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ANALYTICAL AERODYNAMIC MODEL OF A HIGH ALPHA RESEARCH VEHICLE WIND-TUNNEL MODEL

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LIST OF SYMBOLS

ac	Aircraft aerodynamic center (reference)
b	Aerodynamic wingspan (reference)
C_D	Drag force coefficient
C_L	Lift force coefficient
C_y	Side force coefficient
C_ℓ	Roll moment coefficient about body x-axis
C_m	Pitch moment coefficient about body y-wing axis
C_n	Yaw moment coefficient about body z-axis
C_{n_β}	State derivative of C_n with respect to β (other combinations occur where n is changed to D, L, m, y, or ℓ; and β is changed to another state, to a control, to $\dot{\alpha}$ or to 0)
cg	Aircraft center of gravity
$\bar{c}$	Aircraft mean aerodynamic chord (reference)
D	Drag
g	Gravity constant 32.174 ft/sec/sec
HARV	High angle of attack research vehicle
h	altitude
I_x	Moment of inertia about body x-axis
I_y	Moment of inertia about body y-axis
I_z	Moment of inertia about body z-axis
I_{xz}	Product Moment of inertia about body x and z axes
L	Lift

ℓ_x	Position vector component along x-axis from cg to the ac
ℓ_y	Position vector component along y-axis from cg to the ac
ℓ_z	Position vector component along z-axis from cg to the ac
ℓ_{xe}	x-axis vector comp. from cg to the engine thrust center
ℓ_{ye}	y-axis vector comp. from cg to the engine thrust center
ℓ_{ze}	z-axis vector comp. from cg to the engine thrust center
M	Mach number
m	Aircraft mass
p	Aircraft x-body axis roll rate
q	Aircraft y-body axis pitch rate
$\overline{q}$	Dynamic pressure at current altitude and Mach number
$\overline{q}_0$	Dynamic pressure at 15,000 ft altitude, 0.6 Mach
r	Aircraft z-body axis yaw rate
S	Wing area
T_x	Thrust component along body x-axis
T_y	Thrust component along body y-wing axis
T_z	Thrust component along body z-axis
u	Aircraft speed along the x-body axis
v	Aircraft speed along the y-body axis
w	Aircraft speed along the z-body axis
V	Aircraft total airspeed
w	Aircraft weight
X	Body force along aircraft x- axis
Y	Body force along aircraft y- axis
Z	Body force along aircraft z- axis

α	Angle of attack
$\dot{\alpha}$	Time derivative of α
β	Sideslip angle
δa	Aileron deflection (positive is left wing down roll)
δh	Stabilator deflection (positive is nose down pitch)
δr	Rudder deflection (positive is nose left yaw)
δ_T	Throttle, 30^o (idle) to 131^o (full after burner)
ρ	Standard air density at altitude ($\sigma\rho_{sl}$ slugs/ft^3)
ρ_0	Standard air density at 15,000 ft altitude ($\sigma_0\rho_{sl}$ slugs/ft^3)
ρ_{sl}	Standard air density at sea level (.0023769 slugs/ft^3)
ϕ	Aircraft body axes bank angle
ψ	Aircraft body axes yaw angle
σ	Standard air density ratio at current altitude
σ_0	Standard air density ratio at 15,000 ft altitude (0.629)
θ	Aircraft body axes pitch angle

1. Introduction

The objective of this report is to establish an analytical six degrees of freedom (6 DOF) aerodynamic model of a high angle-of-attack (alpha) combat airplane that can be utilized in optimization and control analysis/synthesis studies. Emphasis is placed on deriving such a model with validity in the altitude-Mach flight envelope centered at an altitude h = 15,000 feet and a Mach number M = 0.6. Some effort is made to extend the validity from 0.3 to 0.9 Mach. An engine model is not included. The analytical models of aerodynamic derivatives are derived as nonlinear functions of alpha with all other states and control variables fixed. Consequently, interpolation is required between the parameterized nonlinear functions.

In this report, a six degree of freedom (6 DOF) sub-sonic analytical aerodynamic model is derived from a high angle of attack research vehicle wind-tunnel model. The wind-tunnel model was provided by NASA LaRC, [1], which is based on that contained in [2-3]. The derivation uses only the aerodynamic coefficient data of the wind-tunnel model which corresponds to an altitude h = 15,000 feet and Mach numbers ranging from 0.3 to 0.9. In order to avoid additional complexity, certain effects are not considered: The effects of leading edge flap, trailing edge flap, speed brake, landing gear, etc. The aerodynamic coefficients are considered to be functions of the following control variables as well as angle of attack, sideslip, Mach number, altitude, roll, pitch and yaw rates: Aileron deflection (δa), Rudder deflection (δr) and Stabilator deflection (δh). In addition, lift and pitching moment coefficients have unsteady flow parts due to the time rate of change of angle of attack (alpha dot).

Using body axes, the equations of motion are developed in Chapter 2 in which the center of mass (cg) and the aerodynamic center(ac) may be non-colocated. The aerodynamic coefficients modeled are drag, lift and side forces and rolling, pitching and yawing moments. After presenting the mathematical structure of the aerodynamic coefficients which has a dependency on alpha dot, explicit equations of motion are developed.

The derived 6 DOF analytical model is presented in Chapters 3-8. The derivation is based on a high alpha research vehicle (HARV) wind-tunnel model described in [1]; it is a full, nonlinear 6 DOF, rigid-body dynamic model whose aerodynamic forces and moments are calculated from a large wind-tunnel-derived data base using table look-ups with linear interpolation. The angle of attack range is -10^o to 90^o; sideslip angle range is -20^o to 20^o; Mach number range is 0.2 to 2.0 and altitude range is 0 to 60,000 feet. Only subsonic Mach numbers and the fixed 15,000 ft altitude are considered in fitting analytical models to the data.

In Chapter 3 the drag coefficient is modeled at Mach 0.6 using four nonlinear functions of alpha which are parameterized by stabilator deflections $\delta h = 10.5^o, 0^o, -5^o$ and -24^o. The formulae are given in Table 3.3 and comparisons with the wind-tunnel data are presented in Figure 3.1. In Chapter 4 the lift coefficient is modeled at Mach numbers 0.6 and 0.9 and parameterized by stabilator deflections $\delta h = 10.5^o$ and -24^o. The formulae are given in Table 4.3 and comparisons with the wind-tunnel are presented in Figures 4.1 and 4.2.

Mach numbers 0.3, 0.6, 0.8 and 0.9 are used in Chapter 5 to parameterize the analytical models for the pitching moment coefficient. They are also parameterized by stabilator deflections $\delta h = 10.5^o, 5^o, 2^o, 0^o, -5^o, -12.5^o$ and -24^o. The formulae are given in Tables 5.3 a,b,c,d and comparisons with the wind-tunnel data are presented in Figures 5.1-5.8.

The analytical model of the side force coefficient C_y is given in Chapter 6. It is taken from the wind-tunnel model at an altitude h=15,000 feet and a Mach number M=0.6. The analytical model for C_{y_0} is constructed at $\beta = 0^o, 20^o$; $\delta a = \mp 25^o$; and $\delta r = \mp 30^o$. The analytical models are functions of α from 0^o to 90^o; they are defined in Tables 6.1 and 6.2. The analytical formulae are presented in Table 6.3. Comparisons of the analytical models with the corresponding wind-tunnel model data are shown in Figures 6.1 to 6.3. The roll and yaw rate derivatives C_{y_p} and C_{y_r} are given in Figure 6.3.

The analytical model of the rolling moment coefficient C_ℓ is given in Chapter 7. It is taken from the wind-tunnel model at an altitude h=15,000 feet and Mach numbers M=0.6 and 0.9. The analytical model is parameterized at $\beta = 0^o, 20^o$; $\delta a = \mp 25^o$; and $\delta r = \mp 30^o$. The analytical models are nonlinear functions of α from 0^o to 90^o; they are defined in Tables 7.1 a,b and 7.2 a,b. The analytical formulae are presented in Tables 7.3 a,b. Comparisons of the analytical models with the corresponding wind-tunnel model data are shown in Figures 7.1 to 7.4. The roll and yaw rate derivatives C_{ℓ_p} and C_{ℓ_r} and the sideslip derivative C_{ℓ_β} are given in Figure 7.4.

The analytical model of the yawing moment coefficient C_n is presented in Chapter 8. It is taken from the wind-tunnel model at an altitude h=15,000 feet and Mach numbers M=0.6 and 0.9. The analytical model is parameterized at $\beta = 0^o, 20^o$ and stabilator deflections $\delta h = 10.5^o$ and -24^o; $\delta a = \mp 25^o$; and $\delta r = \mp 30^o$. The analytical models are functions of α from 0^o to 90^o; they are defined in Tables 8.1 a,b,c,d and 8.2 a,b,c,d. The analytical formulae are presented in Tables 8.3 a,b,c,d. Comparisons of the analytical models with the corresponding wind-tunnel model data are shown in Figures 8.1 to 8.7. The roll and yaw rate derivatives C_{n_p} and C_{n_r} and the sideslip derivative $C_{n\beta}$ are given in Figure 8.7.

The wind-tunnel model of [1] was flown in NASA's simulator by a pilot to generate some basic maneuvers at 0.3, 0.6 and 0.9 Mach numbers such as pitch-ups, 360° loaded and unloaded rolls, turn reversals, split S's and level turns. That simulator data was used to check the validity of the 6 DOF analytical model. The accelerations

$$\dot{u},\ \dot{w},\ \dot{q},\ \dot{v},\ \dot{p},\ \dot{r}$$

are computed for the analytical model using the states and controls from the piloted simulated maneuvers. Comparisons with the accelerations from the wind-tunnel data model are shown in Chapters 9, 10 and 11 for the Mach numbers 0.6, 0.9 and 0.3, respectively.

Listings of the computer code developed under this grant are contained in the Appendices A-D. Appendix A contains the code for the equations of motion. Appendices B and C contain the code for the analytical model. Appendix D contains the code for the comparison.

2. Equations of Motions

2.1 Equations of Motions - Body Axes

The following kinematical relations for a rigid symmetric aircraft are given with reference to body axes at the center of gravity, [4]. The state vector is $(u, v, w, p, q, r, \theta, \phi)$. The aerodynamic linear acceleration vector at the center of gravity (cg) is denoted as (X,Y,Z). The aerodynamic angular acceleration vector at cg is given by (FP,FQ,FR). The thrust vector T is represented in body coordinates as (T_x, T_y, T_z).

The force equations with respect to body axes:

$$\dot{u} = rv - qw - g\sin\theta + X + \frac{T_X}{m} \tag{1}$$

$$\dot{v} = pw - ru + g\cos\theta\sin\phi + Y + \frac{T_y}{m} \tag{2}$$

$$\dot{w} = qu - pv + g\cos\theta\cos\phi + Z + \frac{T_z}{m} \tag{3}$$

The moment equations with respect to body axes:

$$\dot{p} = C_{41}pq + C_{42}qr + C_{43}FR + C^{*}FP$$

$$+\frac{C_{43}}{I_z}(\ell_{xe}T_y - \ell_{ye}T_x) + \frac{C^{*}}{I_x}(\ell_{ye}T_z - \ell_{ze}T_y) \tag{4}$$

$$\dot{q} = C_{51}pr + C_{52}(r^2 - p^2) + FQ + \frac{1}{I_y}(\ell_{zc}T_x - \ell_{xe}T_z) \tag{5}$$

$$\dot{r} = C_{61}pq + C_{62}qr + C_{63}FP + C^{*}FR$$

$$+\frac{C_{63}}{I_x}(\ell_{ye}T_z - \ell_{ze}T_y) + \frac{C*}{I_z}(\ell_{xe}T_y - \ell_{ye}T_x) \tag{6}$$

Euler Equations:

$$\dot{\theta} = q\cos\phi - r\sin\phi \qquad (7)$$

$$\dot{\phi} = p + q\tan\theta\sin\phi + r\tan\theta\cos\phi \qquad (8)$$

where he quantities X, Y, Z, FP, FQ and FR depend on the aerodynamic coefficients C_D, C_y, C_L, C_ℓ, C_m, C_n as follows:

$$D = \bar{q}SC_D \quad \text{(Drag)} \qquad (9)$$

$$L = \bar{q}SC_L \quad \text{(Lift)} \qquad (10)$$

$$X = [-D\cos(\alpha) + L\sin(\alpha)]/m \qquad (11)$$

$$Y = \bar{q}SC_y/m \qquad (12)$$

$$Z = [-D\sin(\alpha) - L\cos(\alpha)]/m \qquad (13)$$

$$FP = \left[\bar{q}SbC_\ell + m\left(\ell_y Z - \ell_z Y\right)\right]/I_x \qquad (14)$$

$$FQ = \left[\bar{q}S\bar{c}C_m + m\left(\ell_z X - \ell_x Z\right)\right]/I_y \qquad (15)$$

$$FR = \left[\bar{q}SbC_n + m\left(\ell_x Y - \ell_y X\right)\right]/I_z \qquad (16)$$

and where the constants in the moment equations $(\dot{p}, \dot{q} \; and \; \dot{r})$ are functions of the moment of inertia quantities I_x, I_y, I_z and I_{xz}:

$$C^* = I_x I_z/(I_x I_z - I_{xz}^2) \quad (17)$$

$$C_{41} = C^* I_{xz}(I_z + I_x - I_y)/ I_x I_z \quad (18)$$

$$C_{42} = C^* (I_z (I_y - I_z) - I_{xz}^2)/I_x I_z \quad (19)$$

$$C_{43} = C^* I_{xz}/I_x \quad (20)$$

$$C_{51} = (I_z - I_x)/I_y \quad (21)$$

$$C_{52} = I_{xz}/I_y \quad (22)$$

$$C_{61} = C^* (I_x (I_x - I_y) + I_{xz}^2) / I_x I_z \quad (23)$$

$$C_{62} = C^* I_{xz} (I_y - I_z - I_x)/I_x I_z \quad (24)$$

$$C_{63} = C^* I_{xz}/I_z \quad (25)$$

In the above equations the vector (ℓ_x, ℓ_y, ℓ_z) denotes the position vector from the center of mass (cg) to the aerodynamic center (ac) and the vector $(\ell_{xe}, \ell_{ye}, \ell_{ze})$ denotes the position vector from the center of mass to the engine thrust center.

The thrust vector $T = (T_x,T_y,T_z)$ has the components:

$$T_x = T_R(h,M,\delta_T) \cos(1.98^o) + T_L(h,M,\delta_T) \cos(-1.98^o)$$

$$T_y = T_R(h,M,\delta_T) \sin(1.98^o) + T_L(h,M,\delta_T) \sin(-1.98^o)$$

$$T_z = 0$$

where δ_T is the throttle control variable which varies between 30^o (idle) to 131^o (full after burner). Since only aerodynamic models are considered in this report the engine models for computing the thrust,$T_R(h,M,\delta_T)$, of the right engine and the thrust, $T_L(h,M,\delta_T)$, of the left engine are not provided herein. The thrust angle 1.98° is the position of the engines away from the center line of the aircraft.

The following constants are typical of those for a high alpha research vehicle (HARV), [1].

Table 2.1 Aircraft Constants for a High Alpha Research Vehicle

$m = 1035.308$ slugs

$w = 33310$ lbs

$I_x = 23000$ slugs ft^2

$I_y = 151293$ slugs ft^2

$I_z = 169945$ slugs ft^2

$I_{xz} = -2971$

$S = 400$ ft^2

$\bar{c} = 11.52$ ft

$b = 37.42$ ft

$\ell_x = -0.297$

$\ell_y = 0.$ ft

$\ell_z = 0.233$ ft

$\ell_{xe} = -19.37$ ft

$\ell_{ye} = 0.$ ft

$\ell_{ze} = 0.233$ ft

Dynamic pressure, air density and air density ratio are as follows:

$\bar{q} = 0.5\rho V^2$

$\rho = (\sigma)(.0023769)$ slugs/ft^3

$\sigma =$ Standard air density ratio at current altitude

$\rho_0 = (.629)(.0023769)$ slugs/ft^3 (i.e., h=15,000 ft)

The gravity constant g is 32.174 ft/sec^2.

2.2 Angle of Attack, Sideslip and Total Speed

With respect to body axes, the angle of attack, α, the sideslips angle, β, and the total speed, V, are defined as

$$\alpha = tan^{-1}\left(\frac{w}{u}\right) \qquad -\pi \le \alpha \le \pi \tag{26}$$

$$\beta = Sin^{-1}\left(\frac{v}{V}\right) \qquad -\pi \le \beta \le \pi \tag{27}$$

$$V^2 = u^2 + v^2 + w^2 \tag{28}$$

Our high alpha research vehicle (HARV) analytical model is derived from the wind-tunnel model described in [1]. It is a full, nonlinear 6 DOF, rigid-body dynamic model whose aerodynamic forces and moments are calculated from a large wind-tunnel-derived data base using table look-ups with linear interpolation. The range of angle of attack, sideslip angle, mach number and altitude in that model are given in Table 2.2.

