - Roll Modes
3. Flight Mode Annunciation

Dual flight mode annunciators are provided on the 747. Flight director modes and autopilot modes are displayed side by side on each annunciator panel as shown in Figure 4A.

The basic modes annunciated are:

- ALT SEL (Altitude Select)
- NAV (Navigation)
- GS (Glide Slope)
- FLARE
- GO AROUND

In each mode the annunciator displays an amber light when the particular mode is armed and switches to a green light when the mode is initiated. Table 3 shows each autopilot and Flight Director mode as it will be displayed on the mode annunciator.

Also displayed on the annunciator panel are the autopilot and autothrottle warning and disengage lights.

A press-to-test feature is included in the flight mode annunciator. All amber lights are tested by depressing the left hand section of the panel. All green lights as well as the red warning lights of the autopilot and autothrottle are tested by depressing the right hand section of the panel.

4. Monitor and Logic Unit

The monitor and logic unit is a separate package which contains much of the autopilot/Flight Director engage interlock logic, dual-channel monitoring logic, mode annunciation logic, and the warning light circuits. The physical and electrical arrangement of the monitor and logic unit provides complete channel isolation.

5. Accessory Boxes

The accessory boxes are Boeing supplied units which provide the switching and interconnect functions necessary to interface the autopilot and flight director systems to other airplane systems.

6. Pitch and Roll Computers

The A/P - F/D pitch and roll computers include the computing and logic circuitry necessary to receive data from the aircraft sensors and produce autopilot servo and flight director commands for all modes of operation.
<table>
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<th>MODE</th>
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<th>FLARE</th>
<th>F/D ONLY</th>
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<tr>
<td></td>
<td></td>
<td>ALT. SEL. AMBER</td>
<td>NAV. AMBER</td>
<td>GS AMBER</td>
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<tr>
<td></td>
<td></td>
<td>GREEN</td>
<td>GREEN</td>
<td>GREEN</td>
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<tr>
<td>LOC</td>
<td>ARM</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CAPTURE &amp; CONTROL</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>VOR</td>
<td>ARM</td>
<td></td>
<td>X</td>
<td></td>
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<td>INS</td>
<td>ARM</td>
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<td>X</td>
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<td></td>
<td>CAPTURE &amp; CONTROL</td>
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</tr>
<tr>
<td>ILS</td>
<td>ARM</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>CAPTURE &amp; CONTROL</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
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<td>LAND</td>
<td>ARM</td>
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<td></td>
<td>CAPTURE &amp; CONTROL</td>
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<tr>
<td>GO AROUND</td>
<td>ARM</td>
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<td></td>
<td>CAPTURE &amp; CONTROL</td>
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</table>

Table 7 Flight Mode Annunciator Chart
7. Automatic Stabilizer Trim Unit

The automatic stabilizer trim unit (ASTU) contains the computational circuitry necessary to provide automatic stabilizer trim whenever the autopilot is engaged. The ASTU contains two independent self-monitored trim channels. One channel provides trim operation while the other is in standby. Automatic transfer is provided to the standby channel in the event that the trim monitor detects a malfunction.

8. Self-Test and Maintenance Monitoring

Self-test of the pitch and roll computers, the automatic stabilizer trim unit and the monitor and logic unit is performed with a go/no-go readout by means of the Built-In-Test-Equipment (BITE).

The BITE switches and lights, located on the front panels of each of the above units, permit the rapid isolation of a faulty unit, while the complete system is installed on the airplane.

A typical BITE test is shown in Figure 4b. The BITE sets up input signals and sensors to adjust two or more signal path gains in the unit under test (UUT) as required to achieve a null summation of the signal path outputs, if all circuits are normal. The null condition is sensed by BITE null detection logic. Simultaneously, specific portions of the unit logic are addressed by BITE. The status of the unit logic circuits and the output of the BITE signal null detector are combined in BITE logic to produce a go/no-go output to the BITE readout lights.

Maintenance monitoring has been included in the system as a basic feature to help in isolating the cause of autopilot warning or disengagement during dual-channel autopilot operation.

The maintenance monitoring circuits and readouts are included in the Monitor and Logic Unit. The readout is located in the top portion of the Monitor and Logic Unit front panel, above the BITE readout lights. The maintenance monitor readout consists of four latching indicators which trip to indicate that autopilot warning or disengagement occurred for one of the following reasons:

1. Power loss to channel A (single or dual channel operation)
2. Power loss to channel B (single or dual channel operation)
3. Pitch channel camout monitoring trip (dual channel operation)
4. Roll channel camout monitoring trip (dual channel operation)

The above faults are monitored and displayed permanently by the latched indicators, until these are manually reset.
NOTE: UUT = UNIT UNDER TEST

FIG. 4b - TYPICAL BITE TEST

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9. **ILS Deviation Warning System** (Optional)

The Deviation Warning System is a dual system, monitoring the Captain's and First Officer's navigation receiver outputs. (See Figure 4d)

The system warns the pilots when the outputs of the navigation receivers exceed 20 ua from the localizer beam centerline or 75 ua from the Glide Slope beam centerline with a delay time of 2.2 seconds. The warning system is in operation when the autopilot is engaged in the ILS or LAND mode and the radio altitude is below 500 feet altitude. From 500 feet to 200 feet the system provides a warning if the receiver output exceeds either GS or LOC thresholds. If the nav. receiver signal causing the warning is reduced below the detection threshold, the warning light will be turned off. However, below 200 feet altitude the system becomes latching and once the warning system has been tripped the warning light will remain on even though the signal error has been reduced below the threshold. Below Flare altitude (53 feet) the warning system monitors only LOC deviation signal errors.

The two monitor systems are independent. However, to provide greater redundancy the deviation warning signals are cross fed such that if one monitor is tripped it will also switch on the warning light driver stage of the second monitor, thus illuminating all warning lamps associated with the ILS deviation warning system.

Confidence tests of the system can be performed either on the ground or in flight. The confidence tests are pilot activated and monitored. The tests are activated by proper mode selection and engagement of the A/P and F/D and the deflection of the VHF NAV test switch.
**ILS Deviation Warning System Block Diagram**

- **No Warning Above 500 FT.**
- **Dev. Warning System Armed**
- **GS Flight Path**
- **System Becomes Latching**
- **GS Dev. Warn Inhibited**

---

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**THE BOEING COMPANY**

**Renton, Washington**
C. DESCRIPTION OF THE AUTOPILOT ACTUATOR SYSTEM

When the autopilot is engaged, autopilot commands are coupled into the primary flight control system via parallel servo actuators. Thus, the control wheel and column, as well as the control surfaces, move in response to autopilot commands.

The lateral control system of the 747 utilizes a pair of hydraulic central control actuators which control the hydraulic-powered surface actuators. These central control actuators accept commands from either the autopilot or the manual control system. During all manual or autopilot operation, the two central control actuators are slaved together through a cross link.

The 747 lateral autopilot servo system is mechanized as shown in Figure 5. The pitch axis autopilot servo mechanism is similar in concept to the lateral system.

The mechanization of the servo makes the system fail safe for all single-channel operation and fail passive for all dual-channel (LAND) operation.

1. Single-Channel Operation

Single-channel autopilot operation is used in all modes except LAND. In single-channel operation, either the A channel or B channel autopilot may be selected. The autopilot drives an autopilot servo actuator integral with the central control package. The servo actuator output displacements are proportional to the autopilot command signals. The autopilot actuator drives the manual controls via a force detent. When either autopilot is engaged, both central control packages are driven from the engaged autopilot actuator.

Autopilot authority in the lateral axis is stroke limited to the equivalent of twenty-five degrees of control wheel displacement. In the pitch axis, authority is limited by reacting the force detent against the manual feel pressure system.

The pilot can overpower the autopilot at any time by applying approximately fourteen pounds at the control wheel in the lateral axis and about twenty-seven pounds in the longitudinal axis.
2. Engage Synchronization

Synchronization loops are provided to eliminate engage transients.

When the autopilot is disengaged, the autopilot actuator is hydraulically de-energized and caged to the null position. The synchronizer loop around the servo amplifier holds the servo amplifier output near null. As soon as the autopilot is engaged, hydraulic pressure builds up first in the force detent mechanism moving the autopilot actuator, which is still not pressurized, to a position matching that of the control wheel. Since the autopilot LVDT is active, the voltage resulting from a change in autopilot actuator position will be fed back to the servo amplifier and synchronized within 0.25 sec.

Additional loops are included in the roll autopilot and the pitch autopilot, to synchronize the attitude commands.

3. Dual-Channel Operation

During dual-channel operation, both autopilot actuators are coupled to the manual controls via their respective force detents as shown in Figure 5. The force detents are mechanized to give the characteristics shown in Figure 6a.

To reach equilibrium, the forces applied to the cross link must sum to zero. The forces applied to the cross link are from the two force detents, feel system and control system friction. Since the initial force gradients of the detents are steep, disagreement between the two autopilot actuator positions of more than approximately 0.5° aileron will cause one or both of the detents to reach its maximum force level.

If one channel fails hardover, the second channel and the feel system will keep airplane controls in the trim position. If the second channel should command in the same direction as the hardover, the surfaces will correctly respond to the second channel as illustrated in Figure 6b.

Except in the case of rather precise agreement between autopilot channels, the resultant dual-channel autopilot command is the lesser of the two autopilot commands. Several pertinent points can be concluded:

(a) A hardover command results in a passive failure with negligible surfaces deflection.