Table 2.2. Range of State Variables in Aerodynamic Coefficients

α	-10° to 90°	angle of attack (alpha)
β	−20° to 20°	sideslip (beta)
M	0.2 to 2.0	Mach number
h	0 to 60,000 ft	altitude

The aerodynamic coefficients are functions of the following control variables as well as angle of attack, sideslip, Mach number, altitude, roll, pitch and yaw rates: Aileron deflection (δa), Rudder deflection (δr) and Stabilator deflection (δh). Throttle (δ_T) is an engine control variable. These control variables and their limits are given in Table 2.3. The effects of leading edge flap, trailing edge flap, speed brake, landing gear, etc are not considered.

Table 2.3 Control Variables and Their Limits

δa	Aileron deflection (-25°, 25°)
δr	Rudder deflection (-30°, 30°)
δh	Stabilator deflection (-24°, 10.5°)
δ_T	Throttle 30° (idle) to 131° (full after burner)

2.3 Mathematical Structure of Aerodynamic Coefficients

We consider the following state and control dependency structure for the coefficients of the aerodynamic model of the wind-tunnel based high angle of attack vehicle model. The effects of leading edge flap, trailing edge flap, speed brake, landing gear, etc are not considered. Only lift and pitching moment coefficients have an unsteady flow portion; they include the effect of the time rate-of-change of angle of attack. The other coefficients only have a steady flow part; they are explicit functions of airplane velocity states and control surface positions.

Drag C_D

$$C_D = C_D\ (\alpha, M, h, \delta h) \tag{29}$$

Lift C_L

$$C_L = C_{L_o}(\alpha, M, h, \delta h) + \frac{\bar{c}}{2V}\left[C_{L_q}(\alpha, M, h,)q + C_{L_{\dot{\alpha}}}(\alpha, M, h)\dot{\alpha}\right] \tag{30}$$

Pitching Moment C_m

$$C_m = C_{m_o}(\alpha, M, h, \delta h) + \frac{\bar{c}}{2V}\left[C_{m_q}(\alpha, M, h)q + C_{m_{\dot{\alpha}}}(\alpha, M, h)\dot{\alpha}\right] \tag{31}$$

Side Force C_y

$$C_y = C_{y_o}(\alpha, \beta, M, h, \delta a, \delta r) + C_{y_\beta}(\alpha, M, h)\beta +$$

$$\frac{\bar{b}}{2V}\left[C_{y_p}(\alpha, M, h)p + C_{y_r}(\alpha, M, h)\ r\right] \tag{32}$$

Moment C_ℓ

$$C_\ell = C_{\ell_o}(\alpha, \beta, M, h, \delta a, \delta r) + C_{\ell_\beta}(\alpha, M, h)\beta$$

$$+\frac{\bar{b}}{2V}\left[C_{\ell_p}(\alpha, M, h)p + C_{\ell_r}(\alpha, M, h)\ r\right] \tag{33}$$

Yawing Moment C_n

$$C_n = C_{n_o}(\alpha,\beta,M,h,\delta a,\delta r,\delta h) + C_{n_\beta}(\alpha,M,h)\beta +$$

$$\frac{\bar{b}}{2V}\left[C_{n_p}(\alpha,M,h)p + C_{n_r}(\alpha,M,h)\ r\right] \qquad (34)$$

2.4 Explicit Equations of Motion

Since the lift and pitching moment coefficients depend on $\dot{\alpha}$ the right-hand sides of Eqs. (1), (3), (4)-(6) depend on the differentials $\dot{u}$ and $\dot{w}$ through the relation

$$\dot{\alpha} = \frac{u\dot{w} - \dot{u}w}{u^2 + w^2} \qquad (35)$$

which follows from the definition of α.

Substitution of expressions for X, D, L, C_D and C_L into the $\dot{u}$ Eq.(1) yields

$$\dot{u} = \frac{\left[F_u + C_b sin(\alpha) u \dot{w}\right]}{1 + C_b sin(\alpha) w} \qquad (36)$$

in which

$$F_u = rv - qw - g\,sin(\theta) - F_D\,cos(\alpha) + \frac{T_x}{m}$$

$$+\frac{\bar{q}S}{m} sin(\alpha)\left[C_{L_o} + \frac{\bar{c}}{2V} C_{L_q} q\right] \qquad (37)$$

$$F_D = \frac{\bar{q} S C_{D_o}}{m} \tag{38}$$

$$C_b = \frac{\bar{q} S \frac{\bar{c}}{2V} C_{L_{\dot{\alpha}}}}{m(u^2 + w^2)} \tag{39}$$

Substitution of expressions for Z, D, L, C_D, C_L and $\dot{u}$ into the $\dot{w}$ Eq. (3) yields

$$\dot{w} = \frac{F_w + \frac{C_b \cos(\alpha) w \; F_u}{1 + C_b \sin(\alpha) w}}{B_q} \tag{40}$$

in which

$$F_w = qu - pv + g\, cos(\theta)\, cos(\theta) - F_D\, sin(\alpha) + \frac{T_z}{m}$$

$$-\frac{\bar{q} S}{m}\, cos(\alpha) \left[C_{L_o} + \frac{\bar{c}}{2V} C_{L_q}\, q \right] \tag{41}$$

$$B_q = 1 + C_b\, cos(\alpha) u - \left[\frac{C_b\, cos(\alpha) w C_b\, sin(\alpha) u}{1 + C_b\, sin(\alpha) w} \right] \tag{42a}$$

or, equivalently,

$$B_q = 1 + \frac{C_b \cos(\alpha) u}{1 + C_b \sin(\alpha) w} \tag{42b}$$

Substitution of $\dot{w}$, Eq. (40), into $\dot{u}$, Eq. (36), yields the right-hand-side of $\dot{u}$ without differentials.

Since $\dot{u}$ and $\dot{w}$ have been defined so that their right-hand sides are free of differentials, these expressions, Eqs. (36) and (40), can be substituted into Eq. (35) to give $\dot{\alpha}$ free of differentials in its right-hand side. Consequently, expressions (35), (36) and (40) constitute explicit expressions for $\dot{\alpha}$, $\dot{u}$, and $\dot{w}$ which are free of differentials in their right-hand sides.

3. Analytical Model for Drag Coefficient

The analytical model of the drag coefficient C_D is taken from the wind-tunnel model at an altitude h=15,000 feet and a Mach number M=0.6. The analytical model for C_{D_0} is constructed at stabilator deflections δh = 10.5°, 0°, -5° and -24°. The analytical models are functions of α from 0° to 90°; they are defined in Tables 3.1 and 3.2. The analytical formulae are presented in Table 3.3. Comparisons of the analytical models with the corresponding wind-tunnel model data are shown in Figure 3.1. The analytical models are also given in the computer code listing contained in Appendix B.

Table 3.1 Definitions of C_D Analytical Models

$C_{D_0}(\alpha$, M=0.6, δh= 10.5°, h=15,000 ft) = CD0X(α)
$C_{D_0}(\alpha$, M=0.6, δh= 0°, h=15,000 ft) = CD0Z(α)
$C_{D_0}(\alpha$, M=0.6, δh= -5°, h=15,000 ft) = CD0N5(α)
$C_{D_0}(\alpha$, M=0.6, δh= -24°, h=15,000 ft) = CD0N(α)

Table 3.2 Drag Coefficient Analytical Models

δh	Mach Number = 0.6
δh = 10.5	CD0X(α)
δh = 0	CD0Z(α)
δh = -5	CD0N5(α)
δh = -24	CD0N(α)

Table 3.3 Formulas for C_D Model

$$
\begin{aligned}
CD0X(\alpha^o) = {} & (.4/2.75)\tan^{-1}(((78/80)\alpha^o+7)1/30) \\
& +(.6/2.75)\tan^{-1}(-((78/80)\alpha^o+2)1/8) \\
& +(-.3/2.75)\tan^{-1}(-((78/80)\alpha^o+5)1/90) \\
& +(-.2/2.75)\tan^{-1}(-((78/80)\alpha^o-6)1/5) \\
& +(1.95/2.75)\tan^{-1}(((78/80)\alpha^o-28)1/15) \\
& +(2.2/2.75)\tan^{-1}(((78/80)\alpha^o-58)1/40) \\
& +(1.4/2.75)\tan^{-1}(-((78/80)\alpha^o-73)1/30) \\
& +(2.3/2.75)\tan^{-1}(-((78/80)\alpha^o-138)1/20)-.147
\end{aligned}
$$

$$
\begin{aligned}
CD0Z(\alpha^o) = {} & (2.17/2.10)[(.6/2.75)\tan^{-1}(((77/80)\alpha^o+6)1/30) \\
& +(.6/2.75)\tan^{-1}(-((77/80)\alpha^o+1)1/8) \\
& +(-.3/2.75)\tan^{-1}(-((77/80)\alpha^o+4)1/90) \\
& +(-.2/2.75)\tan^{-1}(-((77/80)\alpha^o-7)1/10) \\
& +(1.95/2.75)\tan^{-1}(((77/80)\alpha^o-29)1/15) \\
& +(2.2/2.75)\tan^{-1}(((77/80)\alpha^o-59)1/40) \\
& +(1.55/2.75)\tan^{-1}(-((77/80)\alpha^o-74)1/30) \\
& +(2.3/2.75)\tan^{-1}(-((77/80)\alpha^o-139)1/20)-.2834] + .0199
\end{aligned}
$$

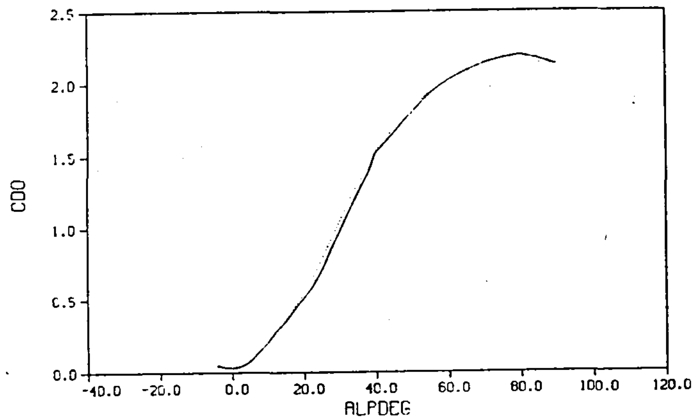
$$
\begin{aligned}
CD0N5(\alpha^o) = {} & (.32/2.75)\tan^{-1}(((80/85)\alpha^o+8)1/30) \\
& +(.6/2.75)\tan^{-1}(-((80/85)\alpha^o+3.5)1/6.5) \\
& +(-.3/2.75)\tan^{-1}(-((80/85)\alpha^o+7)1/90) \\
& +(-.2/2.75)\tan^{-1}(-((80/85)\alpha^o-4)1/15) \\
& +(1.95/2.75)\tan^{-1}(((80/85)\alpha^o-28)1/15) \\
& +(2.25/2.75)\tan^{-1}(((80/85)\alpha^o-68)1/40) \\
& +(1.664/2.75)\tan^{-1}(-((80/85)\alpha^o-90)1/30) \\
& +(2.35/2.75)\tan^{-1}(-((80/85)\alpha^o-140)1/20)-.246
\end{aligned}
$$

$$
\begin{aligned}
CD0N(\alpha^o) = {} & (.5/2.75)\tan^{-1}((\alpha^o+5)1/30) \\
& +(.6/2.75)\tan^{-1}(-(\alpha^o-0)1/6) \\
& +(-.25/2.75)\tan^{-1}(-(\alpha^o+3)1/90) \\
& +(-.15/2.75)\tan^{-1}(-(\alpha^o-4)1/40) \\
& +(1.85/2.75)\tan^{-1}((\alpha^o-30)1/28) \\
& +(2.3/2.75)\tan^{-1}((\alpha^o-60)1/40) \\
& +(1.15/2.75)\tan^{-1}(-(\alpha^o-85)1/30) \\
& +(2.3/2.75)\tan^{-1}(-(\alpha^o-140)1/20)-.2425
\end{aligned}
$$

Analytical Model of C_D

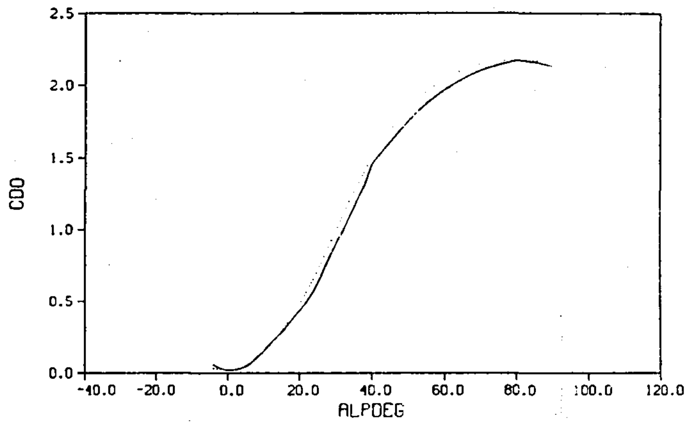
________ Wind-Tunnel .... Analytical

CD0X(α)



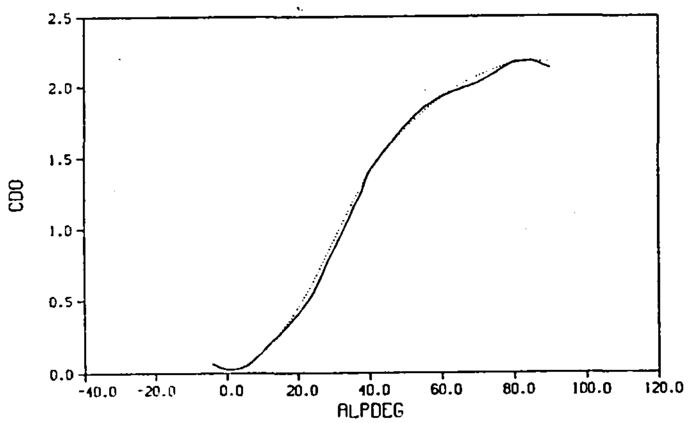
δh=10.5°

CD0Z(α)



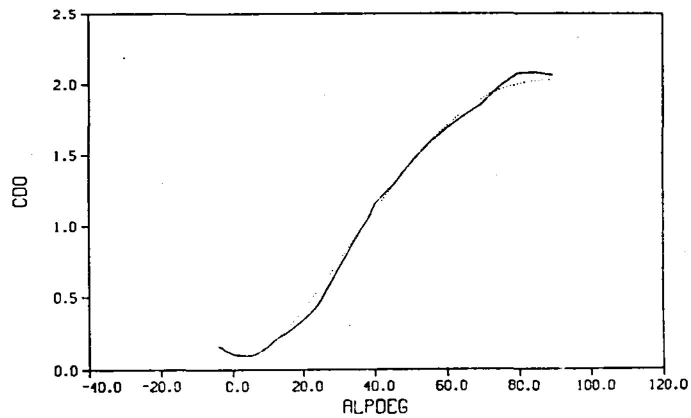
δh=0°

CD0N5(α)



δh= -5°

CD0N(α)



δh= -24°

Figure 3.1: Comparison of Wind-Tunnel and Analytical Drag Coefficient C_{D_0} for M = 0.6 and h=15,000 feet: δh=10.5°, 0°, -5°, -24°.

4. Analytical Model for Lift Coefficient

The analytical model of the lift coefficient C_L is taken from the wind-tunnel model at an altitude h=15,000 feet and Mach numbers M=0.6 and 0.9. The analytical model for C_{L0} is constructed at stabilator deflections δh = 10.5° and -24°. The analytical models are functions of α from 0° to 90°; they are defined in Tables 4.1 and 4.2. The analytical models of pitch and alpha dot rates are constructed at 0.6 Mach. The analytical formulae are presented in Table 4.3. Comparisons of the analytical models with the corresponding wind-tunnel model data are shown in Figures 4.1 and 4.2. The analytical models are also given in the computer code listing contained in Appendix B.

Table 4.1 Definitions of C_L Analytical Models

$C_{L_0}(\alpha$, M=0.6, δh= 10.5°, h=15,000 ft) = CL0X6(α)
$C_{L_0}(\alpha$, M=0.9, δh= 10.5°, h=15,000 ft) = CL0X9(α)
$C_{L_0}(\alpha$, M=0.6, δh= -24°, h=15,000 ft) = CL0N6(α)
$C_{L_0}(\alpha$, M=0.9, δh= -24°, h=15,000 ft) = CL0N9(α)
$C_{L_q}(\alpha$, M=0.6, h=15,000 ft) = CLQ(α)
$C_{L_{\alpha\ dot}}(\alpha$, M=0.6, h=15,000 ft) = CLAD(α)

Table 4.2 Lift Coefficient Analytical Models

δh	Mach Number	
	0.6	0.9
δh = 10.5	CL0X6(α)	CL0X9(α)
δh = -24	CL0N6(α)	CL0N9(α)

Table 4.3 Formulas for C_L Model

$$\begin{aligned}
CL0X6(\alpha^o) = {} & (.86/2.75)\tan^{-1}(-(\alpha^o+5)1/100) \\
& +(2.19/2.75)\tan^{-1}((\alpha^o-5)1/7) \\
& +(.9/2.75)\tan^{-1}((\alpha^o-24)1/17) \\
& +(1.71/2.75)\tan^{-1}(-(\alpha^o-53)2/25) \\
& +(.41/2.75)\tan^{-1}(-(\alpha^o-70)2/7)-.95
\end{aligned}$$

$$\begin{aligned}
CL0X9(\alpha^o) = {} & (.86/2.75)\tan^{-1}(-(\alpha^o+5)1/100) \\
& +(2.59/2.75)\tan^{-1}((\alpha^o-3)1/7) \\
& +(1.6/2.75)\tan^{-1}((\alpha^o-20)1/22) \\
& +(3.41/2.75)\tan^{-1}(-(\alpha^o-57)1/30) \\
& +(.41/2.75)\tan^{-1}(-(\alpha^o-70)1/20)-.65
\end{aligned}$$

$$\begin{aligned}
CL0N6(\alpha^o) = {} & (1.06/2.75)\tan^{-1}(-(\alpha^o+5)1/100) \\
& +(1.79/2.75)\tan^{-1}((\alpha^o-5)1/7) \\
& +(2.5/2.75)\tan^{-1}((\alpha^o-15)1/22) \\
& +(2.71/2.75)\tan^{-1}(-(\alpha^o-59)1/50) \\
& +(1.21/2.75)\tan^{-1}(-(\alpha^o-70)1/20)-.72
\end{aligned}$$

$$\begin{aligned}
CL0N9(\alpha^o) = {} & (1.06/2.75)\tan^{-1}(-(\alpha^o+5)1/100) \\
& +(1.79/2.75)\tan^{-1}((\alpha^o-5)1/7) \\
& +(2.5/2.75)\tan^{-1}((\alpha^o-13)1/22) \\
& +(2.71/2.75)\tan^{-1}(-(\alpha^o-59)1/50) \\
& +(1.21/2.75)\tan^{-1}(-(\alpha^o-70)1/20)-.80
\end{aligned}$$

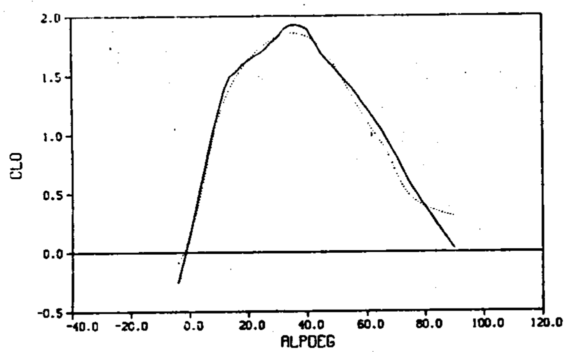
$$\begin{aligned}
CLQ(\alpha^o) = {} & (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/10) \\
& +(-2.39/2.75)\tan^{-1}((\alpha^o-6)1/3) \\
& +(2.4/2.75)\tan^{-1}((\alpha^o-15.5)1/3) \\
& +(2.0/2.75)\tan^{-1}(-(\alpha^o-20)1/5) \\
& +(4.3/2.75)\tan^{-1}((\alpha^o-37)1/4.5) \\
& +(2.2/2.75)\tan^{-1}(-(\alpha^o-45)1/15) \\
& +(2.2/2.75)\tan^{-1}(-(\alpha^o-80)1/15) \\
& +(-.45/2.75)\tan^{-1}(-(\alpha^o-76)1/3.5)+4.2
\end{aligned}$$

$$\begin{aligned}
CLAD(\alpha^o) = {} & (1.32/\pi)\tan^{-1}(-(\alpha^o-5)5\pi/18) \\
& +(-.75)\tan^{-1}((\alpha^o-45)1/2)+1.8
\end{aligned}$$

Analytical Model of C_L

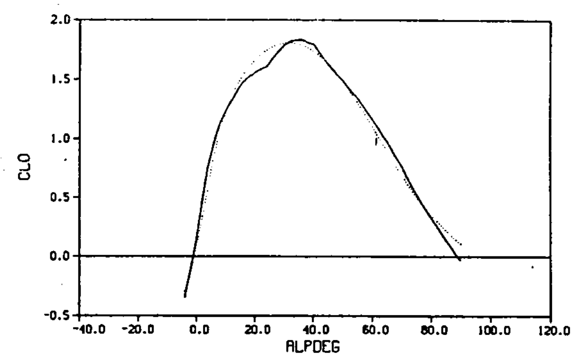
_________ Wind-Tunnel ....Analytical

CL0X6(α)



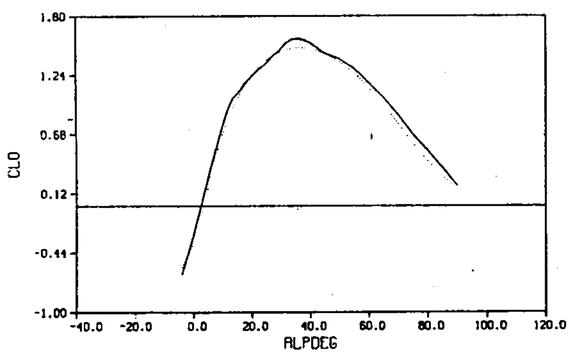
δh= 10.5°, M=0.6

CL0X9(α)



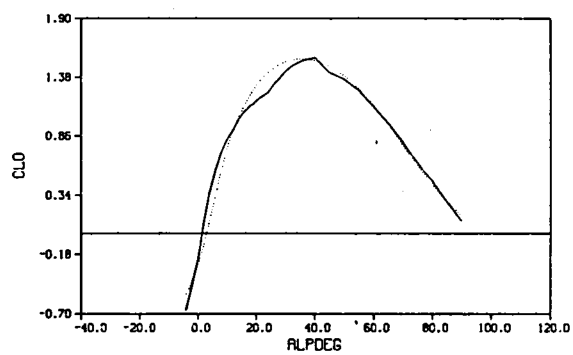
δh= 10.5°,M=0.9

CL0N6(α)



δh= -24°, M=0.6

CL0N9(α)



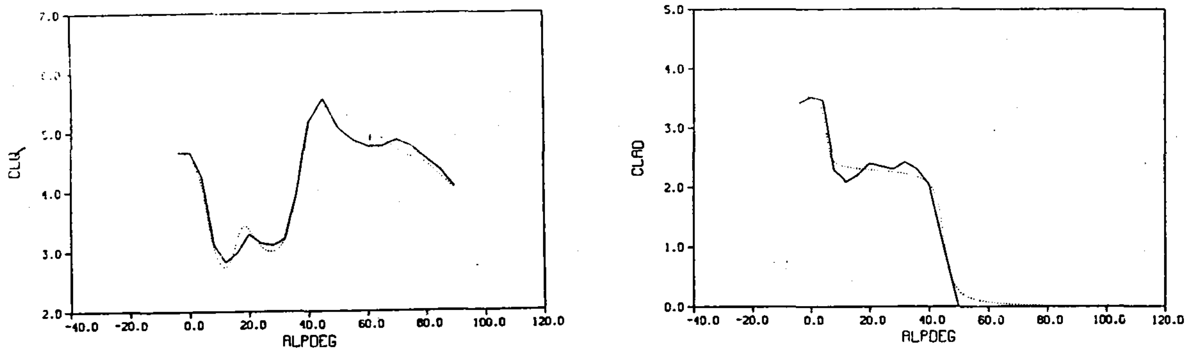
δh= -24°,M=0.9

Figure 4.1: Comparison of Wind-Tunnel and Analytical Lift Coefficient C_{L_0} for h=15,000 feet: δh=10.5°, -24° and M=0.6,0.9.

Analytical Model of C_L

_________ Wind-Tunnel ………Analytical

CLQ(α) CLAD(α)



h= 15,000 feet, M=0.6 h= 15,000 feet, M=0.6

Figure 4.2: Comparison of Wind-Tunnel and Analytical Lift Coefficient Derivatives C_{L_q} and $C_{L_{\alpha dot}}$ for h=15,000 feet and M=0.6.

5. Analytical Model for Pitching Moment Coefficient

The analytical model of the pitching moment coefficient C_m is taken from the wind-tunnel model at an altitude h=15,000 feet. The analytical model for C_{m0} is constructed at stabilator deflections δh = 10.5°, 5°, 2°, 0°, -5°, -12.5° and -24° for the Mach numbers M=0.3, 0.6, 0.8 and 0.9. The analytical models of pitch and alpha dot rates are constructed at 0.6 Mach. The analytical models are functions of α from 0° to 90°; they are defined in Tables 5.1a,b,c,d and 5.2. The analytical formulae are presented in Tables 5.3 a,b,c,d. Comparisons of the analytical models with the corresponding wind-tunnel model data are shown in Figures 5.1 to 5.8. The pitch and alpha dot rates derivatives C_{m_q} and $C_{m_{\alpha\,dot}}$ are given in Figure 5.8. The analytical models are also given in the computer code listing contained in Appendix B.

Table 5.1a Definitions of C_m Analytical Models at 0.6 Mach

C_{m0}(α, M=0.6, δh= 10.5°, h=15,000 ft)	= Cm0X6(α)
C_{m0}(α,M=0.6, δh= 5°, h=15,000 ft)	= Cm0X56(α)
C_{m0}(α, M=0.6, δh= 2°, h=15,000 ft)	= Cm0X26(α)
C_{m0}(α, M=0.6, δh= 0°, h=15,000 ft)	= Cm006(α)
C_{m0}(α, M=0.6, δh= -5°, h=15,000 ft)	= Cm0N56(α)
C_{m0}(α, M=0.6, δh= -12.5°, h=15,000 ft)	= Cm0Z6(α)
C_{m0}(α, M=0.6, δh= -24°, h=15,000 ft)	= Cm0N6(α)
C_{m_q}(α, M=0.6, h=15,000 ft)	= CMQ(α)
$C_{m_{\alpha\,dot}}$(M=0.6, h=15,000 ft)	= CMAD(α)

Table 5.1b Definitions of C_m Analytical Models at 0.8 Mach

C_{m0}(α, M=0.8, δh= 10.5°, h=15,000 ft)	= Cm0X8(α)
C_{m0}(α,M=0.8, δh= 5°, h=15,000 ft)	= Cm0X58(α)
C_{m0}(α, M=0.8, δh= 2°, h=15,000 ft)	= Cm0X28(α)
C_{m0}(α, M=0.8, δh= 0°, h=15,000 ft)	= Cm0X08(α)
C_{m0}(α, M=0.8, δh= -5°, h=15,000 ft)	= Cm0N58(α)
C_{m0}(α, M=0.8, δh= -12.5°, h=15,000 ft)	= Cm0NZ8(α)
C_{m0}(α, M=0.8, δh= -24°, h=15,000 ft)	= Cm0N8(α)

Table 5.1c Definitions of C_m Analytical Models at 0.9 Mach

C_{m0}(α, M=0.9, δh= 10.5°, h=15,000 ft)	= Cm0X9(α)
C_{m0}(α,M=0.9, δh= 5°, h=15,000 ft)	= Cm0X59(α)
C_{m0}(α, M=0.9, δh= 2°, h=15,000 ft)	= Cm0X29(α)
C_{m0}(α, M=0.9, δh= 0°, h=15,000 ft)	= Cm0X09(α)
C_{m0}(α, M=0.9, δh= -5°, h=15,000 ft)	= Cm0N59(α)
C_{m0}(α, M=0.9, δh= -12.5°, h=15,000 ft)	= Cm0NZ9(α)
C_{m0}(α, M=0.9, δh= -24°, h=15,000 ft)	= Cm0N9(α)

Table 5.1d Definitions of C_m Analytical Models at 0.3 Mach

$C_{m_0}(\alpha$, M=0.3, δh= 10.5°, h=15,000 ft) = Cm0X3(α)
$C_{m_0}(\alpha$, M=0.3, δh= -12.5°, h=15,000 ft) = Cm0NZ3(α)
$C_{m_0}(\alpha$, M=0.3, δh= -24°, h=15,000 ft) = Cm0N3(α)

Table 5.2 Pitching Moment Coefficient Analytical Models

δh	Mach Number			
	0.3	0.6	0.8	0.9
10.5	Cm0X3(α)	Cm0X6(α)	Cm0X8(α)	Cm0X9(α)
5	Cm0X56(α)	Cm0X56(α)	Cm0X58(α)	Cm0X59(α)
2	Cm0X26(α)	Cm0X26(α)	Cm0X28(α)	Cm0X29(α)
0	Cm006(α)	Cm006(α)	Cm0X08(α)	Cm0X09(α)
-5	Cm0N56(α)	Cm0N56(α)	Cm0N58(α)	Cm0N59(α)
-12.5	Cm0NZ3(α)	Cm0Z6(α)	Cm0NZ8(α)	Cm0NZ9(α)
-24	Cm0N3(α)	Cm0N6(α)	Cm0N8(α)	Cm0N9(α)

Table 5.3a Formulas for C_m Model at 0.6 Mach

$$
\begin{aligned}
Cm0X6(\alpha^o) = {} & (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/10)+(-.39/2.75)\tan^{-1}((\alpha^o-1)1/8) \\
& +(.8/2.75)\tan^{-1}((\alpha^o-5)1/13)+(.70/2.75)\tan^{-1}(-(\alpha^o-10)1/65) \\
& +(1.2/2.75)\tan^{-1}((\alpha^o-49)1/15)+(2.1/2.75)\tan^{-1}(-(\alpha^o-69)1/15) \\
& +(-.45/2.75)\tan^{-1}(-(\alpha^o-77)1/2)-.398
\end{aligned}
$$

$$
\begin{aligned}
Cm0X56(\alpha^o) = {} & (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/10)+(-.39/2.75)\tan^{-1}((\alpha^o-1)1/12) \\
& +(.9/2.75)\tan^{-1}((\alpha^o-5)1/15)+(.85/2.75)\tan^{-1}(-(\alpha^o-10)1/30) \\
& +(1.35/2.75)\tan^{-1}((\alpha^o-49)1/19)+(2.2/2.75)\tan^{-1}(-(\alpha^o-69)1/15) \\
& +(-.45/2.75)\tan^{-1}(-(\alpha^o-77)1/2)-.368
\end{aligned}
$$

$$
\begin{aligned}
Cm0X26(\alpha^o) = {} & (.26/2.75)\tan^{-1}(-(\alpha^o-2)1/10)+(-.39/2.75)\tan^{-1}((\alpha^o-1)1/10) \\
& +(1/2.75)\tan^{-1}((\alpha^o-3)1/11)+(.85/2.75)\tan^{-1}(-(\alpha^o-7)1/20) \\
& +(1.35/2.75)\tan^{-1}((\alpha^o-51)1/19)+(2.2/2.75)\tan^{-1}(-(\alpha^o-69)1/15) \\
& +(-.45/2.75)\tan^{-1}(-(\alpha^o-77)1/2)-.31
\end{aligned}
$$

$$
\begin{aligned}
Cm006(\alpha^o) = {} & (.36/2.75)\tan^{-1}(-(\alpha^o-5)1/30)+(-.29/2.75)\tan^{-1}((\alpha^o-1)1/15) \\
& +(.9/2.75)\tan^{-1}((\alpha^o-5)1/35)+(.80/2.75)\tan^{-1}(-(\alpha^o-48)1/75) \\
& +(.9/2.75)\tan^{-1}((\alpha^o-52)1/10)+(2.1/2.75)\tan^{-1}(-(\alpha^o-69)1/15) \\
& +(-.45/2.75)\tan^{-1}(-(\alpha^o-77)1/2)-.457
\end{aligned}
$$

$$
\begin{aligned}
Cm0N56(\alpha^o) = {} & (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/30)+(-.39/2.75)\tan^{-1}((\alpha^o-1)1/30) \\
& +(1.2/2.75)\tan^{-1}((\alpha^o-5)1/40)+(.60/2.75)\tan^{-1}(-(\alpha^o-8)1/23) \\
& +(1.3/2.75)\tan^{-1}(-(\alpha^o-60)1/65)+(2.8/2.75)\tan^{-1}((\alpha^o-72)1/55) \\
& +(2.3/2.75)\tan^{-1}(-(\alpha^o-73)1/19)+(-.45/2.75)\tan^{-1}(-(\alpha^o-77)1/2) \\
& -.188
\end{aligned}
$$

$$
\begin{aligned}
Cm0Z6(\alpha^o) = {} & (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/60)+(-.39/2.75)\tan^{-1}((\alpha^o-1)1/14) \\
& +(.8/2.75)\tan^{-1}((\alpha^o-5)1/42)+(.80/2.75)\tan^{-1}(-(\alpha^o-20)1/55) \\
& +(1.8/2.75)\tan^{-1}((\alpha^o-65)1/60)+(2.4/2.75)\tan^{-1}(-(\alpha^o-69)1/20) \\
& +(-.45/2.75)\tan^{-1}(-(\alpha^o-79)1/2)-.158
\end{aligned}
$$

$$
\begin{aligned}
Cm0N6(\alpha^o) = {} & (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/60)+(-.39/2.75)\tan^{-1}((\alpha^o-1)1/30) \\
& +(.8/2.75)\tan^{-1}((\alpha^o-5)1/45)+(.80/2.75)\tan^{-1}(-(\alpha^o-10)1/65) \\
& +(1.8/2.75)\tan^{-1}((\alpha^o-51)1/45)+(2.8/2.75)\tan^{-1}(-(\alpha^o-69)1/23) \\
& +(-.45/2.75)\tan^{-1}(-(\alpha^o-79)1/2)-.148
\end{aligned}
$$

$$
\begin{aligned}
CMQ(\alpha^o) = {} & (-.82/\pi)\tan^{-1}(-(\alpha^o-5)2\pi/18)+(2)\tan^{-1}(-(\alpha^o-32)1/6) \\
& +(4.55)\tan^{-1}((\alpha^o-43)3.5/1)+(-3.5)\tan^{-1}((\alpha^o-57)1/5)-5.8
\end{aligned}
$$

$$
\begin{aligned}
CMAD(\alpha^o) = {} & (-.02/\pi)\tan^{-1}(-(\alpha^o-1)5\pi/18)+(.5)\tan^{-1}((\alpha^o-6)5/1) \\
& +(-.8)\tan^{-1}((\alpha^o-18)1/2)+(0.9)\tan^{-1}((\alpha^o-45)1/2)-.9
\end{aligned}
$$