(b) If the two autopilot commands are opposing, the output is zero and the airplane remains in trim.
APPROXIMATELY FLAT FORCE GRADIENT

\[ \Delta \delta_{\text{CMD}} = (\delta_{\text{CMD AUTOPILOT}} - \delta_{\text{CMD CROSS SHIFT}}) \]

Fig. 62 General Force Detent Characteristics

Fig. 6b General Operating Characteristics of Dual Channel Servo System

Airplane will not track commands of opposite sign from the failure.

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(c) During normal operation, the airplane will track the autopilot command having the lesser value. If one autopilot fails passive, the resultant output is nearly zero. Thus, the dual-channel servo actuator system provides true "Fail Passive" operation for use in the LAND mode.

D. FLIGHT DIRECTOR OPERATION AND MODES

The flight director and autopilot computation paths become separate just prior to the autopilot path integrator as shown in the roll axis and pitch axis computer block diagrams. Command and rate limits are incorporated into the separate autopilot and flight director computer circuits. These limits are switched as a function of the mode selected and the associated submodes. The Flight Director system characteristics are summarized in Table 5 on page 38 for the roll axis and Table 6 on page 45a for the pitch axis.

As shown in the autopilot-Flight Director mode charts (Tables 1 and 2 on pages 17 and 18), the flight director computes and displays the navigational and vertical path data even when the autopilot engage switches are in the OFF position. When the autopilot is off, the pilots can fly the displayed flight director commands using the primary flight controls. When the autopilot is engaged in MANUAL, the flight director commands can be followed using the pitch wheel and turn knob. All modes of the autopilot except turbulence are also provided for the flight director.

There are two control modes which are exclusively flight director modes. These are go-around and back beam (optional). Go-around provides a wings leveling command in the lateral axis and a fixed pitch attitude climb command in the pitch axis. The go-around mode is initiated by the pilot operating either of two go-around switches located on the inboard throttle levers. Operating a go-around switch will cause the autopilot engage switch to drop to the OFF position from either MANUAL or COMMAND.

The back beam mode is initiated by selecting the VOR/LOC mode, then placing the solenoid held back beam switch in ON. In this mode, the flight director provides localizer back beam intercept, capture and track commands which can be flown by the pilot using either the turn knob with the autopilot in MANUAL, or the primary flight controls with the autopilot off. During back beam, any one of several pitch control modes can be chosen to provide flight director pitch commands.
E. ROLL AUTOPILOT

The lateral autopilot computer block diagram is shown in Figure 11 on Page 42. Gains, transfer functions, special gain programs, mode engage and switching logic are summarized in Table 4 and Figures 8, 9 and 10 on Page 37 and following. Finally, a block diagram of the lateral flight control system is shown in Figure 12 on Page 43.

The roll attitude and rate loops (see Figure 11) are basic for all modes of operation. These loops provide both roll mode damping and spiral mode stabilization.

The rate signals are sensed by the gyros installed in each roll autopilot computer. The roll attitude signals are from the Inertial Navigation System. Fixed attitude and rate gains of

\[
\frac{\delta_{\text{roll}}}{\phi} = 3.2 \text{ Deg} \quad \text{and} \quad \frac{\delta_{\text{roll}}}{\dot{\phi}} = 3.6 \text{ Deg/Sec}
\]

When engaged in MANUAL, the roll autopilot responds to bank commands inserted via the turn knob. When zero bank is commanded (turn knob in detent), wings leveling occurs after which the autopilot holds airplane heading. When engaged in COMMAND, the pilot has the option of control by any of the following modes: Heading Select, VOR/Localizer, INS, ILS, or LAND.

Prior to the autopilot engagement, either in the single channel or the dual channel mode, synchronization loops operate to eliminate autopilot engage transients.

1. Engage Synchronization

In addition to the servo amplifier output synchronization mentioned earlier (See page 24), a second loop (command synchronizer) holds the servo amplifier input near zero by synchronizing the attitude command, prior to autopilot engagement in any single channel mode.

A third loop, used only for the dual channel mode, synchronizes the attitude command by nulling the servo amplifier input through feedback to the lateral path integrator of the channel yet to be engaged. This loop operates only after both autopilot switches are in the command position and until the second autopilot channel becomes engaged. During the operation of this loop, the previously mentioned command synchronizer loop is inhibited.


The manual mode is engaged by placing the autopilot engage switch in the MANUAL position. The autopilot cannot be engaged with the
turn knob out of detent. When the turn knob is in its center detent position, wings leveling occurs and the autopilot flies to hold heading. The heading reference is established by the Magnetic Heading Reference Unit (MHRU).

The turn knob produces a bank angle command proportional to turn knob displacement. The turn knob output is generated by a shaped pot with a dead-zone in the center equivalent to ±16° of knob rotation. The maximum range of rotation of the turn knob is ±28° which commands ±30° bank angle. Maximum roll rate for the Manual Mode is ±4°/sec. Provisions are available for a 7 degrees/second rate limit.

When the magnetic heading clutch in the MHRU is engaged, the heading error synchro is clutched to a magnetic heading repeater and provides a heading error signal. When the turn knob is in detent, the clutch automatically engages.

Proportional and integral heading error signals produce the bank angle command necessary to maintain the airplane heading. The integral of heading error reduces heading errors to zero in the presence of thrust asymmetry or other lateral control system mis-trim. Both gains are scheduled as a function of true airspeed to maintain consistent system performance throughout the flight regime.

Certain airline customers will have control wheel steering incorporated instead of a turn knob. The control wheel steering option will be usable at all times when the autopilot is engaged in Manual Mode. In addition, when the autopilot is engaged in "Command" roll control wheel steering is available in the arm phase of lateral path modes such as LOC, VOR, or INS. Thus the control wheel steering will be available to establish the intercept angle desired prior to the capture maneuver on these modes. A special switch is included on the Mode Select Panel as shown in Figure 2a. This switch allows either CWS or Heading Select to be used for the above mentioned arm phases.

The roll control wheel steering block diagram is shown in figure 11a. Force on the control wheel commands roll rate via an integral path. The integrator is bypassed with a displacement or "boost" path to minimize the velocity error or overshoot which results when force is abruptly removed from the wheel. Constant CWS gains are used over the speed range of the 747 so that light feel forces are present at all times in roll.

Two electronic detents are used. The lower detent activates the CWS mode and is equivalent to the turn knob detent. The higher value detent is used in the autopilot to disconnect path modes and drop the engage switch from command to manual. This action overrides these modes and provides the CWS function.
3. Turbulence Mode

The turbulence mode may be engaged at any time except when the nav. mode selector is on ILS or LAND.

If the autopilot engage switch is in COMMAND when the turbulence mode is engaged, the switch will revert from COMMAND to MANUAL.

The system configuration in turbulence is identical with the MANUAL configuration except that the gains are reduced by approximately one half and the heading hold signal is removed.

4. Command

a. Heading Select Mode

The heading select mode allows the pilot to use the autopilot to fly on a desired heading.

The desired heading is selected by means of the heading knob on the Mode Select Panel. The heading select mode is engaged by placing the Nav. mode select switch in HDG and positioning the autopilot engage switch in COMMAND.

The command signal is the Heading Selector error (instantaneous heading of the airplane minus the selected heading). The gain is scheduled as a function of true airspeed to maintain consistent system performance throughout the flight regime.

The attitude command limit for the Heading Select mode is ±30° with the option for change to ±10° for TAS above 500 feet/sec. The roll rate limit is variable from 1.5deg/sec to ±3 deg/sec as a function of the amount of heading select error.

b. Localizer Mode

Use of this mode requires the following pilot procedures:

(1) Tune in the localizer receivers.
(2) Dial in the runway heading with the course selectors on the mode select panel.
(3) Position the mode select switch in VOR/LOC.
(4) Dial in the desired localizer beam intercept heading displayed on the Heading Select window.
(5) Position the Automatic pilot engage switch in COMMAND.

The autopilot is in the Heading Select mode until the localizer capture sensor operates and the capture mode is initiated.
After capture, the system switches to the localizer on-course mode when the on-course logic is satisfied.

The basic damping signal in the localizer mode is ground heading, obtained by summing drift angle with course error.

The use of ground heading is contingent upon receipt of a drift angle valid signal (DAV) from the INS. If this signal is lost, the roll computer automatically reverts to the use of derived beam rate, washed out heading, and lagged roll for localizer mode damping. The beam displacement and integral parameters are the same for the drift angle valid and non-valid conditions.

The localizer system has three submodes of operation; namely: capture, on-course, and on-course approach. The circuit implementation of the system is such that it will automatically switch to the proper submode configuration when predetermined requirements are satisfied.

(1) LOC Capture

The localizer capture is initiated when a summed combination of intercept angle and derived beam rate becomes equal to or less than the instantaneous beam error or when beam error is less than one degree. The exact capture and on-course logic and gains are shown in Table 4.

When the drift angle valid signal is present, the displacement command is the localizer beam error and damping is provided by the derived ground heading signal. If the drift angle valid signal is lost, the ground heading signal is removed and derived beam rate and course error are substituted.

(2) LOC On-Course

The LOC on-course submode is initiated when predetermined conditions of bank angle, beam displacement and beam rate are satisfied, as summarized in Table 4.

The localizer on-course configuration is similar to the capture configuration, with the following modifications:

a signal proportional to the integral of beam error is introduced to reduce the steady state error in presence of thrust asymmetry and lateral mistrim conditions,

a thirty-three second time constant high pass filter in the ground heading and course error path washes out steady state errors due to INS and course error signals offsets, as well as heading errors due to crosswinds in the drift angle non-valid condition,
a signal proportional to lagged roll is added for increased damping in the drift angle non-valid condition.

(3) LOC On-Course Approach

The autopilot switches from the on-course submode to on-course approach submode at 1500 feet of altitude.

Mechanization of this submode is similar to that of the on-course submode when the drift angle is valid. When the drift angle is not valid, the washed out course error signal is removed to improve wind shear performance. The beam displacement and integral gains are scheduled linearly with radio altitude to compensate for beam convergence while the damping parameter gains are increased to improve close-in performance.

The submode gains, command limits and engage logic are summarized in Table 4.

C. VOR Mode

The procedure for the pilot to engage this mode is identical to that of the localizer except that the VOR frequency has to be selected rather than the LOC frequency. The VOR mode has three submodes; namely: capture, on-course, and over the station. The basic damping parameter is ground heading. If the drift angle valid signal is lost, the INS drift angle signal is removed, leaving the course heading error as the system damping signal. The displacement command is the beam error for both drift angle valid and non-valid conditions. System gains are scheduled as a function of TAS to maintain good performance throughout the flight regime. The system gains, limits and mode initiation logic are summarized in Table 4.

(1) Capture

When the VOR mode is first selected and the aircraft is outside the capture threshold, the autopilot is in the heading select mode which steers the airplane to the desired intercept angle established with the heading select control on the Mode Select Panel. The capture sensor is armed.

The variable engage point logic used for VOR capture is shown in Table 4. For intercept angles between 90 degrees and 10 degrees, the capture starts at beam error between 1.8 and 0.2 dots. The greater the intercept angle, the earlier the capture maneuver is initiated.

A 34 degrees course cut limit is provided.
(2) On-Course

The on-course submode is initiated when the bank angle is less than 3 degrees and the course error is less than 15 degrees.

The beam displacement gain is reduced to one-half the value used during capture. A beam integral signal is introduced to reduce the beam error in presence of thrust asymmetry and lateral control surface mistrims. A 200-second washout of the ground heading signal is also introduced to eliminate INS drift angle and course error static offsets. In the drift angle non-valid condition, this washout improves the system performance under cross wind conditions.

Maximum position and rate commands are limited to + 10 degrees and ± 1.5 degrees/second respectively during the VOR on-course submode.

(3) Over the Station

The VOR over-the-station sensor initiates this submode upon detection of beam rates higher than 0.5 degrees/second. The system automatically reverts to the on-course mode, after passing the station, when the beam rate signal has decreased below 0.5 degrees/second for 20 seconds.

During the time that the airplane is over the station, the VOR beam signal is removed and the autopilot command signal is either ground heading for the drift angle valid condition, or course error for drift angle non-valid condition. If the pilot desires to make a course change while over the station, he may dial in the change in course setting and the system will track outbound on the new radial.

d. INS Mode

The autopilot may be used to capture and track any of the great circle routes that have been programmed into the INS computer.

The INS mode is armed by placing the Nav. mode selector switch of the autopilot mode select panel in the INS position. Figure 7 shows a typical control sequence. If the aircraft is further than 7.5 nautical miles off the desired great circle course, the autopilot is in the heading select mode, and steers the airplane to the desired intercept angle established with the heading select knob. In order for the Heading Select mode to operate on those airplanes with remote set preselect heading where the heading error signal is developed in the HSI, the INS-RADIO switch must be left in RADIO position until the INS capture point is reached. When the 7.5 mile point is reached, the INS mode is initiated.

Cross-track deviation and track angle error outputs of the INS are used to compute the desired steering command.
Control is similar to VOR control with the following exceptions:

a. Since the INS provides the equivalent of a non-convergent beam, the distance from destination does not affect system performance.

b. The damping signal, track angle error, is not susceptible to cross-wind effects which would result in lateral displacement from the desired course.

(1) INS Capture

The capture maneuver is automatically initiated at 7.5 nautical miles from the desired INS course. The bank angle command is limited to 30 degrees and bank rate is limited to 1 degree per second during capture. The system gains are summarized in Table 4. A 25-degree course cut limiter is employed.

(2) INS On-Course

The capture is complete and on-course control is initiated when the cross-track deviation is reduced below 1,070 feet and track angle is below 3 degrees. The same gains are employed in the autopilot as during capture. The on-course sensor downshifts the bank and bank rate limiters to 10 degrees and 1.5 degrees per second respectively.

(3) Waypoint switching

Automatic switching from one great circle course to another is provided. On the INS system Control and Display Unit, the "Auto-Manual" switch must be set to the "Auto" position to use this feature. If this is not done, the autopilot will overfly the waypoint and continue on the extension of the great circle. If the "Auto" sequence is used, switching of the autopilot to the next route occurs a short distance before the waypoint is reached. (See Table 4) It will occur at 3.5 nautical miles for cases where the angular change between successive courses is small. Restoration of the capture bank limits is provided automatically. When the on-course conditions are again satisfied, the reduced bank and bank rate limits are automatically reinstated.

e. ILS Mode

The ILS mode is identical to the Localizer Mode for the roll autopilot. Glideslope control is armed by this mode and the autopilot continues to fly toward the glideslope beam on either pitch attitude, vertical speed, altitude or IAS hold (optional mode) until a predetermined glideslope signal level is reached. (See pitch axis system description).
f. Land Mode

The autopilot LAND mode provides the Boeing 747 with a fail-passive dual-channel automatic approach and landing system. The LAND mode features dual ILS and flare coupling.

The LAND mode is properly selected when the following prerequisites are satisfied:

1) Nav. Mode Selector switch in LAND
2) Both course controls set to the runway heading
3) Heading select control set for the desired intercept angle with the localizer
4) VHF/NAV receivers set to the proper localizer frequency
5) Both autopilot engage switches in the command position.

Upon selection of this mode, single-channel operation, identical to that for ILS mode, is initiated. Dual-channel operation does not begin until after the autopilot is on Loc. approach, glide slope capture is completed, and the airplane is less than 1,500 feet altitude above the surface. The second channel synchronizes to the controlling channel until it is engaged; at this point, the flare computer is armed and equalization and monitoring of both channels begins.

(1) Equalization

Equalization is accomplished by taking the difference of the central control actuator and the autopilot actuator LVDT signals and feeding this signal back to the autopilot path integrator.

The output position of the central control actuator will be equal to the output position of the autopilot actuator having the least value (see Section C). Thus, the channel having the greater command will be different from the central control actuator output by the difference between the A and B autopilot commands.

The channel with the lower command signal receives no equalization signal since the difference between commanded and output position is zero, while the channel having the higher signal receives an equalization signal that tends to reduce its output signal to match that of the controlling channel. It should be noted that each channel has an independent equalization system and that there are no cross ties between channels.

The equalization signal in the lateral axis is limited, so that ramp faults of relatively low values may be detected. The equalization signal is also gain scheduled as a function of radio altitude from 1 to 0.5. Thus, equalization is decreased as the airplane approaches touchdown.
(2) Monitoring

The monitoring system on the 747 dual-channel autopilot acts on the measured difference between the output position of each autopilot actuator and the output position of the central control actuator associated with that autopilot actuator. A block diagram of the monitoring system is shown in Figure 13. The two actuator position sensors used in the equalization circuit also feed the monitor. Each channel has a pair of monitors: one for pitch and one for roll. A failure is indicated by the monitor if an autopilot channel disagrees with the central control actuator output by a given amount for a set length of time. These values are presently set at six degrees and 20 seconds in the roll channel. A steady red cockpit warning light is initiated any time a monitor is tripped. Thus, early warning of any potential problems is brought quickly to the pilot's attention without disconnecting the autopilots. Should the warning light be activated by noise or radio beam masking, it is not latched to the ON condition; and thus, goes out at the conclusion of these temporary disturbances.
# FLIGHT DIRECTOR (ROLL AXIS)

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<th>GAIN</th>
<th>DISPL LIMIT</th>
<th>RATE LIMIT</th>
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<td>IN/DEG</td>
<td>THIS SIGNAL IN &quot;ON&quot; ALL F/D MODES</td>
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<td>DEG/DEG/SEC</td>
<td>THIS SIGNAL IN &quot;ON&quot; AT F/D LOC O/C MODES</td>
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<td>INS CAP: 4°/SEC</td>
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<td>INS O/C: 1.5°/SEC</td>
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<td>LOC O/C: 4.0°/SEC</td>
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</table>

**Table 5**

**SUMMARY OF FLIGHT DIRECTOR ROLL AXIS**
F. PITCH AUTOPilot

A summary of Autopilot/Flight Director pitch axis characteristics is contained in Tables 6 and 7.

The 747 autopilot operates through a parallel servo system. Thus all actuator response due to a command from the autopilot is also fed back to the control column. The feedback path is the primary elevator control system. At the frequencies which the autopilot normally operates, the control column can be assumed to be directly proportional to the elevator surface motion. Figure 23a shows the linearized transfer functions for the Autopilot servo and elevator power control unit. The normal gain between column and elevator is \( \Delta \text{deg} / \Delta \text{deg} = 0.478 \) degrees of column per degree of elevator displacement about surface neutral. The full column to elevator curve is shown in Figure 23b.