Table 5.3b Formulas for C_m Model at 0.8 Mach

$$Cm0X8(\alpha^o) = (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/15)+(-.33/2.75)\tan^{-1}((\alpha^o-1)1/7) +(.72/2.75)\tan^{-1}((\alpha^o-5)1/15)+(.70/2.75)\tan^{-1}(-(\alpha^o-35)1/75) +(1.13/2.75)\tan^{-1}((\alpha^o-51)1/11)+(2.08/2.75)\tan^{-1}(-(\alpha^o-67)1/17) +(-.45/2.75)\tan^{-1}(-(\alpha^o-78)1/4)-.440$$

$$Cm0X58(\alpha^o) = (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/10)+(-.39/2.75)\tan^{-1}((\alpha^o-1)1/12) +(.7/2.75)\tan^{-1}((\alpha^o-5)1/15)+(.85/2.75)\tan^{-1}(-(\alpha^o-20)1/40) +(1.45/2.75)\tan^{-1}((\alpha^o-52)1/15)+(2.2/2.75)\tan^{-1}(-(\alpha^o-69)1/15) +(-.45/2.75)\tan^{-1}(-(\alpha^o-77)1/3.4)-.338$$

$$Cm0X28(\alpha^o) = (.36/2.75)\tan^{-1}(-(\alpha^o-5)1/35)+(-.29/2.75)\tan^{-1}((\alpha^o-1)1/30) +(1/2.75)\tan^{-1}((\alpha^o-15)1/90)+(.75/2.75)\tan^{-1}(-(\alpha^o-48)1/110) +(.9/2.75)\tan^{-1}((\alpha^o-52)1/9)+(2.1/2.75)\tan^{-1}(-(\alpha^o-69)1/17) +(-.45/2.75)\tan^{-1}(-(\alpha^o-77)1/3)-.387$$

$$Cm0X08(\alpha^o) = (.36/2.75)\tan^{-1}(-(\alpha^o-5)1/35)+(-.29/2.75)\tan^{-1}((\alpha^o-1)1/30) +(1/2.75)\tan^{-1}((\alpha^o-15)1/90)+(.80/2.75)\tan^{-1}(-(\alpha^o-48)1/90) +(.9/2.75)\tan^{-1}((\alpha^o-52)1/9)+(2.1/2.75)\tan^{-1}(-(\alpha^o-69)1/17) +(-.45/2.75)\tan^{-1}(-(\alpha^o-77)1/3)-.387$$

$$Cm0N58(\alpha^o) = (.36/2.75)\tan^{-1}(-(\alpha^o-5)1/35)+(-.29/2.75)\tan^{-1}((\alpha^o-1)1/30) +(1.3/2.75)\tan^{-1}((\alpha^o-15)1/95)+(.80/2.75)\tan^{-1}(-(\alpha^o-47)1/35) +(1/2.75)\tan^{-1}((\alpha^o-53)1/10)+(2.15/2.75)\tan^{-1}(-(\alpha^o-69)1/18) +(-.45/2.75)\tan^{-1}(-(\alpha^o-78)1/2)-.367$$

$$Cm0NZ8(\alpha^o) = (.36/2.75)\tan^{-1}(-(\alpha^o-5)1/35)+(-.29/2.75)\tan^{-1}((\alpha^o-1)1/30) +(1.25/2.75)\tan^{-1}((\alpha^o-15)1/95)+(.80/2.75)\tan^{-1}(-(\alpha^o-47)1/28) +(1/2.75)\tan^{-1}((\alpha^o-53)1/10)+(2.25/2.75)\tan^{-1}(-(\alpha^o-69)1/18) +(-.45/2.75)\tan^{-1}(-(\alpha^o-78)1/2)-.317$$

$$Cm0N8(\alpha^o) = (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/40)+(-.45/2.75)\tan^{-1}((\alpha^o-4)1/30) +(.7/2.75)\tan^{-1}((\alpha^o-2)1/40)+(.80/2.75)\tan^{-1}(-(\alpha^o-37)1/25) +(1.9/2.75)\tan^{-1}((\alpha^o-52)1/25)+(2.7/2.75)\tan^{-1}(-(\alpha^o-69)1/20) +(-.45/2.75)\tan^{-1}(-(\alpha^o-79)1/2)-.198$$

Table 5.3c Formulas for C_m Model at 0.9 Mach

$$\begin{aligned} Cm0X9(\alpha^o) = {} & (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/10)+(-.39/2.75)\tan^{-1}((\alpha^o-0)1/10) \\ & +(1/2.75)\tan^{-1}((\alpha^o-3)1/25)+(.70/2.75)\tan^{-1}(-(\alpha^o-7)1/25) \\ & +(1.3/2.75)\tan^{-1}((\alpha^o-50)1/16)+(2.1/2.75)\tan^{-1}(-(\alpha^o-69)1/15) \\ & +(-.45/2.75)\tan^{-1}(-(\alpha^o-76)1/3.5)-.433 \end{aligned}$$

$$\begin{aligned} Cm0X59(\alpha^o) = {} & (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/4)+(-.39/2.75)\tan^{-1}((\alpha^o+2)1/5) \\ & +(1/2.75)\tan^{-1}((\alpha^o-1)1/15)+(.60/2.75)\tan^{-1}(-(\alpha^o-18)1/13) \\ & +(1.3/2.75)\tan^{-1}((\alpha^o-51)1/14)+(2.15/2.75)\tan^{-1}(-(\alpha^o-69)1/15) \\ & +(-.45/2.75)\tan^{-1}(-(\alpha^o-76)1/3.5)-.490 \end{aligned}$$

$$\begin{aligned} Cm0X29(\alpha^o) = {} & (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/10)+(-.39/2.75)\tan^{-1}((\alpha^o+4)1/7) \\ & +(1.33/2.75)\tan^{-1}((\alpha^o-1)1/40)+(.60/2.75)\tan^{-1}(-(\alpha^o-19)1/17) \\ & +(1.9/2.75)\tan^{-1}((\alpha^o-51)1/9)+(2.05/2.75)\tan^{-1}(-(\alpha^o-69)1/15) \\ & +(-.45/2.75)\tan^{-1}(-(\alpha^o-76)1/3.5)-.450 \end{aligned}$$

$$\begin{aligned} Cm0X09(\alpha^o) = {} & (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/10)+(-.39/2.75)\tan^{-1}((\alpha^o+2)1/10) \\ & +(1.3/2.75)\tan^{-1}((\alpha^o-1)1/40)+(.60/2.75)\tan^{-1}(-(\alpha^o-19)1/15) \\ & +(.9/2.75)\tan^{-1}((\alpha^o-51)1/9)+(2.11/2.75)\tan^{-1}(-(\alpha^o-69)1/15) \\ & +(-.45/2.75)\tan^{-1}(-(\alpha^o-76)1/3.5)-.490 \end{aligned}$$

$$\begin{aligned} Cm0N59(\alpha^o) = {} & (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/11)+(-.39/2.75)\tan^{-1}((\alpha^o+2)1/10) \\ & +(1.5/2.75)\tan^{-1}((\alpha^o-1)1.1/48)+(.60/2.75)\tan^{-1}(-(\alpha^o-19)1/15) \\ & +(.8/2.75)\tan^{-1}((\alpha^o-51)1/10)+(2.32/2.75)\tan^{-1}(-(\alpha^o-70)1/20) \\ & +(-.45/2.75)\tan^{-1}(-(\alpha^o-78)1/3.5)-.490 \end{aligned}$$

$$\begin{aligned} Cm0NZ9(\alpha^o) = {} & (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/7)+(-.39/2.75)\tan^{-1}((\alpha^o-0)1/10) \\ & +(1.6/2.75)\tan^{-1}((\alpha^o-5)1/50)+(.60/2.75)\tan^{-1}(-(\alpha^o-32)1/11) \\ & +(.8/2.75)\tan^{-1}((\alpha^o-51)1/11)+(2.23/2.75)\tan^{-1}(-(\alpha^o-69)1/19) \\ & +(-.45/2.75)\tan^{-1}(-(\alpha^o-78)1/3.5)-.410 \end{aligned}$$

$$\begin{aligned} Cm0N9(\alpha^o) = {} & (.16/2.75)\tan^{-1}(-(\alpha^o-5)1/40)+(-.39/2.75)\tan^{-1}((\alpha^o-3)1/8) \\ & +(1.2/2.75)\tan^{-1}((\alpha^o-15)1/120)+(.70/2.75)\tan^{-1}(-(\alpha^o-25)1/50) \\ & +(2/2.75)\tan^{-1}((\alpha^o-52)1/75)+(2/2.75)\tan^{-1}(-(\alpha^o-69)1/20) \\ & +(-.42/2.75)\tan^{-1}(-(\alpha^o-79)1/4)-.068 \end{aligned}$$

Table 5.3d Formulas for C_m Model at 0.3 Mach

$$Cm0X3(\alpha^o) = (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/10)+(-.39/2.75)\tan^{-1}((\alpha^o-1)1/8) +(.75/2.75)\tan^{-1}((\alpha^o-5)1/13)+(.70/2.75)\tan^{-1}(-(\alpha^o-10)1/65) +(1.2/2.75)\tan^{-1}((\alpha^o-49)1/15)+(2.1/2.75)\tan^{-1}(-(\alpha^o-69)1/15) +(-.45/2.75)\tan^{-1}(-(\alpha^o-77)1/2)-.398$$

$$Cm0NZ3(\alpha^o) = (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/60)+(-.39/2.75)\tan^{-1}((\alpha^o-1)1/14) +(.85/2.75)\tan^{-1}((\alpha^o-5)1/42)+(.80/2.75)\tan^{-1}(-(\alpha^o-50)1/60) +(1.8/2.75)\tan^{-1}((\alpha^o-70)1/54)+(2.4/2.75)\tan^{-1}(-(\alpha^o-69)1/25) +(-.45/2.75)\tan^{-1}(-(\alpha^o-79)1/2)-.158$$

$$Cm0N3(\alpha^o) = (.26/2.75)\tan^{-1}(-(\alpha^o-5)1/60)+(-.39/2.75)\tan^{-1}((\alpha^o-1)1/30) +(.8/2.75)\tan^{-1}((\alpha^o-5)1/45)+(.80/2.75)\tan^{-1}(-(\alpha^o-10)1/65) +(1.8/2.75)\tan^{-1}((\alpha^o-49)1/40)+(2.8/2.75)\tan^{-1}(-(\alpha^o-69)1/23) +(-.45/2.75)\tan^{-1}(-(\alpha^o-79)1/2)-.138$$

$$Cm0N53(\alpha^o) = Cm0N56(\alpha^o)$$

$$Cm0X03(\alpha^o) = Cm006(\alpha^o)$$

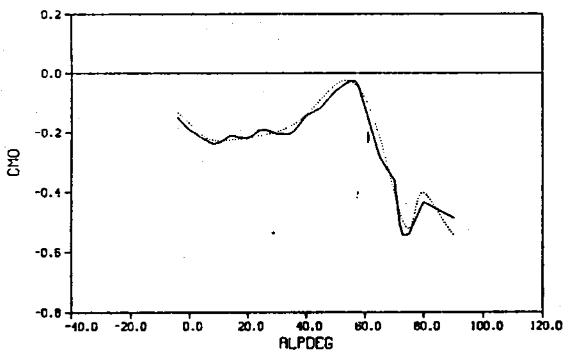
$$Cm0X23(\alpha^o) = Cm0X26(\alpha^o)$$

$$Cm0X53(\alpha^o) = Cm0X56(\alpha^o)$$

Analytical Model of C_m

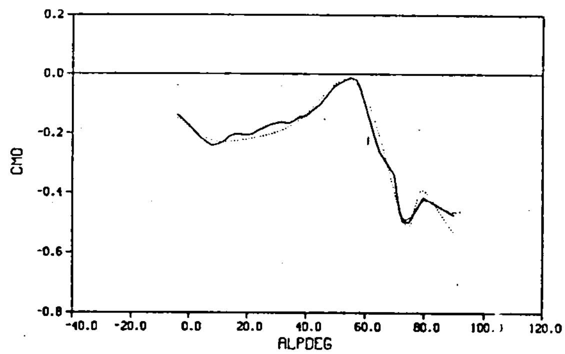
________ Wind-Tunnel ....Analytical

CM0X3(α)



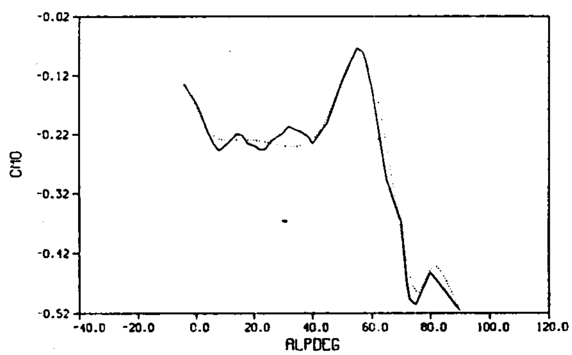
M=0.3

CM0X6(α)



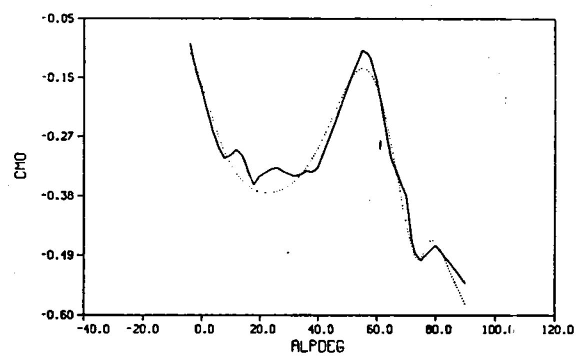
M=0.6

CM0X8(α)



M=0.8

CM0X9(α)



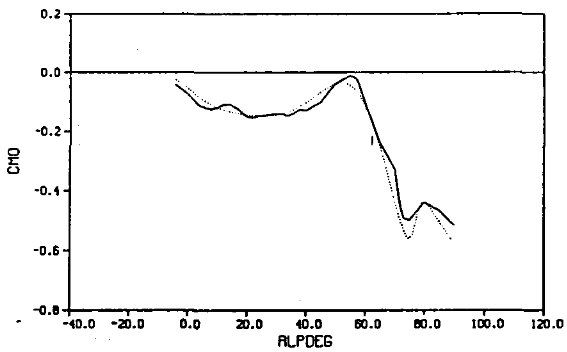
M=0.9

Figure 5.1: Comparison of Wind-Tunnel and Analytical Pitching Moment Coefficient C_{m_0} for h=15,000 feet and δh=10.5°.

Analytical Model of C_m

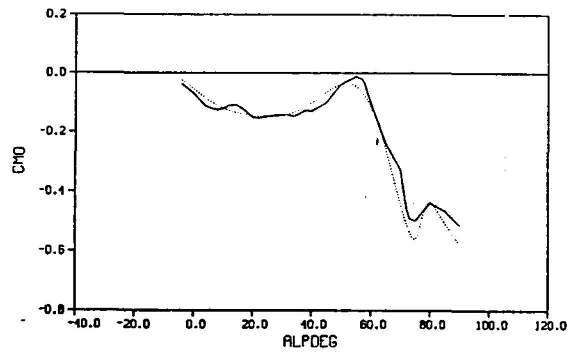
_________ Wind-Tunnel ....Analytical

CM0X56(α)



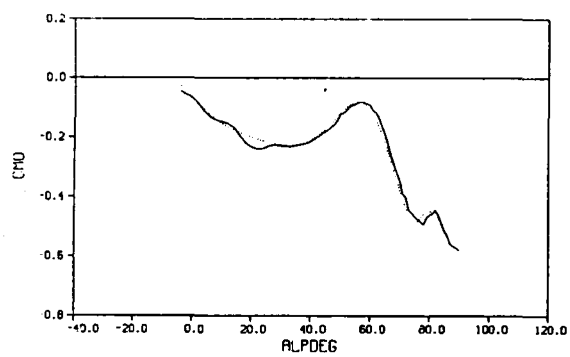
M=0.3

CM0X56(α)



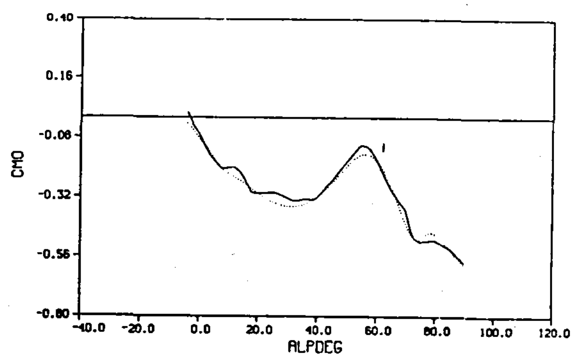
M=0.6

CM0X58(α)



M=0.8

CM0X59(α)



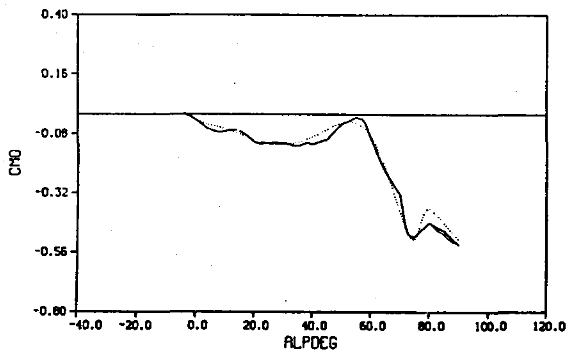
M=0.9

Figure 5.2: Comparison of Wind-Tunnel and Analytical Pitching Moment Coefficient C_{m_0} for h=15,000 feet and $\delta h=5^{o}$.

Analytical Model of C_m

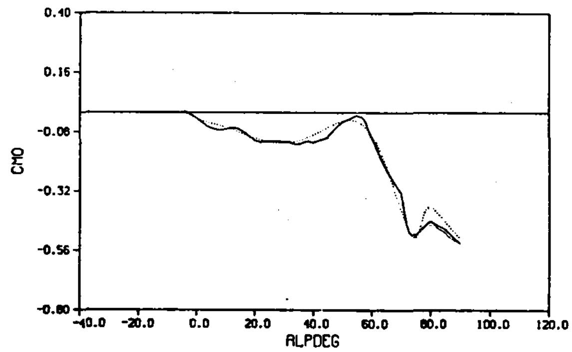
__________ Wind-Tunnel ....Analytical

CM0X26(α)



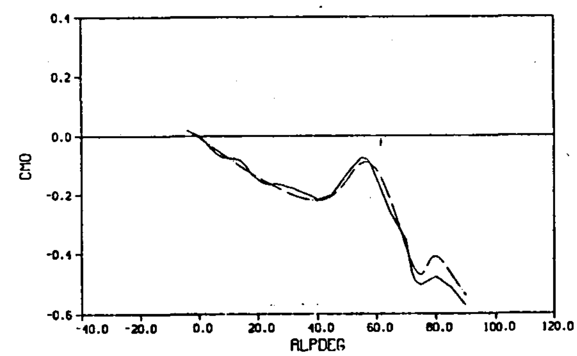
M=0.3

CM0X26(α)



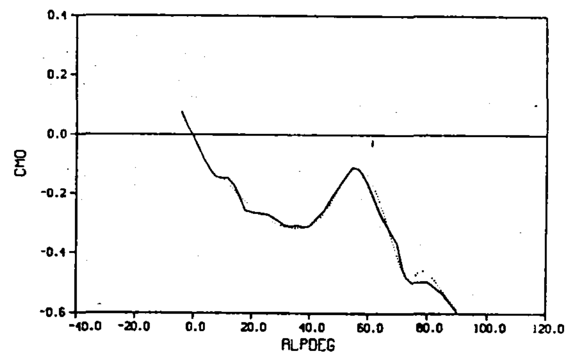
M=0.6

CM0X28(α)



M=0.8

CM0X29(α)



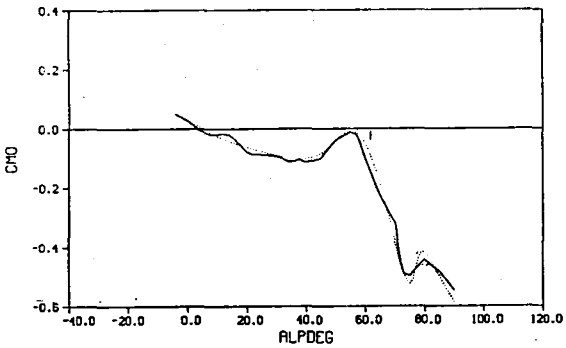
M=0.9

Figure 5.3: Comparison of Wind-Tunnel and Analytical Pitching Moment Coefficient C_{m_0} for h=15,000 feet and $\delta h=2^{o}$.

Analytical Model of C_m

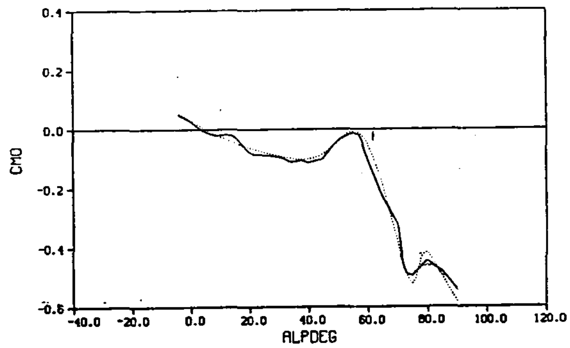
_________ Wind-Tunnel .... Analytical

CM006(α)



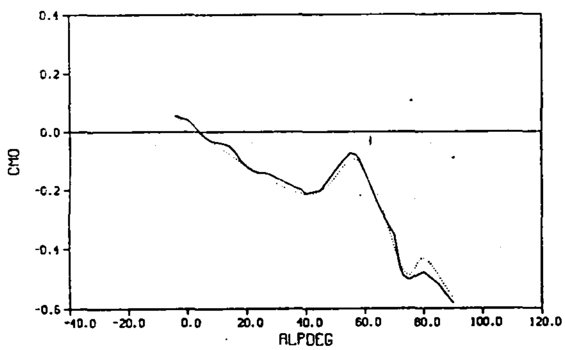
M=0.3

CM006(α)



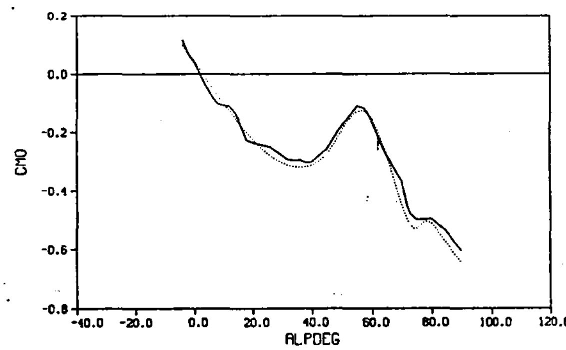
M=0.6

CM0X08(α)



M=0.8

CM0X09(α)



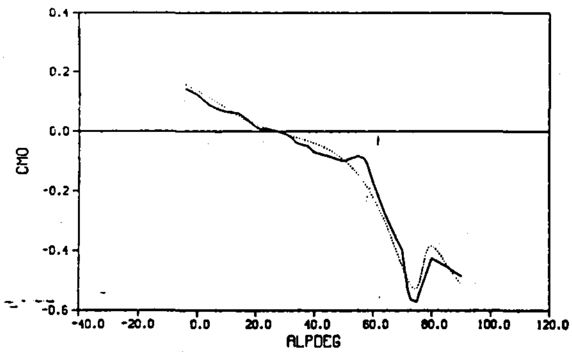
M=0.9

Figure 5.4: Comparison of Wind-Tunnel and Analytical Pitching Moment Coefficient C_{m_0} for h=15,000 feet and δh=0°.

Analytical Model of C_m

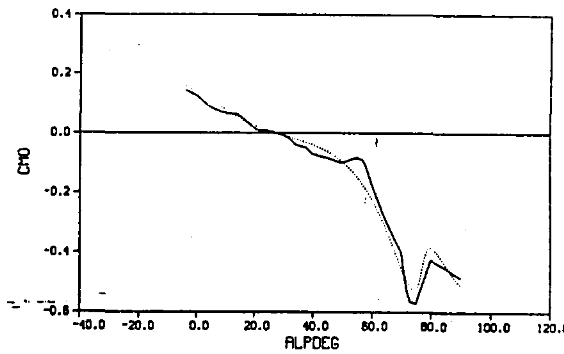
________ Wind-Tunnel ....Analytical

CM0N56(α)



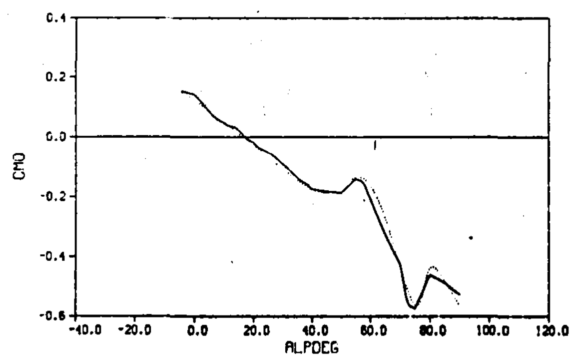
M=0.3

CM0N56(α)



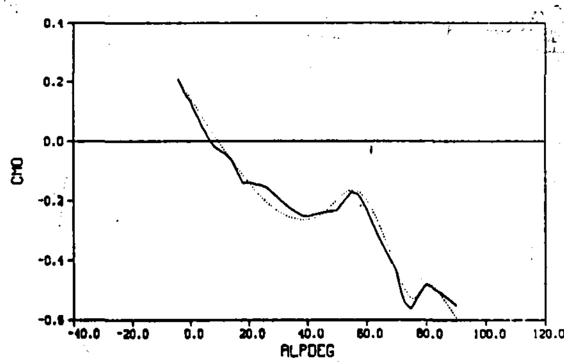
M=0.6

CM0N58(α)



M=0.8

CM0N59(α)



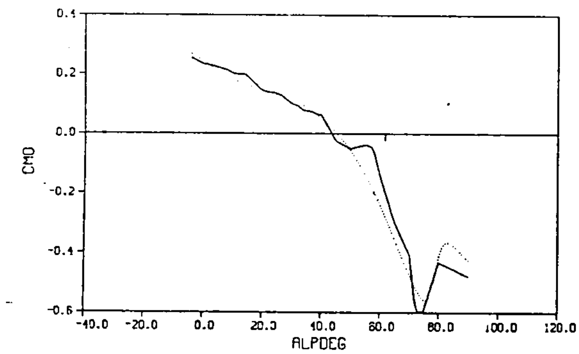
M=0.9

Figure 5.5: Comparison of Wind-Tunnel and Analytical Pitching Moment Coefficient C_{m_0} for h=15,000 feet and δh=-5°.

Analytical Model of C_m

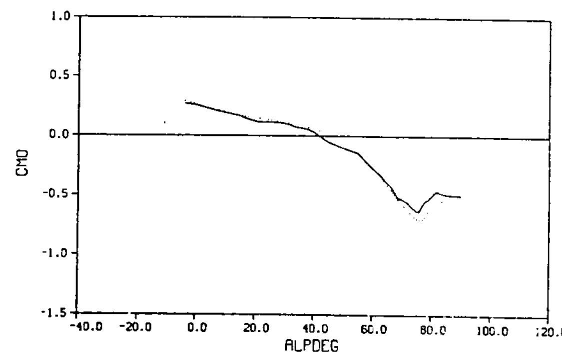
_________ Wind-Tunnel ………Analytical

CM0NZ3(α)



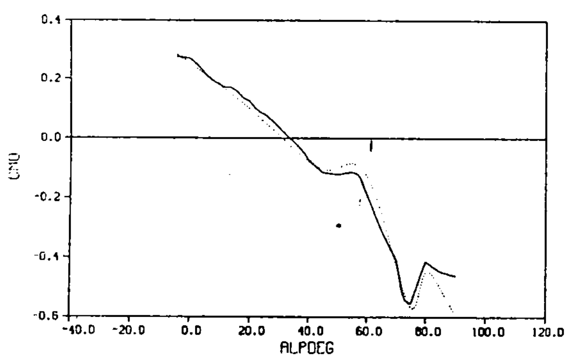
M=0.3

CM0Z6(α)



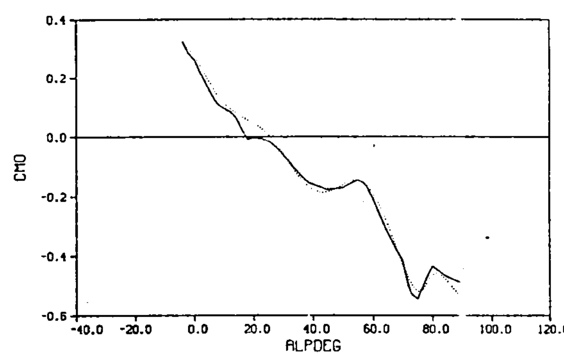
M=0.6

CM0NZ8(α)



M=0.8

CM0NZ9(α)



M=0.9

Figure 5.6: Comparison of Wind-Tunnel and Analytical Pitching Moment Coefficient C_{m_C} for h=15,000 feet and δh=-12.5°.

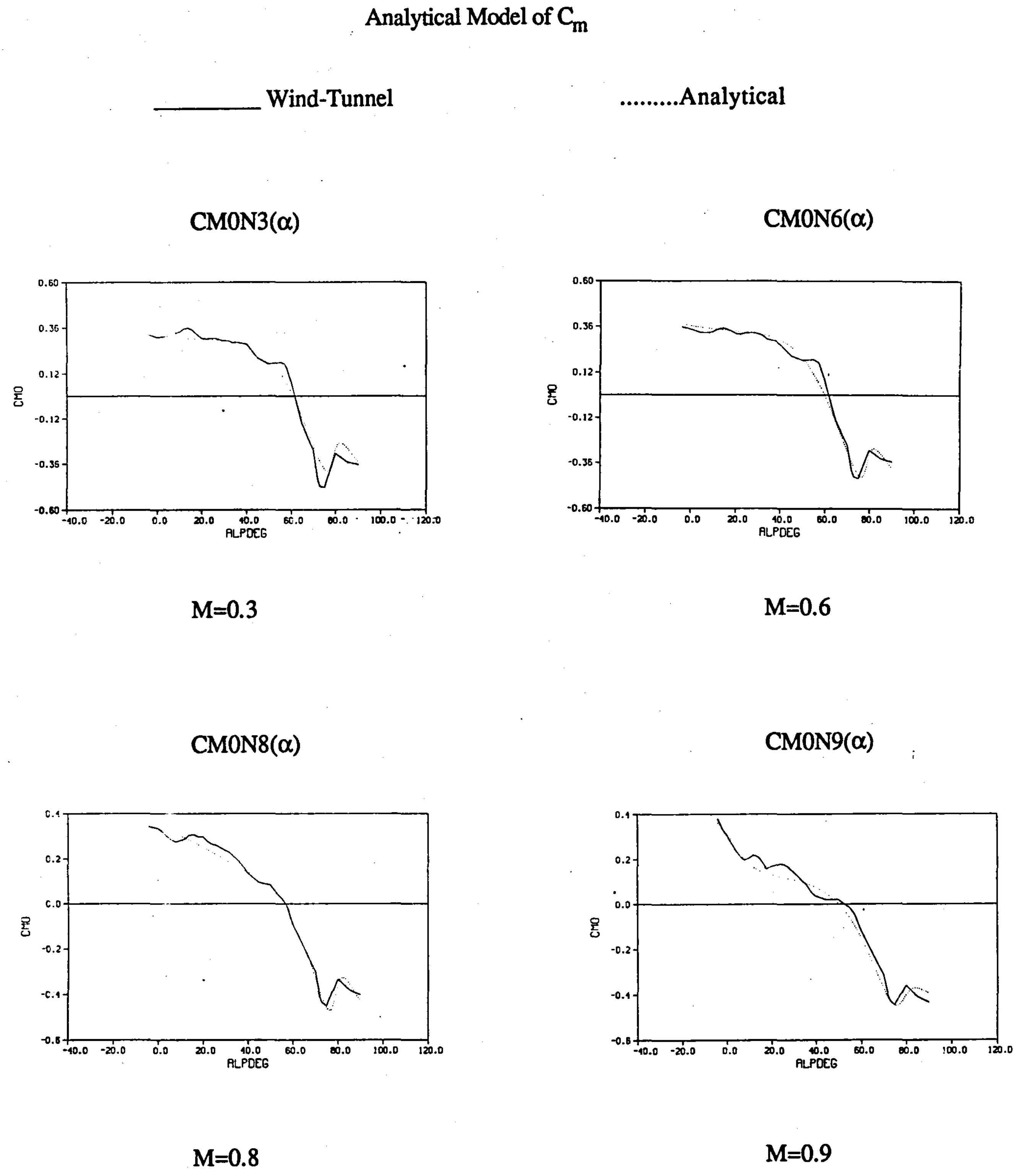
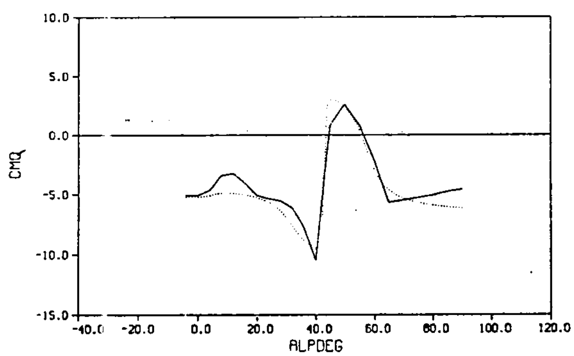


Figure 5.7: Comparison of Wind-Tunnel and Analytical Pitching Moment Coefficient C_{m_0} for h=15,000 feet and δh=-24°.