Figure 14 is the block diagram of the basic pitch autopilot control system. Pitch attitude and rate loops are basic for pitch modes of operation. These loops provide both short and long period stabilization and damping. The rate signals are sensed by gyro installed in each autopilot computer. Attitude signals are from Inertial Navigation System (INS). Fixed attitude and rate gains of \( \frac{\Delta \phi}{\Delta \text{deg}} = 3.5 \) Deg and \( \Delta \text{deg} = 2.2 \) Deg/Sec are employed for flaps up flight. Rate damping is increased from 2.2 to 3.5 for flaps down flight. The pitch rate is passed through a \( 1/(0.05s+1) \) lag for higher frequency suppression, a \( 1/(ts+1) \) lag for structural mode decoupling and a washout \( ts/(ts+1) \) where \( t = 2 \) for flaps up and to provide roll compensation. The compensation signal \( 1-\cos \phi \) is gain scheduled as a function of airspeed.

When the autopilot is on, the automatic trim system maintains pitch trim of the airplane. This is true for all autopilot modes except turbulence. When this mode is engaged, pitch trim is not active.

When engaged in MANUAL, the pitch autopilot responds to commands inserted via the pitch knob. When engaged in COMMAND, the pilot has the option of control by any of the following modes: ALT. HOLD, ALT. SELECT, IAS HOLD, V/S (Vertical Speed Control), MACH HOLD, ILS, or LAND.

1. Engage Synchronization

Before the autopilot is engaged, the output of the servo amplifier is fed back to the path integrator at a high gain. This loop maintains the output of the servo amplifier at zero in order to obtain transient-free elevator when the A/P is engaged. At engagement, the synchronizing path is opened. The integrator hold circuit tracks airplane attitude which serves as the reference for attitude hold, the initial mode of the A/P.


The MANUAL mode is engaged by placing the autopilot engage switch in the MANUAL position. Synchronization is provided so there is no attitude transient when the mode is engaged.

a. PITCH WHEEL: If the pilot desires to change the airplane pitch attitude, the pitch wheel on the flight controller is used. The pitch wheel produces an attitude command proportional to wheel displacement.
b. CONTROL WHEEL STEERING (CWS): (CWS is alternative to Pitch Wheel.) CWS enables the pilot, by applying a force to the column to insert a command signal into the A/P to change the airplane attitude. The force signal is processed as in Figure 11a. Force on the control column commands pitch rate via an integral path, the gain of which is programmed with True Airspeed to give uniform performance over the flight regime. When the force is removed, the path integrator is synchronized to the airplane attitude at the time of force release.

When the A/P is in MANUAL or in COMMAND and not in any path mode, the A/P will be in the CWS mode. If in COMMAND and in a path mode and the high detent force (19 pounds) is exceeded, the path mode drops off and the A/P drops to MANUAL except when in Altitude Hold. When in CWS and the deadzone (low detent) is exceeded, the automatic trim is inhibited. Whenever an attitude of ±25 degrees is reached and the pilot applies a force in the direction to increase this attitude, the rate path is inhibited (MANEUVER LIMIT CONTROL).

3. Turbulence

In a turbulent environment TURB. may be engaged on the Turb/Speed mode select switch when the NAV mode switch is not in ILS or LAND. With TURB engaged, the autopilot is automatically switched from COMMAND to MANUAL and the flight director pitch trim control becomes effective. The pitch attitude and pitch rate gains are reduced by one-half. The automatic stabilizer trim is off in the turbulence mode.
### Table 6
Flight Director Pitch Axis

<table>
<thead>
<tr>
<th>Gain</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Submode</th>
<th>Value</th>
<th>Units</th>
<th>Shaping</th>
<th>Program</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bar Sensitivity</td>
<td>G</td>
<td></td>
<td>0.059</td>
<td>m/deg</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rate Damping</td>
<td>( \delta \theta )</td>
<td></td>
<td>20</td>
<td>deg/deg/deg</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lift Comp PFR GRAD</td>
<td>( \delta \theta / \delta \eta )</td>
<td></td>
<td>16.8</td>
<td>deg</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alt Hold</td>
<td>( \theta _{H} )</td>
<td></td>
<td>-0.16</td>
<td>deg/ft</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alt Hold Rate</td>
<td>( \delta \theta _{H} )</td>
<td></td>
<td>+0.2</td>
<td>deg/ft/sec</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alt Hold Attitude</td>
<td>( \theta _{H} )</td>
<td></td>
<td>1</td>
<td>deg/deg</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alt Hold Attitude</td>
<td>( \delta \theta _{H} )</td>
<td></td>
<td>100</td>
<td>deg/deg</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>MACH Hold</td>
<td>( \delta \theta _{M} )</td>
<td></td>
<td>13</td>
<td>deg/deg</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Airspeed Hold</td>
<td>( \delta \theta _{A} )</td>
<td></td>
<td>95</td>
<td>deg/mach</td>
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<td></td>
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<td></td>
<td>Vertical Speed Hold</td>
<td>( \delta \theta _{V} )</td>
<td></td>
<td>-0.05</td>
<td>deg/ft/sec</td>
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<td></td>
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<tr>
<td></td>
<td>Attitude Select</td>
<td>( \delta \theta _{H} )</td>
<td></td>
<td>1</td>
<td>deg/deg</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Attitude Hold</td>
<td>( \delta \theta _{H} )</td>
<td></td>
<td>1</td>
<td>deg/deg</td>
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<tr>
<td></td>
<td>Attitude Error Gain</td>
<td>( \delta \theta _{E} )</td>
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<td>0.925</td>
<td>deg/ft</td>
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<td></td>
<td>Attitude Rate</td>
<td>( \delta \theta _{R} )</td>
<td></td>
<td>0.03</td>
<td>deg/sec</td>
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<td></td>
<td>Capture Gains</td>
<td>( \delta \theta _{C} )</td>
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<td>-21</td>
<td>deg/ft/sec</td>
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<td></td>
<td>Beam Error</td>
<td>( \delta \theta _{B} )</td>
<td></td>
<td>28</td>
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<td>Path Damping</td>
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<td>2.5</td>
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<td>Flare</td>
<td>( \delta \theta _{F} )</td>
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<td>0.12</td>
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<td>Sink Rate Error</td>
<td>( \delta \theta _{S} )</td>
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<td>1</td>
<td>deg/ft/sec</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Sink Rate Integral</td>
<td>( \delta \theta _{I} )</td>
<td></td>
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<td>deg/sec</td>
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<td></td>
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<tr>
<td></td>
<td>Flare Ratio</td>
<td>( \delta \theta _{R} )</td>
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<td>deg/sec</td>
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<td>Damping</td>
<td>( \delta \theta _{D} )</td>
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<td>deg/sec/ft</td>
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<td></td>
<td>Pitch Rate</td>
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<td>1.2</td>
<td>deg/sec/ft</td>
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<tr>
<td></td>
<td>Pitch Attitude</td>
<td>( \delta \theta _{A} )</td>
<td></td>
<td>1</td>
<td>deg/deg</td>
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</tr>
<tr>
<td></td>
<td>Go-Around</td>
<td>( \delta \theta _{G} )</td>
<td></td>
<td>12</td>
<td>deg</td>
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</table>

1) AUTOMATIC STABILIZER TRIM IS INHIBITED DURING THESE MODES.
2) SEE DIAGRAM 1 FOR CAS GAIN PROGRAM.
3) THE GAIN PATH INCLUDES THE PATH FILTER AS WELL AS AN 8 DEG & AMPLITUDE LIMIT.
4) WITH THE RADIO ALTIMETER, VALID SIGNAL PRESENT GAINS ARE PROGRAMMED AS PER DIAGRAM 2 WITH RADIO ALTITUDE. OTHERWISE, THEY ARE PROGRAMMED WITH THE TIME BASE PROGRAM SHOWN IN DIAGRAM 4.
5) SEE DIAGRAM 3 FOR CAS GAIN PROGRAM.
6) IN FOR GLIDE SLOPE GAIN PROGRAM.
7) IN FOR CAS GAIN PROGRAM.
<table>
<thead>
<tr>
<th>Mode</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Submod</th>
<th>Value</th>
<th>Units</th>
<th>Shaping</th>
<th>Program</th>
<th>Remarks</th>
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<td>Attitude Hold</td>
<td>ATTITUDE</td>
<td>°/°</td>
<td>OTHER</td>
<td>3.2</td>
<td>DEG/DEG</td>
<td>1/(000+1)</td>
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<td>Damping</td>
<td>°/°</td>
<td>FLAPS UP</td>
<td>1.4</td>
<td>DEG</td>
<td>25</td>
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<td>LIFT COUPLING</td>
<td>°/°/°/°</td>
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<td>DEG/SEC</td>
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<tr>
<td>Turbulence</td>
<td>ALL ABOVE GAINS</td>
<td>°/°</td>
<td></td>
<td>-</td>
<td>DEG/°/°</td>
<td>1/(000+1)</td>
<td></td>
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<td>Control</td>
<td>CWS GAIN</td>
<td>°/Lb</td>
<td></td>
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<td>1/(000+1)</td>
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<td>CWS INTEGRAL GAIN</td>
<td>°/°/°/°</td>
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<td>-</td>
<td>DEG/°/°</td>
<td>1/(000+1)</td>
<td></td>
<td>-</td>
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<td>ALT HOLD</td>
<td>°/°/°/°</td>
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<td>DEG/°/°</td>
<td>1/(000+1)</td>
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<tr>
<td></td>
<td>IAS</td>
<td>°/°/°/°</td>
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<td>-</td>
<td>DEG/°/°</td>
<td>1/(000+1)</td>
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<tr>
<td></td>
<td>MACH HOLD</td>
<td>°/°/°/°</td>
<td></td>
<td>-</td>
<td>DEG/°/°</td>
<td>1/(000+1)</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>VERTICAL</td>
<td>°/°/°/°</td>
<td></td>
<td>-</td>
<td>DEG/°/°</td>
<td>1/(000+1)</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>ALTITUDE SELECT</td>
<td>°/°/°/°</td>
<td></td>
<td>-</td>
<td>DEG/°/°</td>
<td>1/(000+1)</td>
<td></td>
<td>-</td>
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<tr>
<td></td>
<td>GLIDE SLOPE</td>
<td>°/°/°/°</td>
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<td>-</td>
<td>DEG/°/°</td>
<td>1/(000+1)</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>FLARE</td>
<td>°/°/°/°</td>
<td></td>
<td>-</td>
<td>DEG/°/°</td>
<td>1/(000+1)</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>DISENGAGE</td>
<td>°/°/°/°</td>
<td></td>
<td>-</td>
<td>DEG/°/°</td>
<td>1/(000+1)</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