Analytical Model of C_m

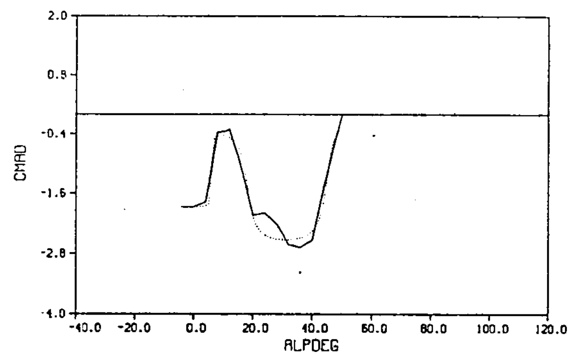
_________ Wind-Tunnel ………Analytical

CMQ(α)



h= 15,000 feet, M=0.6

CMAD(α)



h= 15,000 feet, M=0.6

Figure 5.8: Comparison of Wind-Tunnel and Analytical Lift Coefficient Derivatives C_{m_q} and $C_{m_{\alpha dot}}$ for h=15,000 feet and M=0.6.

6. Analytical Model for Side Force Coefficient

The analytical model of the side force coefficient C_y is taken from the wind-tunnel model at an altitude h=15,000 feet and a Mach number M=0.6. The analytical model for C_{y0} is constructed at $\beta = 0^o, 20^o$; $\delta a = \mp 25^o$; and $\delta r = \mp 30^o$. The analytical models are functions of α from 0^o to 90^o; they are defined in Tables 6.1 and 6.2. The analytical formulae are presented in Table 6.3. Comparisons of the analytical models with the corresponding wind-tunnel model data are shown in Figures 6.1 to 6.3. The sideslip derivative C_{y_β} is taken as the constant .000206. The roll and yaw rate derivatives C_{y_p} and C_{y_r} are given in Figure 6.3. The analytical models are also given in the computer code listing contained in Appendix C.

Table 6.1 Definitions of C_y Analytical Models

$C_{y_0}(\alpha, \beta=20^o, M=0.6, \delta a= 25^o, \delta r=-30^o, h=15{,}000 \text{ ft}) = Cy0XNB2(\alpha)$
$C_{y_0}(\alpha, \beta=20^o, M=0.6, \delta a= 25^o, \delta r= 30^o, h=15{,}000 \text{ ft}) = Cy0XXB2(\alpha)$
$C_{y_0}(\alpha, \beta=20^o, M=0.6, \delta a=-25^o, \delta r=-30^o, h=15{,}000 \text{ ft}) = Cy0NNB2(\alpha)$
$C_{y_0}(\alpha, \beta=20^o, M=0.6, \delta a=-25^o, \delta r= 30^o, h=15{,}000 \text{ ft}) = Cy0NXB2(\alpha)$
$C_{y_0}(\alpha, \beta=0^o, M=0.6, \delta a= 25^o, \delta r=-30^o, h=15{,}000 \text{ ft}) = Cy0XNB0(\alpha)$
$C_{y_0}(\alpha, \beta=0^o, M=0.6, \delta a= 25^o, \delta r= 30^o, h=15{,}000 \text{ ft}) = Cy0XXB0(\alpha)$
$C_{y_p}(\alpha, M=0.6, h=15{,}000 \text{ ft}) = CYP(\alpha)$
$C_{y_r}(\alpha, M=0.6, h=15{,}000 \text{ ft}) = CYR(\alpha)$
$C_{y_\beta}(M=0.6, h=15{,}000 \text{ ft}) = CYB(\alpha)$

Table 6.2 Side Force Coefficient Analytical Models: M = 0.6

Sideslip	Aileron \ Rudder	δr = -30	δr = 30
β = 20	δa = 25	Cy0XNB2(α)	Cy0XXB2(α)
	δa = -25	Cy0NNB2(α)	Cy0NXB2(α)
β = 0	δa = 25	Cy0XNB0(α)	Cy0XXB0(α)
	δa = -25	-Cy0XXB0(α)	-Cy0XNB0(α)

Table 6.3 Formulas for C_y Model

$$Cy0XNB2(\alpha^o) = (.232/\pi)\tan^{-1}((\alpha^o-16)11\pi/18) - .394$$

$$\begin{aligned}Cy0XXB2(\alpha^o) = {} & (.06/\pi)\tan^{-1}(\alpha^o/3) \\ & +(.09/\pi)\tan^{-1}((\alpha^o-31)5/8) \\ & + (.06/\pi)\tan^{-1}(-(\alpha^o-46)3/10) \\ & +(.03/\pi)\tan^{-1}((\alpha^o-63)3/7) \\ & +(.09/\pi)\tan^{-1}(-(\alpha^o-75)3/5) \\ & +(.04/\pi)\tan^{-1}((\alpha^o-85)4/5) - .285\end{aligned}$$

$$\begin{aligned}Cy0NNB2(\alpha^o) = {} & (.219544/\pi)\tan^{-1}((\alpha^o-21)5/56) \\ & +(.0636375/\pi)\tan^{-1}(-(\alpha^o-74)1/4) \\ & + (.0709125/\pi)\tan^{-1}((\alpha^o-85)3/10) - .36444\end{aligned}$$

$$\begin{aligned}Cy0NXB2(\alpha^o) = {} & (.047/\pi)\tan^{-1}(\alpha^o/2) \\ & +(.021/\pi)\tan^{-1}(-(\alpha^o-17)5/4) \\ & + (.037/\pi)\tan^{-1}((\alpha^o-32)5/3) \\ & +(.06/\pi)\tan^{-1}(-(\alpha^o-76)5/4) \\ & +(.043/\pi)\tan^{-1}(\alpha^o-85) - .248\end{aligned}$$

$$\begin{aligned}Cy0XNB0(\alpha^o) = {} & (.029624)\tan^{-1}((\alpha^o-20)4/25) \\ & +(-.0020868)\tan^{-1}(-(\alpha^o-12)5) \\ & +(6.99)\exp(-(\alpha^o+17.6)) - .075535\end{aligned}$$

$$\begin{aligned}Cy0XXB0(\alpha^o) = {} & (.01216/2.75)\tan^{-1}(\alpha^o 3/4) \\ & +(.03247/2.75)\tan^{-1}(-(\alpha^o-13)1/4) \\ & +(.00891/2.75)\tan^{-1}((\alpha^o-29.5)2/3) \\ & +(.03058/2.75)\tan^{-1}(-(\alpha^o-46)2/5) \\ & +(.02759/2.75)\tan^{-1}(-(\alpha^o-75)3/40) + .03477\end{aligned}$$

$$Cy0NXB0(\alpha^o) = - Cy0XNB0(\alpha^o)$$

$$Cy0NNB0(\alpha^o) = - Cy0XXB0(\alpha^o)$$

$$\begin{aligned}CYP(\alpha^o) = {} & (.086/\pi)\tan^{-1}(\alpha^o 10\pi/18) \\ & +(.096/\pi)\tan^{-1}(-(\alpha^o-23)10\pi/18) \\ & + (.22/\pi)\tan^{-1}(-(\alpha^o-45)10\pi/18) \\ & +(.256/\pi)\tan^{-1}((\alpha^o-54)10\pi/18) - .047\end{aligned}$$

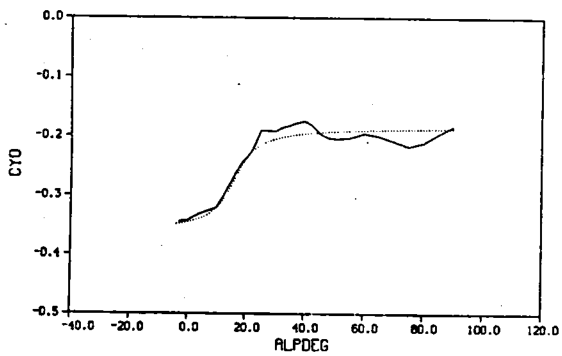
$$\begin{aligned}CYR(\alpha^o) = {} & (.17/\pi)\tan^{-1}((\alpha^o-4)10\pi/18) \\ & +(.55/\pi)\tan^{-1}(-(\alpha^o-20)10\pi/18) \\ & + (.54/\pi)\tan^{-1}((\alpha^o-45)10\pi/18) \\ & +(.26/\pi)\tan^{-1}(-(\alpha^o-61)10\pi/18) \\ & +.07\end{aligned}$$

$$CYB(\alpha^o) = .000206$$

Analytical Model of C_y

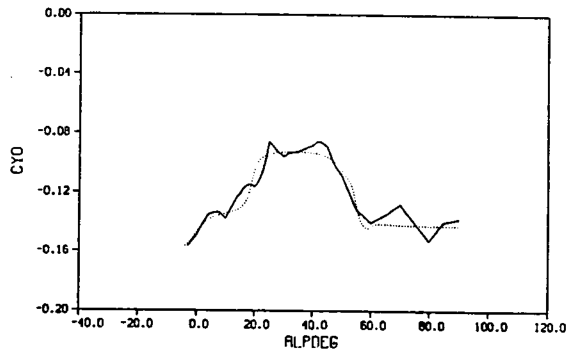
________ Wind-Tunnel ....Analytical

CY0XNB2(α)



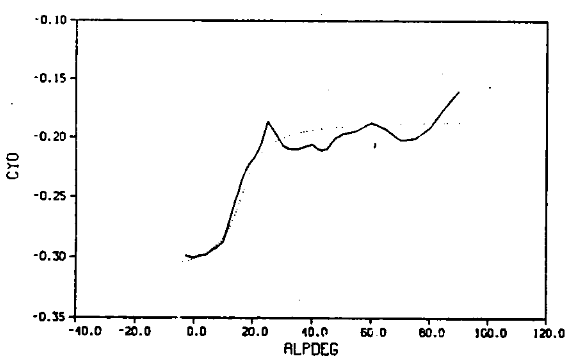
δa= 25°, δr= -30°

CY0XXB2(α)



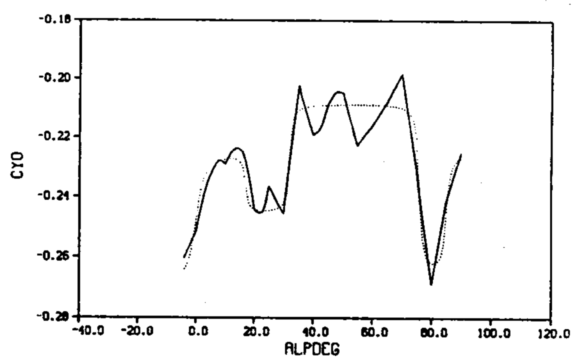
δa= 25°, δr= 30°

CY0NNB2(α)



δa= -25°, δr= -30°

CY0NXB2(α)



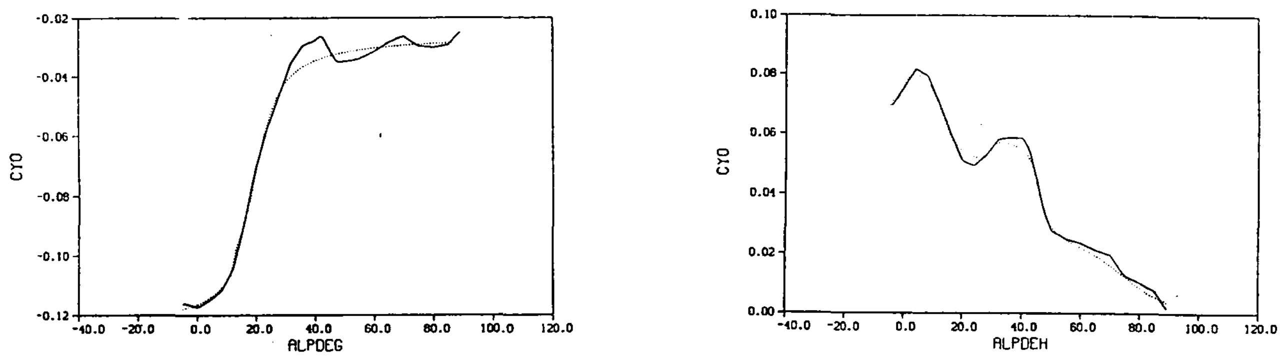
δa= -25°, δr= 30°

Figure 6.1: Comparison of Wind-Tunnel and Analytical Side Force Coefficient C_{y_0} for h=15,000 feet: $\beta=20^o$ and M=0.6.

Analytical Model of C_y

_________ Wind-Tunnel ....Analytical

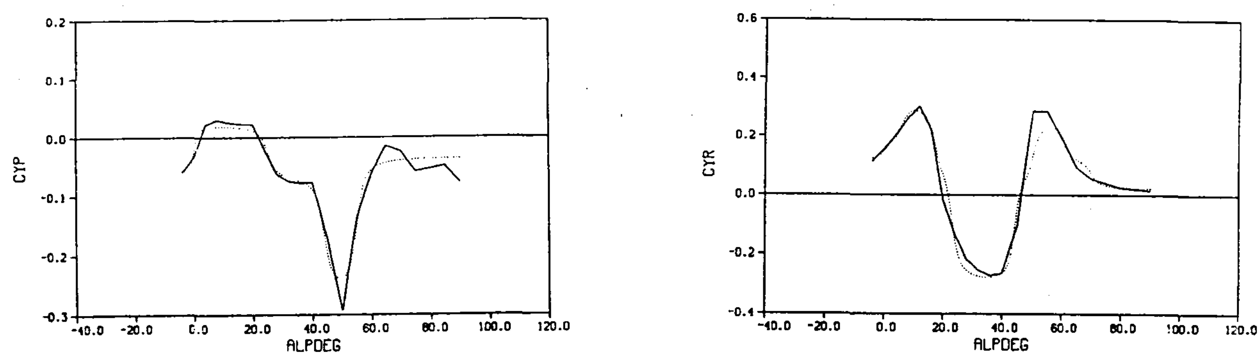
CY0XNB0(α) CY0XXB0(α)



δa= 25°, δr= -30° δa= 25°, δr= 30°

Figure 6.2: Comparison of Wind-Tunnel and Analytical Side Force Coefficient C_{y_0} for h=15,000 feet: β=0° and M=0.6.

$C_{y_p}(\alpha)$ $C_{y_r}(\alpha)$



h= 15,000 feet, M=0.6 h= 15,000 feet, M=0.6

Figure 6.3: Comparison of Wind-Tunnel and Analytical Side Force Coefficient Derivatives C_{y_p} and C_{y_r} for h=15,000 feet and M=0.6.

7. Analytical Model for Rolling Moment Coefficient

The analytical model of the rolling moment coefficient C_ℓ is taken from the wind-tunnel model at an altitude h=15,000 feet and Mach numbers M=0.6 and 0.9. The analytical model for C_{ℓ_0} is constructed at $\beta = 0^o, 20^o$; $\delta a = \mp 25^o$; and $\delta r = \mp 30^o$. The analytical models are functions of α from 0^o to 90^o; they are defined in Tables 7.1 a,b and 7.2 a,b. The analytical formulae are presented in Tables 7.3 a,b. Comparisons of the analytical models with the corresponding wind-tunnel model data are shown in Figures 7.1 to 7.4. The roll and yaw rate derivatives C_{ℓ_p} and C_{ℓ_r} and the sideslip derivative C_{ℓ_β} are given in Figure 7.4. The analytical models are also given in the computer code listing contained in Appendix C.

Table 7.1a Definitions of C_ℓ Analytical Models at 0.6 Mach

$C_{\ell_0}(\alpha, \beta=20^o, M=0.6, \delta a= 25^o, \delta r=-30^o, h=15{,}000\ ft)$	= Cℓ0XNB2(α)
$C_{\ell_0}(\alpha, \beta=20^o, M=0.6, \delta a= 25^o, \delta r= 30^o, h=15{,}000\ ft)$	= Cℓ0XXB2(α)
$C_{\ell_0}(\alpha, \beta=20^o, M=0.6, \delta a=-25^o, \delta r=-30^o, h=15{,}000\ ft)$	= Cℓ0NNB2(α)
$C_{\ell_0}(\alpha, \beta=20^o, M=0.6, \delta a=-25^o, \delta r= 30^o, h=15{,}000\ ft)$	= Cℓ0NXB2(α)
$C_{\ell_0}(\alpha, \beta=0^o, M=0.6, \delta a= 25^o, \delta r=-30^o, h=15{,}000\ ft)$	= Cℓ0XNB0(α)
$C_{\ell_0}(\alpha, \beta=0^o, M=0.6, \delta a= 25^o, \delta r= 30^o, h=15{,}000\ ft)$	= Cℓ0XXB0(α)
$C_{\ell_p}(\alpha, M=0.6, h=15{,}000\ ft)$	= LCℓP(α)
$C_{\ell_r}(\alpha, M=0.6, h=15{,}000\ ft)$	= CℓR(α)
$C_{\ell_\beta}(M=0.6, h=15{,}000\ ft)$	= CℓB(α)

Table 7.1b Definitions of C_ℓ Analytical Models at 0.9 Mach

$C_{\ell_0}(\alpha, \beta=20^o, M=0.9, \delta a= 25^o, \delta r=-30^o, h=15{,}000\ ft)$	= Cℓ0XN2(α)
$C_{\ell_0}(\alpha, \beta=20^o, M=0.9, \delta a= 25^o, \delta r= 30^o, h=15{,}000\ ft)$	= Cℓ0XX2(α)
$C_{\ell_0}(\alpha, \beta=20^o, M=0.9, \delta a=-25^o, \delta r=-30^o, h=15{,}000\ ft)$	= Cℓ0NN2(α)
$C_{\ell_0}(\alpha, \beta=20^o, M=0.9, \delta a=-25^o, \delta r= 30^o, h=15{,}000\ ft)$	= Cℓ0NX2(α)
$C_{\ell_0}(\alpha, \beta=0^o, M=0.9, \delta a= 25^o, \delta r=-30^o, h=15{,}000\ ft)$	= Cℓ0XN0(α)
$C_{\ell_0}(\alpha, \beta=0^o, M=0.9, \delta a= 25^o, \delta r= 30^o, h=15{,}000\ ft)$	= Cℓ0XX0(α)
$C_{\ell_p}(\alpha, M=0.9, h=15{,}000\ ft)$	= HCℓP(α)

Table 7.2a Rolling Moment Coefficient Analytical Models: M = 0.6

Sideslip	Aileron \ Rudder	$\delta r = -30$	$\delta r = 30$
$\beta = 20$	$\delta a = 25$	$C\ell 0XNB2(\alpha)$	$C\ell 0XXB2(\alpha)$
	$\delta a = -25$	$C\ell 0NNB2(\alpha)$	$C\ell 0NXB2(\alpha)$
$\beta = 0$	$\delta a = 25$	$C\ell 0XNB0(\alpha)$	$C\ell 0XXB0(\alpha)$
	$\delta a = -25$	$-C\ell 0XXB0(\alpha)$	$-C\ell 0XNB0(\alpha)$

Table 7.2b Rolling Moment Coefficient Analytical Models: M = 0.9

Sideslip	Aileron \ Rudder	$\delta r = -30$	$\delta r = 30$
$\beta = 20$	$\delta a = 25$	$C\ell 0XN2(\alpha)$	$C\ell 0XX2(\alpha)$
	$\delta a = -25$	$C\ell 0NN2(\alpha)$	$C\ell 0NX2(\alpha)$
$\beta = 0$	$\delta a = 25$	$C\ell 0XN0(\alpha)$	$C\ell 0XX0(\alpha)$
	$\delta a = -25$	$-C\ell 0XX0(\alpha)$	$-C\ell 0XN0(\alpha)$

Table 7.3a Formulas for C_ℓ Model at 0.6 Mach

$$C\ell 0XNB2(\alpha^o) = (.085/2.75)\tan^{-1}(-(\alpha^o-15)8/92) - .0065$$

$$\begin{aligned} C\ell 0XXB2(\alpha^o) = & (.02771/2.75)\tan^{-1}(-(\alpha^o-2)1/5) \\ & +(.06763/2.75)\tan^{-1}(-(\alpha^o-19)1/4) \\ & +(.006/2.75)\tan^{-1}((\alpha^o-22)2/1) + .00081 \end{aligned}$$

$$\begin{aligned} C\ell 0NNB2(\alpha^o) = & (.0344/2.75)\tan^{-1}(-(\alpha^o-5)3/13) \\ & +(.037/2.75)\tan^{-1}((\alpha^o-24)2/5) \\ & +(.011/2.75)\tan^{-1}(-(\alpha^o-38)2/1) \\ & +(.012/2.75)\tan^{-1}((\alpha^o-42)7/4) \\ & +(.011/2.75)\tan^{-1}(-(\alpha^o-52)3/8) \\ & +(.0176/2.75)\tan^{-1}((\alpha^o-73)3/13) - .0553 \end{aligned}$$

$$\begin{aligned} C\ell 0NXB2(\alpha^o) = & (.0395/2.75)\tan^{-1}(-(\alpha^o-5)3/13) \\ & +(.0295/2.75)\tan^{-1}((\alpha^o-25)3/7) \\ & +(.0126/2.75)\tan^{-1}(-(\alpha^o-38)4/3) \\ & +(.0114/2.75)\tan^{-1}((\alpha^o-42)2/1) \\ & +(.0082/2.75)\tan^{-1}(-(\alpha^o-51)1/2) \\ & +(.0132/2.75)\tan^{-1}((\alpha^o-70)2/5) - .0479 \end{aligned}$$

$$\begin{aligned} C\ell 0XNB0(\alpha^o) = & (.0041/2.75)\tan^{-1}(-(\alpha^o-4)2/3) \\ & +(.003/2.75)\tan^{-1}(-(\alpha^o-20)1/3) \\ & +(.011/2.75)\tan^{-1}(-(\alpha^o-59)2/5) \\ & +(-.00144/2.75)\tan^{-1}(-(\alpha^o+1)8/1) + .01793 \end{aligned}$$

$$\begin{aligned} C\ell 0XXB0(\alpha^o) = & (.04226/2.75)\tan^{-1}(-(\alpha^o-20)2/7) \\ & +(.00831/2.75)\tan^{-1}(-(\alpha^o-53)4/7) \\ & +(.00997/2.75)\tan^{-1}((\alpha^o-65)4/5) \\ & +(.0101/2.75)\tan^{-1}(-(\alpha^o-77.5)8/15) \\ & +(-.002/\pi)\tan^{-1}(-(\alpha^o-8)10)+.0286 \end{aligned}$$

$$\begin{aligned} LC\ell P(\alpha^o) = & (.15/\pi)\tan^{-1}((\alpha^o-12)10\pi/18) \\ & +(.25/\pi)\tan^{-1}(-(\alpha^o-28)100\pi/18) \\ & +(.55/\pi)\tan^{-1}((\alpha^o-41)100\pi/18) \\ & +(.33/\pi)\tan^{-1}(-(\alpha^o-50)10\pi/18)-.341 \end{aligned}$$

$$\begin{aligned} C\ell R(\alpha^o) = & (.304/\pi)\tan^{-1}((\alpha^o-3)10\pi/18) \\ & +(.22/\pi)\tan^{-1}(-(\alpha^o-50)2\pi/18) \\ & +(-.026)\exp((\alpha^o-85)1/100)+.018 \end{aligned}$$

$$C\ell B(\alpha^o) = (.0001)[(6.32/\pi)\tan^{-1}(-(\alpha^o-13)100\pi/18) + 3.26]$$

Table 7.3b Formulas for C_ℓ Model at 0.9 Mach

$$C\ell 0XN2(\alpha^o) = (.048/2.75)\tan^{-1}(-(\alpha^o-18)8/92)$$
$$+(.030/2.75)\tan^{-1}(-(\alpha^o-23)8/92)$$
$$+(.045/2.75)\tan^{-1}((\alpha^o-80)8/92) - .0105$$

$$C\ell 0XX2(\alpha^o) = (.085/2.75)\tan^{-1}(-(\alpha^o-15)8/92) - .0198$$

$$C\ell 0NN2(\alpha^o) = -[(.0544/2.75)\tan^{-1}(-(\alpha^o-7)3/13)$$
$$+(.087/2.75)\tan^{-1}((\alpha^o-17)2/7)$$
$$+(.008/2.75)\tan^{-1}(-(\alpha^o-25)2/1)$$
$$+(.019/2.75)\tan^{-1}((\alpha^o-28)7/4)$$
$$+(.051/2.75)\tan^{-1}(-(\alpha^o-42)3/8)$$
$$+(.0096/2.75)\tan^{-1}((\alpha^o-55)3/13) - .0553](1/2.6)$$
$$- .074$$

$$C\ell 0NX2(\alpha^o) = (.0295/2.75)\tan^{-1}(-(\alpha^o-25)3/13)$$
$$+(.0295/2.75)\tan^{-1}((\alpha^o-42.5)3/7)$$
$$+(.0086/2.75)\tan^{-1}(-(\alpha^o-15)4/3)$$
$$+(.0014/2.75)\tan^{-1}((\alpha^o-42)2/1)$$
$$+(.0162/2.75)\tan^{-1}(-(\alpha^o-51)1/2)$$
$$+(.0012/2.75)\tan^{-1}((\alpha^o-70)2/5) - .0466$$

$$C\ell 0XN0(\alpha^o) = [(.0041/2.75)\tan^{-1}((\alpha^o-8)2/3)$$
$$+(.012/2.75)\tan^{-1}(-(\alpha^o-11)1/3)$$
$$+(.010/2.75)\tan^{-1}(-(\alpha^o-15)1/3)$$
$$+(.012/2.75)\tan^{-1}(-(\alpha^o-35)1/3)$$
$$+(.005/2.75)\tan^{-1}(-(\alpha^o-100)2/5)$$
$$+(-.00144/2.75)\tan^{-1}(-(\alpha^o-2)8) + .01793](1/2)$$
$$- .0032$$

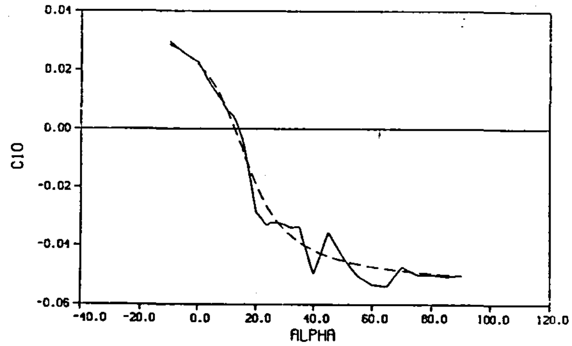
$$C\ell 0XX0(\alpha^o) = [(.04226/2.75)\tan^{-1}(-(\alpha^o-8.5)2/7)$$
$$+(.01031/2.75)\tan^{-1}(-(\alpha^o-35)4/7)$$
$$+(.00997/2.75)\tan^{-1}((\alpha^o-65)4/5)$$
$$+(.0131/2.75)\tan^{-1}(-(\alpha^o-77.5)8/15)$$
$$+(-.002/\pi)\tan^{-1}(-(\alpha^o-8)10) + .0286](1/1.8)$$

$$HC\ell P(\alpha^o) = (.28/\pi)\tan^{-1}((\alpha^o-10)10\pi/18)$$
$$+(.25/\pi)\tan^{-1}(-(\alpha^o-41)100\pi/18)$$
$$+(.55/\pi)\tan^{-1}((\alpha^o-41)100\pi/18)$$
$$+(.33/\pi)\tan^{-1}(-(\alpha^o-50)10\pi/18) - .471$$

Analytical Model of C_ℓ

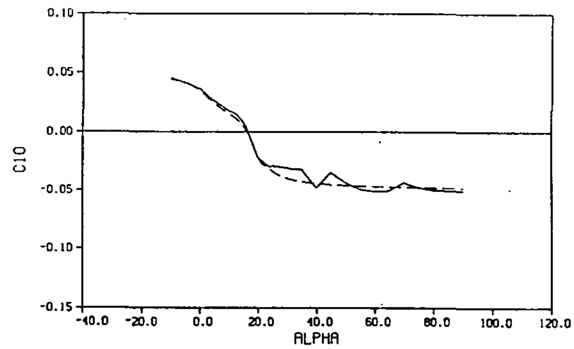
_________ Wind-Tunnel ………Analytical

$C\ell 0XNB2(\alpha)$



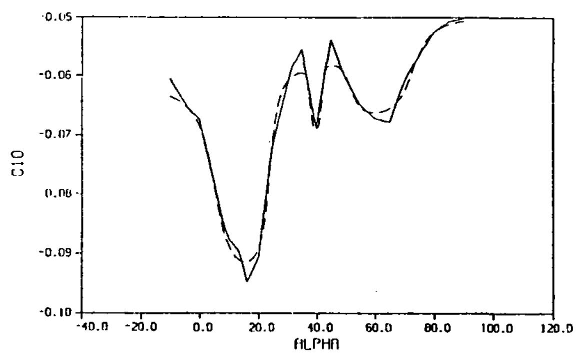
$\delta a = 25^o$, $\delta r = -30^o$

$C\ell 0XXB2(\alpha)$



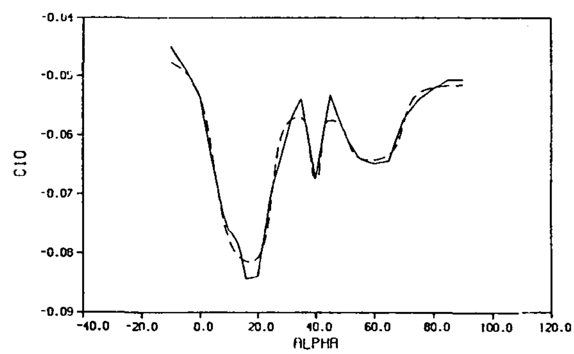
$\delta a = 25^o$, $\delta r = 30^o$

$C\ell 0NNB2(\alpha)$



$\delta a = -25^o$, $\delta r = -30^o$

$C\ell 0NXB2(\alpha)$



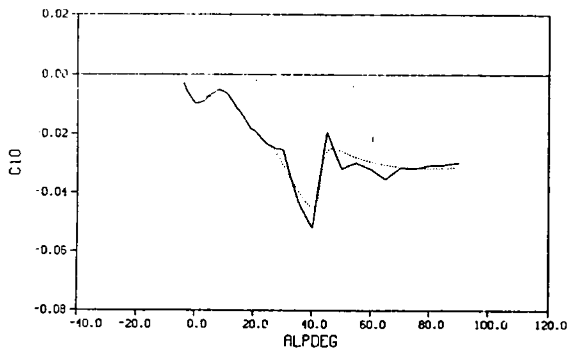
$\delta a = -25^o$, $\delta r = 30^o$

Figure 7.1: Comparison of Wind-Tunnel and Analytical Rolling Moment Coefficient C_{ℓ_0} for h=15,000 feet , M=0.6 and $\beta = 20^o$.

Analytical Model of C_ℓ

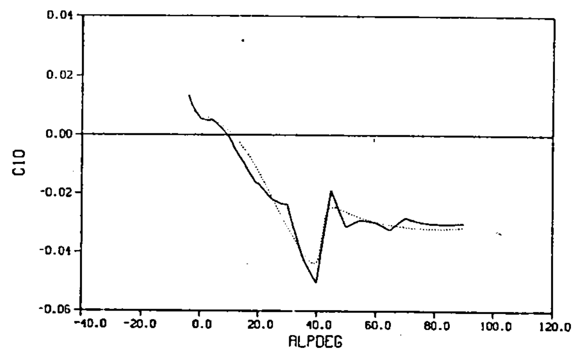
________ Wind-Tunnel .... Analytical

$C\ell 0XN2(\alpha)$



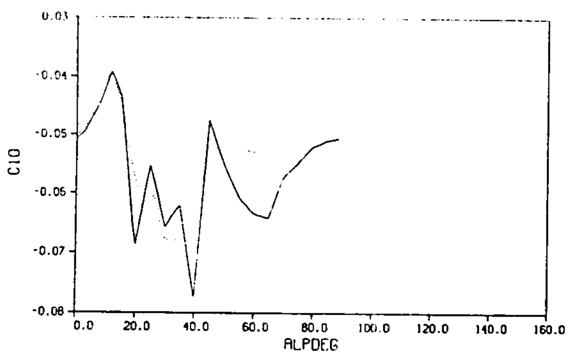
$\delta a= 25^o, \delta r= -30^o$

$C\ell 0XX2(\alpha)$



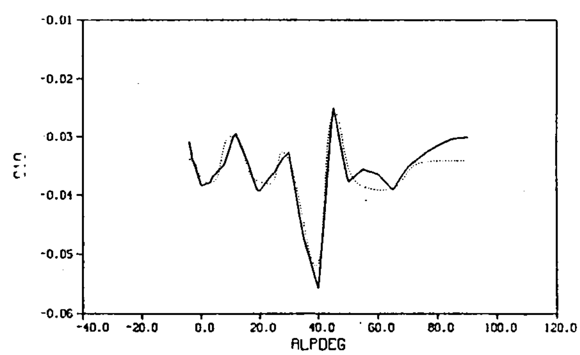
$\delta a= 25^o, \delta r= 30^o$

$C\ell 0NN2(\alpha)$



$\delta a= -25^o, \delta r= -30^o$

$C\ell 0NX2(\alpha)$



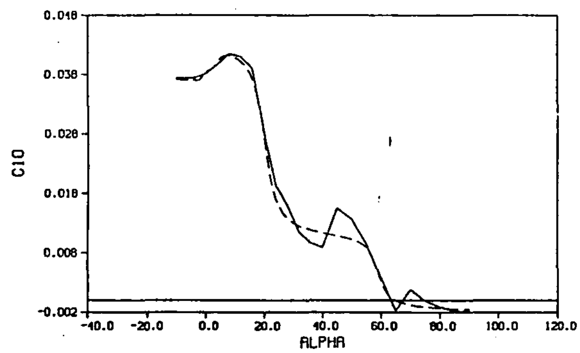
$\delta a= -25^o, \delta r= 30^o$

Figure 7.2: Comparison of Wind-Tunnel and Analytical Rolling Moment Coefficient C_{ℓ_0} for h=15,000 feet , M=0.9 and β=20^o.