1. AUTOMATIC STABILIZER TRIM IS INHIBITED DURING THESE MODES.
2. SEE DIAGRAM 7 FOR CAS GAIN PROGRAM.
3. THE GAIN PATH INCLUDES THE PATH FILTER AS WELL AS AN 8 DEG/SEC AMPLITUDE LIMIT.
4. WITH THE RADIO ALTIMETER, VALID SIGNAL PRESENT GAINS ARE PROGRAMMED AS PER FIGURE 16. WITH RADIO ALTITUDE, OTHERWISE, THEY ARE PROGRAMMED WITH THE TIME BASE PROGRAM.
5. SEE FIGURE 16 FOR TAS GAIN PROGRAM.
6. LIMITED AT 30 DEGREES ELEVATOR DIFFERENCE.
7. CAM OUT LEVEL +60 DEGREES ELEVATOR DIFFERENCE, WARNING LIGHT DELAY 1 SECOND.

---

**Note:** The table above is a portion of the AUTOPILOT PITCH AXIS section from a document, detailing various parameters, values, and units for different modes of operation. The table includes columns for parameter, symbol, submode, value, units, shaping, program, and remarks. Each row represents a different parameter and value combination, with specific conditions and limitations noted in the remarks column. The table is part of a larger document, possibly related to aviation or aerospace engineering, and includes references to other diagrams and figures for additional information.
PITCH CONTROL WHEEL STEERING AND MACH HOLD OPTIONS
4. Command

When engaged in COMMAND and no other pitch mode is selected, the A/P is in pitch attitude hold and the pitch knob is operative.

a. Altitude Hold

The altitude Hold mode holds the airplane at the altitude existing when the mode is engaged. This mode can be engaged in either MANUAL or COMMAND. If the mode is engaged with the airplane climbing or descending at a reasonable rate, the airplane returns to and holds the engage altitude.

The Air Data Computer provides the reference signal for this mode. This altitude error signal is provided after clutching a mechanically nulled synchro to the altitude shaft at mode engage. Aircraft altitude rate (or vertical speed) is also sensed and provided by the Air Data Computer.

The block diagram and gains for the Altitude Hold mode are included as part of Figure 15.

The altitude error signal commands attitude changes required to maneuver the airplane toward zero altitude error. Altitude rate is added to improve damping. Integral control on the altitude error removes standoffs. The gains used are programmed down at high speeds to about 1/3 of the low speeds. (See Figure 16.)

b. Altitude Select

The Altitude Select mode allows the pilot to select a desired flight altitude. If the selected altitude is more than 1200 feet from actual altitude, the pilot also selects the desired mode of climb or descent. With these selections made and the mode engaged, the autopilot maneuvers the airplane to smoothly capture and hold the selected altitude. This mode is particularly useful when a number of successive altitude changes are required.

Altitude Select has three submodes: arm, capture, and track. (See Figures 15 and 17.)

(1) Arm

In the arm submode, the pilot selects some other pitch mode of the autopilot, such as vertical speed, IAS hold, or pitch knob, to command the aircraft to climb or descend toward the desired altitude. In this submode, the altitude select switch is engaged and the capture logic is armed.
TAS GAIN PROGRAM

0 100 200 300 400 500 600 700
TRUE AIRSPEED (TAS) - KNOTS

0 50 100 150 200 250 300 350
COMPUTED AIRSPEED (CAS) - KNOTS

CAS GAIN PROGRAM

D6 - 30643 - RESTRICTED USE - See Notice on Cover

THE BOEING COMPANY

FIG. 16
D6-30643
Vol. II

PITCH PATH MODE
GAIN SCHEDULE

CALC
CHECK
APR
APR

REvised
Rev. C
10-10-69
(2) Capture

Capture is initiated when the aircraft's altitude approaches the selected altitude to within 1200 feet, and the altitude error (in feet) is less than 15 times the altitude rate (in feet/sec) as sensed by the coincidence detector. The detector uses course altitude and rate data from the CADC to determine the switching point. When the detector is satisfied, it switches off the previously used climb or descent mode and initiates capture. During capture, the fine altitude data from the CADC and altitude rate information are summed as indicated by the following control equation to command the aircraft to maneuver and capture the selected altitude:

\[ \Delta \theta_c = G_m (0.006 \Delta h + 0.09 \, \dot{h}) \]

where:
- \( G_m \) is the gain program with computed airspeed (unity at low speed)
- \( \Delta \theta_c \) is pitch attitude command in degrees
- \( \Delta h \) is altitude error in feet
- \( \dot{h} \) is rate of climb in feet per second

This produces a flare toward the selected altitude which is rate limited to reduce "g" forces if initiated from steep climbs or descents.

(3) Track

The track phase is initiated when the airplane approaches within 100 feet of the selected altitude, with a rate not exceeding 5 feet/seconds. The control equation is as follows:

\[ \Delta \theta_c = G_m (0.29 \Delta h + 0.05 \, \dot{h}) \] with the units defined as above.

c. Vertical Speed

The vertical speed mode is selected by the Turb/Speed switch on the Mode Select Panel. Prior to selection, the vertical speed wheel on the Mode Select Panel is synchronized to aircraft
vertical speed. It is driven by an electro-mechanical servo follow-up to accomplish this repeating function. Upon engagement of this mode, the motor of this follow-up de-activates to provide the reference required to generate a vertical speed error signal. Should the pilot desire to operate at a different vertical speed, the command wheel is moved to establish a new reference. The vertical speed wheel has 1000 ft/minute graduations between the limits of operation which are +4000 ft/minute to -8000 ft/minute.

The block diagram and gains used for the vertical speed mode are shown in Figure 15. An acceleration limiter provides smooth system response to command changes. Gain scheduling is included to allow good performance over the speed range of the 747.

d. IAS Hold

This mode gives the pilot automatic Indicated Airspeed hold capability.

A clutched synchro on the computed airspeed shaft of the CADC provides an IAS error signal which is the difference between actual IAS and the IAS at the time of mode engage. The error signal commands pitch attitude required to hold the reference airspeed. The block diagram and gains used are shown in Figure 15.

3. Mach Hold

The Mach Hold mode provides the capability to automatically hold the airplane Mach existing when the mode is engaged. The mode is selected by the Turb/Speed select switch on the Mode Select Panel. The Mach error signal is generated in the CADC by a clutched synchro. The error signal commands the airplane pitch attitude required to zero the Mach error signal. The block diagram and gains are shown in Figure 15.

f. ILS Mode

The pitch axis control system for dual channel automatic landing is shown in Figure 19. The ILS mode uses part of one channel, that is, glide slope capture and control. Upon selection of ILS, glide slope capture is armed and the glide slope indicator light on the mode annunciator panel is amber. During the glide slope arm phase, a glide slope intercept path from above or below the glide path can be flown on ALT. HOLD, ALT. SELECT, MANUAL, MACH, IAS, or V/S. When the glide slope receiver is within ± 30 mv (± 1/4") of beam center, the vertical beam sensor is tripped and glide slope capture begins. A sink rate error signal, barometric altitude rate plus a 12.5 fps bias, is switched into the path integrator for 10 seconds to produce a pitch angle approximately equal to that needed to fly the glide slope.
Normal acceleration, through a washout to eliminate steady state accelerometer outputs and filtered through a 10 second lag to pseudo-integrate, is switched in for beam damping. During the 10 second pitch down, beam error is synchronized by a limited integrator at the integrator's high rate. At the end of the 10 seconds, the sink rate error signal is switched off and glide slope control begins.

Beam error minus the synchronized signal stored on the rate-limited integrator is switched in, with this stored value bleeding down at the low rate of the integrator to give an easing on of the signal. On glide slope, beam error is programmed with radio altitude to provide a nearly constant elevator deflection per foot of beam error. The gain programmer is shown in Figure 18. In the event of a radio altimeter failure, a time-based gain program is also provided. (Figure 18-2).

g. Land Mode

The LAND Mode is shown in Figure 19. It is selected on the NAV mode selector when dual-channel, fail passive localizer, glide slope, and flare is planned. Sequencing during the LAND mode is shown in Figure 20.

Upon selecting of the LAND mode and with one channel in COMMAND, the autopilot is in single channel operation. The mode is the same as ILS except that the autopilot warning light flashes amber and the autopilot will automatically disengage at 150 ft. if the second channel is not engaged.

The second channel is locked in OFF until the automatic confidence test of the dual-channel camout monitor is completed. This takes about 1 second after LAND is selected and the first channel is engaged in COMMAND. Upon moving the second channel engage switch to COMMAND, the flashing amber warning light is extinguished and the second channel is armed. The system will operate in this configuration until the dual channel engage interlock logic is satisfied.

The autopilot remains in single channel operation until all of the following conditions are met:

- LOC on-course
- Rad. Altitude less than 1,500 ft.
- Glide Slope control
- Rad. Altitude valid

When these conditions are met, dual-channel operation begins and is annunciated after a three second delay by an amber A/P FLARE ARM light on the Mode Annunciator Panel. The non-latching autopilot camout monitor gives the pilot a steady red warning light on the Mode Annunciator Panel if a
camout exists (Page 61) in either channel for two seconds. Interlocks for the LAND mode are shown in flow diagram, Figure 21.

(2) Synchronization

When in LAND with both channel engage switches in COMMAND, but still flying single channel, the second channel actuator is in the caged position and its servo amplifier output is being nulled by the path integrator by means of the synchronization loop. At A/P FLARE ARM, the hydraulic pressure builds up first in the force detent mechanism moving the autopilot actuator to a position matching that of the elevator. The LVDT signal generated when the autopilot actuator is moved into position is fed back to the servo amplifier, and is nulled out by the synchronization loop. The actuator is then pressurized and the synchronization loop is opened. Since the servo amp was held to zero, the actuator does not move until it is commanded from the autopilot.

(3) Glide Slope

The glide slope control law for each channel is the same as that of ILS. Figure 19 shows all switches in position for glide slope control.

During dual-channel operation, equalization is in effect, without signal intertie between channels. An equalization command proportional to the difference, if any, between the autopilot actuator and the elevator is fed back to the path integrator. The equalizer signal to the path integrator is limited. The equalization gain is programmed down as a function of altitude since the requirement for equalization to reduce null offsets is likewise reduced.

(4) Flare

At the flare point, the FLARE light on the mode annunciator changes from amber to green. The camout monitor remains active.

Since the gain programmer is zero, beam error and the gain programmed portion of equalization are not applied during flare. However, a small fixed gain equalization signal remains on throughout flare.

The flare law:

\[ h_e = h_{\text{DER}} + \frac{h}{6} + 2; \quad h_{\text{DER}} = h - \frac{S}{S+1} + a \frac{1}{S+1} \]

commands an airplane descent rate, linearly decreasing with altitude, from the descent rate at flare to 2 feet/second.
The descent rate is derived from the radio altitude and vertical accelerometer signals. The descent rate error is summed with filtered acceleration for damping and then passed through direct and integral paths to produce an attitude command. A synchronizer loop maintains the command to zero until flare.

\[ \theta_{CF} = K_h e + K_A q_z + \frac{1}{3} (K_i e + K_A a_z + BIAS) \]

The flare command is limited to 7.5° nose up and 7.5° nose down pitch attitude.

(5) Fail-Passive Actuators

The autopilot actuators are located on the two inboard elevator control packages. Figures 22 and 23 show the autopilot elevator control configuration.

The feel computer provides a centering force for all autopilot and manual control commands. Feel force is programmed as a function of dynamic pressure and stabilizer position and provides authority limitation to the autopilot. The autopilot actuators are tied to the main valve inputs through force limited detents. In single-channel operation, only one detent is engaged and both main valves follow the engaged autopilot actuator.

Figure 5 shows a schematic of the detents and servo system mechanization for the roll axis. Pitch mechanization is similar. In dual-channel operation, both autopilot actuators are powered and the detents are engaged. If the autopilot actuator positions disagree, the elevators will follow the command nearer zero. The detent monitors associated with each autopilot channel measure the disagreement of the autopilot actuators with the output. A disagreement of 6.0° elevator will give a camout and a consequent pilot warning light after a one-second delay. Dual-channel elevator authority is double the single-channel authority or approximately +10, -30 degrees at final approach speed. The detent authority remains constant at 27 pounds stick force, maximum. At maximum q conditions, elevator single-channel authority diminishes to +1.5 degrees elevator.
Fig. 22 Elevator Control System
G. AUTOPILOT AUTOMATIC STABILIZER TRIM

The autopilot is provided with two separate stabilizer trim systems. During single-channel cruise operation of the autopilot, the A trim system is utilized with the "A autopilot" and the B trim system is utilized with the "B autopilot". During dual-channel operation of the autopilot, both trim systems are capable of operation. One of the two is utilized and the other is armed and in a standby state. Suitable monitoring and logic is included to effect an automatic transfer to the standby trim, should a malfunction occur in the active channel of trim.

The auto-trim unit drives the stabilizer to reduce steady state elevator displacement from neutral when the autopilot is engaged. This reduces to a low level the transient which occurs when autopilot is disengaged. Auto-trim is obtained during all autopilot modes except Turbulence.

The stabilizer has no direct connection with the primary control system. Thus, motions of the stabilizer show up on the column only as the amount of elevator surface which must be held on the column to maintain airplane trim. When the autopilot is engaged the autopilot commands the amount of elevator needed to maintain the desired flight path and airplane trim. When the autopilot is commanding an elevator position greater than the trim threshold (Figure 24) the trim system will drive the stabilizer until the elevator required to maintain the desired flight path is reduced below .185 degrees of elevator. The effect of automatic trim as seen on the column is a smooth return of the column to near neutral as the trim system operates. The rate of stabilizer trim is inversely proportional to the impact pressure (P). Thus, the column rate of return is similarly reduced.

Autopilot Stabilizer Trim Unit (ASTU) channel is shown in Figure 24. The arm and control circuits are identical. Trim is effected by the presence of discretes from both arm and control when there is hydraulic pressure to operate the brake pressure switch. When the elevator exceeds the trim threshold for five seconds, the stabilizer is driven until the elevator decreases to 0.185 degrees. The trim rate and thresholds are variable with feel pressure as indicated in Figures 24b and 24c.

The trim warning monitor is activated 0.5 seconds after an active or passive failure of the arm or control circuits or brake pressure switch. A warning is also obtained for an out-of-trim condition sustained for 12 seconds.

Dual-Channel Autopilot Mode (Autoland)

One auto-trim channel is engaged in this condition; and in the event of failure, this channel is automatically disengaged and the other standby channel is engaged by the changeover switches in the Boeing accessory box. Thus, "fail operational" trim is provided during automatic landing. Should a canout occur, the ASTU is inhibited from moving the stabilizer.
"A" TRIM SYSTEM

FEEL PRESSURE LVDT NO.1

FEEL PRESSURE LVDT NO.2

ELEV. LVDT NO.1

ELEV. LVDT NO.2

BIAS

FEEL PROCESSOR

ELEV. PROCESSOR

BIAS

DETECTOR

PHASE SENSITIVE CONTROL (5 SEC DELAY)

LIMITED AUTHORITY GAIN CHANGE PATH

TRIM BIAS CONTROL

STAB WARNING LIGHT

UP

DOWN

"B" TRIM SYSTEM

IDENTICAL TO

"A" TRIM SYSTEM

30%

DROPOUT THRESHOLD 185 DEG

30%

CONTROL CIRCUIT

AUTOMATIC STABILIZER TRIM

THE BOEING COMPANY
II. MACH TRIM SYSTEM

(System not installed on 747 airplane)
Pages 63 - 68 deleted.
III. YAW DAMPER SYSTEM

A. GENERAL

The 747 directional control system comprises dual rudders, each independently powered by a dual tandem hydraulic actuator. Dual redundant yaw damping is provided on the 747 by incorporating an independent electro-hydraulic augmentation system with each rudder segment.

Yaw damping signals are connected to the rudder actuators in a series fashion such that the pilot's rudder pedals are not displaced by yaw damper commands. This feature permits the yaw dampers to be operative at all times through take-off, cruise, and landing without interfering with normal pilot rudder control.

A preflight cockpit operated confidence test is provided to check each yaw damper system prior to departure from the ramp area. Disengage switches mounted on the pilot's overhead panel are provided to enable the flight crew to shut off either yaw damper system should a malfunction occur. Figure 27 is a pictorial diagram of the lower rudder yaw damper system.

In addition to providing additional damping of basic airframe lateral directional oscillations (dutch roll), the 747 yaw damper system has an added feature designed to improve airplane response to turning maneuvers in flap down flight conditions. This system is called the "turn coordinator" and deflects rudders proportional to roll rate in a "turn coordinating" sense, thereby improving roll control response.

Due to a favorable phase relationship, the turn coordinator feature has the added benefit of further improving basic dutch roll damping beyond that available from the yaw damping mode alone.

The "turn coordinator" system is used at flaps down condition only. An "easy on/off" circuit is implemented in the "turn coordinator" command path to eliminate transient rudder kicks resulting from the flap switching should the aircraft not be at zero roll attitude.

The design objective is to provide additional dutch roll damping and turn coordination with a system which provides no potentially hazardous failure conditions. (See document D6-13647, IEFCS Failure Analysis).
B. SYSTEM DESCRIPTION

Figure 28 is the block diagram of the 7L7 dutch roll damper and turn coordination system. Its mathematical model is shown in Figure 29.

1. Dutch Roll Damping Signals

Dutch roll damping is provided by a yaw rate (Ψ) signal. At flaps down condition, additional bank angle signal is provided to increase system damping. Yaw rate is sensed by a rate gyro, mounted in the yaw damper chassis. Bank angle is obtained from the Inertial Navigation System (INS). These signals are independently demodulated.

2. Band Pass Filter

At flaps up condition, the yaw rate signal passes through a band pass filter into the servo amplifier. The band pass filter is composed of R-C components and operational amplifiers. The transfer function of the filter can be expressed in Laplace form as the following:

\[
\frac{2.72S}{(2.72S+1)(.272S+1)}
\]

At flaps down condition, roll attitude signal passes through a similar band pass filter and is summed with the filtered yaw rate signal into the servo amplifier. This additional filtered roll attitude signal provides additional dutch roll damping.

The functions of the band pass filter are:

(1) To washout the steady yaw rate and roll attitude signals and to eliminate null offset of sensors.

(2) To provide dutch roll damping signals with minimum phase shift at dutch roll frequencies, in order to achieve optimum damping.

(3) To reduce high frequency signal amplitudes so as to minimize possible coupling with structural modes.

The Bode and phase angle plots of the band pass filter are shown in Figures 31 and 32.

3. Dutch Roll Damper Gain

At flaps down condition, the yaw rate and the roll attitude gains are

\[
2.5 \ \frac{\dot{\Psi}}{\Psi} \ \text{(degree)} \ \text{and} \ \ .076 \ \frac{\dot{\Omega}}{\Omega} \ \text{(degree)}
\]

respectively.
At flaps up condition, the yaw rate gain is 1.25
\[
\frac{\dot{\phi}_{R} \text{ (degree)}}{\psi \text{ (degree/sec)}}
\]
For detail information, refer to Figure 33 root loci plot.

4. Turn Coordination

A shaping circuit is used to derive a roll rate signal from the roll angle input. The rate circuit used has a transfer function of 
\[
\frac{1.1s}{(1.1s + 1)^2}
\]
which yields a derived roll rate signal from roll angle at turn entry frequencies, but cuts off at frequencies above 1.4 cps in order to minimize the effects of system noise.

The turn coordinator system operates at flaps down flight conditions only. Switching is accomplished by a flaps switch.

The system gain is 0.693
\[
\frac{\dot{\phi}_{R} \text{ (degree)}}{\psi \text{ (degree/sec)}}
\]

5. Easy On-Off Circuit

An easy on-off circuit is implemented in the filtered roll attitude signals path to eliminate transient rudder kicks when the roll attitude signal is turned off or on by the flap actuated switches.

6. Yaw Damper Electro-Hydraulic Servo

The servo valve amplifier accepts dutch roll damper, turn coordinator, and servo feedback inputs and provides an output to the electro-hydraulic transfer valve. The transfer valve controls motion of the yaw damper actuator which is linked to the main power control unit valve via a summing link. The electro-hydraulic transfer valve is supplied system pressure via a solenoid operated shut-off valve when the yaw damper is engaged. The yaw damper servo actuator is self-centered by caging springs when the system is de-energized. This preserves the integrity of manual commands when the yaw damper is not energized.

The maximum rudder rate which the yaw damper can command is controlled by the area of the servo actuator orifice and by the area of the piston and is ± 15 deg/sec at no load. The maximum rudder displacement is controlled by the summing lever stops and is ± 3.6 degrees.
There are two feedback paths in the yaw damper. The first path directly feeds back yaw damper actuator position. This feedback is required so that yaw damper servo output will follow command inputs. The second path feeds back yaw damper actuator position via \( \frac{853 + 1}{\delta} \) in parallel with the normal position feedback. When the yaw damper system is disengaged, the servo amplifier output is fed back through this lag to provide synchronization.

7. Self-Test and Confidence Test

The yaw damper computer provides self-test circuitry for the two categories of fault isolation testing: Line Replaceable Unit test (electronic components) and system test (electronic components plus the actuator loop). The self-tests are performed by positioning the test switch and momentarily depressing the press-to-test switch on the yaw damper front panel. The monitor light on the front panel will indicate the test results (go or no go).

Confidence Test is a pilot actuated and monitored system test. Channel confidence tests can be initiated singularly or simultaneously by use of the cockpit mounted test switches. By observing the upper and lower rudder surfaces position indicator located on the pilot's instrument panel, the operating status of the systems can be assessed.

The confidence test and self-test are interlocked to prevent test initiation in flight.

Separate confidence tests are provided for the dutch roll damping and the turn coordinator functions.

8. Performance

Analog computer simulation and digital computer root locus analysis were conducted to investigate yaw damper system performance. Results indicate that the system performs well at all flight conditions. The lowest augmented airplane dutch roll damping ratio is 0.30 at the landing approach 33 degrees flaps down condition. System performance for various flight conditions are summarized in root loci plots in Figure 33.

9. Tolerance

Phase shifts and gain variations affect system performance. Root locus analysis were conducted to investigate the effect of tolerances on performance. The Bode plot and phase angle plot for the nominal and the maximum time constants of the rudder to sensors input transfer function are shown in Figures 31 and 32 respectively. The two flight conditions, which describe the lower and upper bound of the unaugmented dutch roll frequency...
were investigated. They are the landing approach 33 degrees flaps down and maximum dynamic pressure conditions where the dutch roll frequencies are 0.12 cps and 0.20 cps respectively.

The yaw damper system performance for the above two conditions is summarized in Figures 34 and 35. If the system components are within the design tolerances, the system performances as described by the envelope in the figures is satisfactory. The upper and lower bounds of the envelope are the gain tolerance limits while the left and right bounds are the phase angle tolerance limits.

10. Failure Mode Design Features

At flaps down condition, three sensed signals are used in the yaw damper. The yaw rate, roll angles, and derived roll rate signals each provide an increment of dutch roll damping. If failures occur in any of these signal chains such that one or more of the signals is not driving the rudder, the remaining signals will continue to provide some dutch roll damping. All three of these signals are washed out and thus cannot command a continuous steady-state rudder position.

At flaps up condition, roll angle and derived roll rate signals are removed by the easy on-off circuit and the delayed flaps energized switch. Monitoring circuitry is implemented to detect failure of this flap actuated switching. A red light is illuminated on the yaw damper control panel if flap switching failure occurs.

Any type of malfunction causing a no-signal condition or a sustained large signal will not cause more than a modest transient airplane response. Control excursions are positively limited by hydraulic system velocity and force limits, plus displacement stops effective at all speeds.
IV. AUTOTHROTTLE SYSTEM

A. GENERAL

The 747 is equipped with a single-channel autothrottle system. This system is designed to capture and hold a selected indicated airspeed during terminal area maneuvering, and approach and landing flight regimes by automatically positioning the throttles. It may be used for indicated airspeeds up to 400 kts. Figures 36 and 37 pictorially describe the system. Salient features of the autothrottle are:

1. Clutches in the mechanical drive to the throttles enable the pilot to override the action of the system at any time.

2. The system is operable during manual flight control or while the Autopilot is engaged.

3. The system limits the rate of change of commanded airspeed so that throttle motions occur smoothly.

4. Thrust changes following pitch maneuvering are minimized, and the magnitude of transient thrust changes arising from wind gusts are limited by a gust filter.

5. A throttle retard function, interlocked with the Autopilot Land Mode, is provided to automatically retard the throttles during an autopilot flare.

B. SYSTEM DESCRIPTION

A block diagram of the autothrottle system is shown in Figure 38. A more detailed description is provided below.

1. Command and Airspeed Error Signals

The system engage switch and the speed control knob are situated on the AFCS Mode Select Panel.

The Autothrottle computer receives an airspeed error control signal from the Captain's airspeed indicator. Whenever a difference exists between the pilot-selected airspeed command, indicated in digital form on the AFCS Mode Select Panel, and the actual captain's airspeed, throttle action to reduce the error is commanded. The servo-motor is geared to the throttle levers via clutches which allow the pilot to easily override the system.
2. **Accelerometer, Attitude, and Elevator Signals**

The longitudinal accelerometer, which is an integral part of the computer, provides rate of change of speed information.

The pitch attitude input, obtained from the Inertial Navigation System, cancels the attitude component of the accelerometer output.

3. **Computation**

The computer utilizes transformer coupling for the A.C. input signals. A differential amplifier is used for the D.C. radio altimeter signal to provide isolation and noise rejection.

All A.C. signals are demodulated prior to shaping, filtering, and error level detection. The processed D.C. signals are summed and modulated for use in the A.C. power amplifier which drives the servo-motor. Prior to engagement, the system is synchronized for inputs other than airspeed error. See block diagram Figure 38.

The basic airspeed error input signal is processed through an acceleration limiting circuit. This circuit asymmetrically limits the airspeed command rate. The rate limited command signal is passed through an asymmetric gain program which reduces the gain for overspeed errors larger than 2 kt to \( \frac{1}{25} \) of its value. This gain reduction for large overspeed errors compensates for the fast deceleration of the engine and the higher authority of the throttle in the aft direction. The IAE signal is summed with the compensated longitudinal accelerometer signal and passed through the gust filter to suppress the effects of air turbulence on system activity.

4. **Throttle Control and Limits**

Control of the throttle levers is accomplished by a proportional plus integral servo configuration. The servo proportional response is obtained by integrating the tachometer output.

Switches are provided to limit forward and aft throttle motion. The forward limit position is set to avoid exceeding the maximum allowable engine pressure ratio or temperature; the aft position closely corresponds to the flight idle thrust value. Whenever
the throttles are driven to either limit position, the integrator is put into a "hold" condition to prevent it from computing an erroneous throttle position. The system remains engaged and will drive the throttles out of the limit position when the appropriate signal is developed.

5. ADI Signal

The demodulated output from the airspeed indicator, filtered by a 3-second lag, is supplied to fast-slow indicators on the two Attitude Director Indicators in the cockpit.

6. Airspeed Error Warning

When the Autothrottle is engaged, an airspeed error greater than ten knots causes the amber Flight Mode Annunciator light to illuminate.

7. Disengage

A pilot can disengage the system by means of any of the following:

(a) The engage switch on the AFCS mode selector panel.

(b) Disconnect switches on throttle levers 1 and 4.

(c) Go-around switches on throttle levers 2 and 3.

8. Flare

In conjunction with the Land Mode of the Autopilot, the system provides automatic throttle retard during the flare maneuver. The conditions necessary to activate this function are that the Autopilot must have been armed for flare, the Autopilot flare must have commenced, and the radio altimeter signal must be below the trigger altitude. The logic requirements prevent inadvertent operation of the retard function.

9. Test

Incorporated in the computer is an automatic test arrangement which can isolate a failure to the computer or servo-motor without requiring the use of supplementary ground-test equipment. This test is accomplished by means of a rotary switch and a push-button switch located on the front panel of the computer. The rotary switch is used to select the unit to be tested (i.e., the computer or the servo-motor) and the push-button initiates the test. The rotary switch will remain in the selected
position until it is manually returned to the "OFF" position. The Autothrottle system cannot be engaged, and a steady red warning light shows on the front panel (and in the cockpit) when the switch is not in the "OFF" position.

The test results are indicated by lights located on the computer's front panel. A "test-in-progress" light is illuminated on initiation of a test; and a "go" light is illuminated upon successful completion. A failure is indicated by the "test-in-progress" light being extinguished without a "go" indication.

The equipment functionally tests the entire Autothrottle system in approximately one minute. The testing is performed by injecting test signals into the various computer inputs while monitoring both the input and output of the feedback integrator in the servo loop. If each of these monitoring devices yields the proper indication, then the test step is completed and the next step is performed. If each test step is successful, the program will proceed to the last step and yield a "go" indication is withheld.
19.0 APPENDIX E - REVISED SIMULATION DATA

The data in this section contains revisions that Boeing recommends incorporating in the NASA simulation.
### SUMMARY OF AREAS AND DIMENSIONS

<table>
<thead>
<tr>
<th>ITEM</th>
<th>VALUE</th>
<th>DIMENSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Area (S)</td>
<td>5500</td>
<td>Ft.²</td>
</tr>
<tr>
<td>Wing Mean Aerodynamic Chord (MAC)</td>
<td>27.31</td>
<td>Ft.</td>
</tr>
<tr>
<td>Wing Span (b)</td>
<td>195.68 Ft.</td>
<td></td>
</tr>
<tr>
<td>Wheel Base</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wing Gear</td>
<td>78.96</td>
<td>Ft.</td>
</tr>
<tr>
<td>Body Gear</td>
<td>88.96</td>
<td>Ft.</td>
</tr>
<tr>
<td>Wheel Tread</td>
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<td></td>
</tr>
<tr>
<td>Wing Gear</td>
<td>36.16</td>
<td>Ft.</td>
</tr>
<tr>
<td>Body Gear</td>
<td>12.5</td>
<td>Ft.</td>
</tr>
<tr>
<td>Effective Engine Moment Arms</td>
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<td></td>
</tr>
<tr>
<td>Inboard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma_{E1} )</td>
<td>39.6</td>
<td>Ft.</td>
</tr>
<tr>
<td>( Z_{E1} )</td>
<td>0.3 (air)</td>
<td>Ft.</td>
</tr>
<tr>
<td></td>
<td>8.5 (ground)</td>
<td>Ft.</td>
</tr>
<tr>
<td>Outboard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \gamma_{E0} )</td>
<td>69.4</td>
<td>Ft.</td>
</tr>
<tr>
<td>( Z_{E0} )</td>
<td>3.1 (air)</td>
<td>Ft.</td>
</tr>
<tr>
<td></td>
<td>4.8 (ground)</td>
<td>Ft.</td>
</tr>
</tbody>
</table>

Note: The transition between the ground and air values for the effective engine pitching arms, \( Z_{E1} \) and \( Z_{E0} \), is a function of the averaged main landing gear compression ratio, \( \eta \).

For \( 0 \leq \eta \leq 1 \),

\[
Z_{E0} = Z_{E0\text{air}} + \eta \Delta Z_{E0}
\]

\[
Z_{E1} = Z_{E1\text{air}} + \eta \Delta Z_{E1}
\]

where \( \Delta Z_{E0} = Z_{E0\text{ground}} - Z_{E0\text{air}} = 1.7 \text{ Ft.} \)

\( \Delta Z_{E1} = Z_{E1\text{ground}} - Z_{E1\text{air}} = 0.2 \text{ Ft.} \)

and \( \eta = \frac{1}{18n} \sum_{n=1}^{\infty} \text{Main Landing Gear Oleo Compression (inches)} \)

where \( n = \text{number of main landing gears} \).
NOTE: LOW SPEED

X-KAP DEGREES

FLAP POSITION, \( \delta_f \)

0 5 10 15 20 25 30

UP

0 5 10 15 20 25 30

0 5 10 15 20

ANGLE OF ATTACK FOR STICK SHAKER ACTUATION

THE BOEING COMPANY

747

DG-30643

Vol. II

PAGE 19.0-5
NOTE
1. LOW SPEED
2. USE DATA ON P. 2.0-36 FOR FLAPS UP

REFERENCE: P. 2.0-36

<table>
<thead>
<tr>
<th>CALC</th>
<th>LOW</th>
<th>REvised</th>
<th>DATE</th>
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<tbody>
<tr>
<td>CHECK</td>
<td>FOSTER</td>
<td>LOW</td>
<td>6-4-69</td>
</tr>
<tr>
<td>APR</td>
<td></td>
<td>LOW</td>
<td>1-29-70</td>
</tr>
<tr>
<td>APR</td>
<td></td>
<td>BYSTROM</td>
<td>6-30-70</td>
</tr>
<tr>
<td>INK</td>
<td>ODEGARD</td>
<td>6-30-70</td>
<td></td>
</tr>
</tbody>
</table>
NOTE: FOR SPEED BRAKES AT THE GROUND STOP, USE THE IN-FLIGHT DETENT CURVES FOR PANELS 3, 4, 5-8, 9-10. FOR PANELS 11-12 USE THE CURVE FOR PANELS 3, 4. FOR PANELS 11-12 USE THE CURVE FOR PANELS 9-10. PANELS 11-12 REMAIN AT 20° FOR ALL WHEEL ANGLES.

INTERMEDIATE IN-FLIGHT SPEED BRAKE (SPEED BRAKE HANDLE = 21.5°)

REFERENCE WHEEL ANGLE, $\delta_{w}$, DEG

CALC: MOOIWEER 12-5-67
CHECK: HOLTZNER 1-15-68
REVISED DATE
APR KUPC15 6-2-69
APR
INK: ODEGARD 12-5-67

LATERAL CONTROL
SPOILER PROGRAM AT COMBINED LATERAL CONTROL-SPEED BRAKES
THE BOEING COMPANY
NOTE
1. SPEED BRAKE HANDLE FRICTION FORCE = 20 LBS PULL, 10 LBS PUSH

2. MAXIMUM AVAILABLE IN-FLIGHT SPEED BRAKE HANDLE POSITION = 37 DEG. (IN-FLIGHT DETENT)

3. SPEED BRAKES BEYOND THE IN-FLIGHT DETENT ARE AVAILABLE ONLY ON THE GROUND.
APPENDIX F - AIRPLANE RESPONSE TO CONTROL INPUTS

Time histories of airplane response to control inputs are presented in the following pages.

<table>
<thead>
<tr>
<th>CONTROL</th>
<th>CONDITION</th>
<th>PAGE</th>
</tr>
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<tbody>
<tr>
<td>Elevator</td>
<td>Climbout</td>
<td>20.0-2</td>
</tr>
<tr>
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<td>Approach</td>
<td>20.0-3, -4, -5</td>
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<tr>
<td>Aileron</td>
<td>Climbout</td>
<td>20.0-6</td>
</tr>
<tr>
<td></td>
<td>Approach</td>
<td>20.0-7, -8</td>
</tr>
<tr>
<td>Rudder</td>
<td>Approach</td>
<td>20.0-9, -10</td>
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<tr>
<td></td>
<td>Brake Release and</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acceleration</td>
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</tr>
<tr>
<td></td>
<td>Rotate and Initial</td>
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<tr>
<td></td>
<td>Climbout</td>
<td>20.0-12, -13, -14</td>
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<tr>
<td>SC4020 PLOT 11/20/69 0317</td>
<td>FLIGHT DATA FOR SIMULATOR</td>
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<tr>
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<td>---------------------------</td>
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<td></td>
<td>THE BOOK COMPANY</td>
</tr>
<tr>
<td>APPD</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ELEVATOR INPUT DURING FLAPS 10° GEAR UP

GROSS WEIGHT = 693,100 lbs
C.G. POSITION = 23.1% M