Analytical Model of C_ℓ

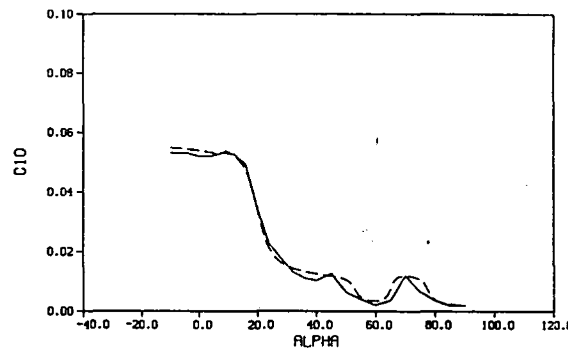
________ Wind-Tunnel ……… Analytical

$C\ell 0XNB0(\alpha)$



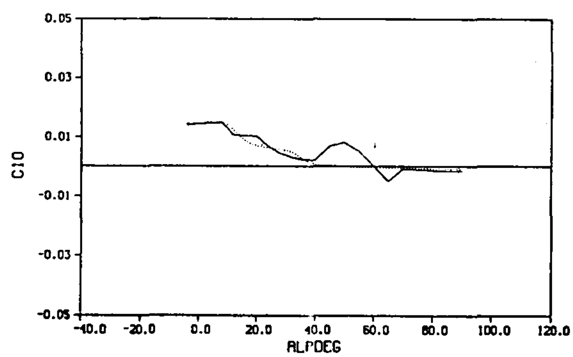
$\delta r= -30^o$, M=0.6

$C\ell 0XXB0(\alpha)$



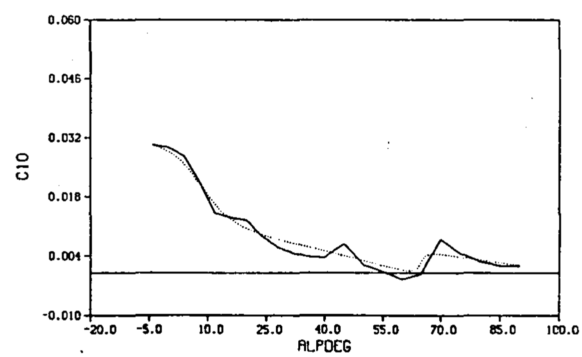
$\delta r= 30^o$, M=0.6

$C\ell 0XN0(\alpha)$



$\delta r= -30^o$, M=0.9

$C\ell 0XX0(\alpha)$



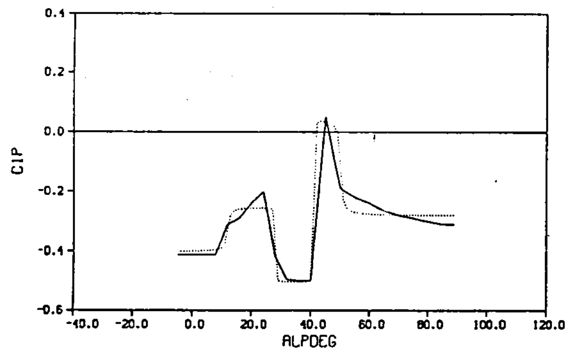
$\delta r= 30^o$, M=0.9

Figure 7.3: Comparison of Wind-Tunnel and Analytical Rolling Moment Coefficient C_{ℓ_0} for h=15,000 feet , $\delta a= 25^o$ and $\beta=0^o$.

Analytical Model of C_ℓ

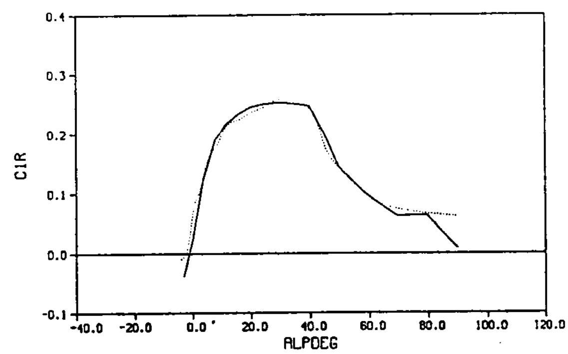
________ Wind-Tunnel ....Analytical

$LC\ell P(\alpha)$ [C_{ℓ_p}]



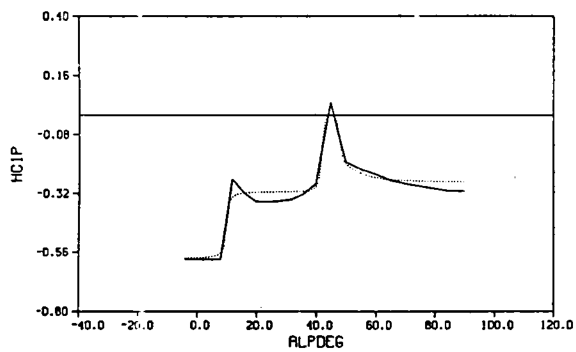
M=0.6

$C\ell R(\alpha)$ [C_{ℓ_r}]



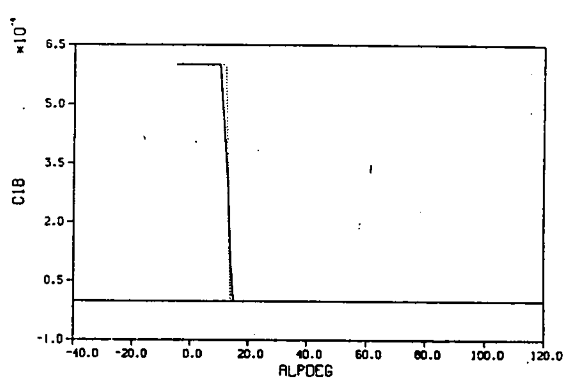
M=0.6

$HC\ell P(\alpha)$ [C_{ℓ_p}]



M=0.9

$C\ell B(\alpha)$ [C_{ℓ_β}]



M=0.6

Figure 7.4: Comparison of Wind-Tunnel and Analytical Rolling Moment Coefficient Derivatives C_{ℓ_p}, C_{ℓ_r} and C_{ℓ_β} for h=15,000 feet and M=0.6, 0.9.

8. Analytical Model for Yawing Moment Coefficient

The analytical model of the yawing moment coefficient C_n is taken from the wind-tunnel model at an altitude h=15,000 feet and Mach numbers M=0.6 and 0.9. The analytical model for C_{n_0} is constructed at $\beta = 0^o, 20^o$; stabilator deflections $\delta h = 10.5^o$ and -24^o; $\delta a = \mp 25^o$; and $\delta r = \mp 30^o$. The analytical models are functions of α from 0^o to 90^o; they are defined in Tables 8.1 a,b,c,d and 8.2 a,b,c,d. The analytical formulae are presented in Tables 8.3 a,b,c,d. Comparisons of the analytical models with the corresponding wind-tunnel model data are shown in Figures 8.1 to 8.7. The roll and yaw rate derivatives C_{n_p} and C_{n_r} and the sideslip derivative $C_{n\beta}$ are given in Figure 8.7. The analytical models are also given in the computer code listing contained in Appendix C.

Table 8.1a Definitions of C_n Analytical Models at $M=0.6, \delta h=10.5^o$

$C_{n_0}(\alpha, \beta=20^o, M=0.6, \delta a= 25^o, \delta r=-30^o, h=15{,}000 \text{ ft})$	$= C_nXNXB2(\alpha)$
$C_{n_0}(\alpha, \beta=20^o, M=0.6, \delta a= 25^o, \delta r= 30^o, h=15{,}000 \text{ ft})$	$= C_nXXXB2(\alpha)$
$C_{n_0}(\alpha, \beta=20^o, M=0.6, \delta a=-25^o, \delta r=-30^o, h=15{,}000 \text{ ft})$	$= C_nNNXB2(\alpha)$
$C_{n_0}(\alpha, \beta=20^o, M=0.6, \delta a=-25^o, \delta r= 30^o, h=15{,}000 \text{ ft})$	$= C_nNXXB2(\alpha)$
$C_{n_0}(\alpha, \beta=0^o, M=0.6, \delta a= 25^o, \delta r=-30^o, h=15{,}000 \text{ ft})$	$= C_nXNXB0(\alpha)$
$C_{n_0}(\alpha, \beta=0^o, M=0.6, \delta a= 25^o, \delta r= 30^o, h=15{,}000 \text{ ft})$	$= C_nXXXB0(\alpha)$
$C_{n_p}(\alpha, M=0.6, h=15{,}000 \text{ ft})$	$= C_nP(\alpha)$
$C_{n_r}(\alpha, M=0.6, h=15{,}000 \text{ ft})$	$= C_nR(\alpha)$
$C_{n_\beta}(M=0.6, h=15{,}000 \text{ ft})$	$= C_nB(\alpha)$

Table 8.1b Definitions of C_n Analytical Models at $M=0.6, \delta h=-24^o$

$C_{n_0}(\alpha, \beta=20^o, M=0.6, \delta a= 25^o, \delta r=-30^o, h=15{,}000 \text{ ft})$	$= C_nXNNB2(\alpha)$
$C_{n_0}(\alpha, \beta=20^o, M=0.6, \delta a= 25^o, \delta r= 30^o, h=15{,}000 \text{ ft})$	$= C_nXXNB2(\alpha)$
$C_{n_0}(\alpha, \beta=20^o, M=0.6, \delta a=-25^o, \delta r=-30^o, h=15{,}000 \text{ ft})$	$= C_nNNNB2(\alpha)$
$C_{n_0}(\alpha, \beta=20^o, M=0.6, \delta a=-25^o, \delta r= 30^o, h=15{,}000 \text{ ft})$	$= C_nNXNB2(\alpha)$
$C_{n_0}(\alpha, \beta=0^o, M=0.6, \delta a= 25^o, \delta r=-30^o, h=15{,}000 \text{ ft})$	$= C_nXNNB0(\alpha)$
$C_{n_0}(\alpha, \beta=0^o, M=0.6, \delta a= 25^o, \delta r= 30^o, h=15{,}000 \text{ ft})$	$= C_nXXNB0(\alpha)$

Table 8.1c Definitions of C_n Analytical Models at $M=0.9, \delta h=10.5^o$

$C_{n_0}(\alpha, \beta=20^o, M=0.9, \delta a= 25^o, \delta r=-30^o, h=15{,}000 \text{ ft})$	$= C_nXNX2(\alpha)$
$C_{n_0}(\alpha, \beta=20^o, M=0.9, \delta a= 25^o, \delta r= 30^o, h=15{,}000 \text{ ft})$	$= C_nXXX2(\alpha)$
$C_{n_0}(\alpha, \beta=20^o, M=0.9, \delta a=-25^o, \delta r=-30^o, h=15{,}000 \text{ ft})$	$= C_nNNX2(\alpha)$
$C_{n_0}(\alpha, \beta=20^o, M=0.9, \delta a=-25^o, \delta r= 30^o, h=15{,}000 \text{ ft})$	$= C_nNXX2(\alpha)$
$C_{n_0}(\alpha, \beta=0^o, M=0.9, \delta a= 25^o, \delta r=-30^o, h=15{,}000 \text{ ft})$	$= C_nXNX0(\alpha)$
$C_{n_0}(\alpha, \beta=0^o, M=0.9, \delta a= 25^o, \delta r= 30^o, h=15{,}000 \text{ ft})$	$= C_nXXX0(\alpha)$

Table 8.1d Definitions of C_n Analytical Models at $M=0.9, \delta h=-24^o$

$C_{n_0}(\alpha, \beta=20^o, M=0.9, \delta a= 25^o, \delta r=-30^o, h=15{,}000\ ft) = C_nXNN2(\alpha)$
$C_{n_0}(\alpha, \beta=20^o, M=0.9, \delta a= 25^o, \delta r= 30^o, h=15{,}000\ ft) = C_nXXN2(\alpha)$
$C_{n_0}(\alpha, \beta=20^o, M=0.9, \delta a=-25^o, \delta r=-30^o, h=15{,}000\ ft) = C_nNNN2(\alpha)$
$C_{n_0}(\alpha, \beta=20^o, M=0.9, \delta a=-25^o, \delta r= 30^o, h=15{,}000\ ft) = C_nNXN2(\alpha)$
$C_{n_0}(\alpha, \beta=0^o, M=0.9, \delta a= 25^o, \delta r=-30^o, h=15{,}000\ ft) = C_nXNN0(\alpha)$
$C_{n_0}(\alpha, \beta=0^o, M=0.9, \delta a= 25^o, \delta r= 30^o, h=15{,}000\ ft) = C_nXXN0(\alpha)$

Table 8.2a Yawing Moment Coefficient Analytical Models: M = 0.6, δh=10.5

Sideslip	Rudder / Aileron	δr = -30	δr = 30
β = 20	δa = 25	CnXNXB2(α)	CnXXXB2(α)
	δa = -25	CnNNXB2(α)	CnNXXB2(α)
β = 0	δa = 25	CnXNXB0(α)	CnXXXB0(α)
	δa = -25	-CnXXXB0(α)	-CnXNXB0(α)

Table 8.2b Yawing Moment Coefficient Analytical Models: M = 0.6, δh=-24

Sideslip	Rudder / Aileron	δr = -30	δr = 30
β = 20	δa = 25	CnXNNB2(α)	CnXXNB2(α)
	δa = -25	CnNNNB2(α)	CnNXNB2(α)
β = 0	δa = 25	CnXNNB0(α)	CnXXNB0(α)
	δa = -25	-CnXXNB0(α)	-CnXNNB0(α)

Table 8.2c Yawing Moment Coefficient Analytical Models: M = 0.9, δh=10.5

Sideslip	Rudder / Aileron	δr = -30	δr = 30
β = 20	δa = 25	CnXNX2(α)	CnXXX2(α)
	δa = -25	CnNNX2(α)	CnNXX2(α)
β = 0	δa = 25	CnXNX0(α)	CnXXX0(α)
	δa = -25	-CnXXX0(α)	-CnXNX0(α)

Table 8.2d Yawing Moment Coefficient Analytical Models: M = 0.9, δh=-24

Sideslip	Rudder / Aileron	δr = -30	δr = 30
β = 20	δa = 25	CnXNN2(α)	CnXXN2(α)
	δa = -25	CnNNN2(α)	CnNXN2(α)
β = 0	δa = 25	CnXNN0(α)	CnXXN0(α)
	δa = -25	-CnXXN0(α)	-CnXNN0(α)

Table 8.3a Formulas for C_n Model at M=0.6, δh=10.5°

$$CnXNXB2(\alpha^o)=(.06482/2.75)\tan^{-1}(-(\alpha^o-20)3/14) +(.04937/2.75)\tan^{-1}(-(\alpha^o-41)5/14) +(.053/2.75)\tan^{-1}((\alpha^o-60)1/6) +(.005/2.75)\tan^{-1}(-(\alpha^o-8)4) + .0211$$

$$CnXXXB2(\alpha^o)=(.077832/2.75)\tan^{-1}(-(\alpha^o-27.5)4/45) +(.0744/2.75)\tan^{-1}((\alpha^o-58.5)4/25) +(.02885/2.75)\tan^{-1}(-(\alpha^o-79)7/20) +(.006/2.75)\tan^{-1}(-(\alpha^o-43)) - .022$$

$$CnNNXB2(\alpha^o)=(.11977/2.75)\tan^{-1}(-(\alpha^o-28.5)3.5/51) +(.04303/2.75)\tan^{-1}((\alpha^o-58.5)4/13) +(.02532/2.75)\tan^{-1}(-(\alpha^o-74)2/5) + .01184$$

$$CnNXXB2(\alpha^o)=(.06132/2.75)\tan^{-1}(-(\alpha^o-31)1/10) +(.05521/2.75)\tan^{-1}((\alpha^o-55)2/9) +(.04659/2.75)\tan^{-1}(-(\alpha^o-77.5)4/15) - .03235$$

$$CnXNXB0(\alpha^o)=(.02026/2.75)\tan^{-1}(-(\alpha^o-19)3/14) +(.022/2.75)\tan^{-1}(-(\alpha^o-49)2/7) +(.03393/2.75)\tan^{-1}((\alpha^o-73)1/7) +(.002/2.75)\tan^{-1}(-(\alpha^o-14)2) +(.003/2.75)\tan^{-1}((\alpha^o-76)2) + .02769$$

$$CnXXXB0(\alpha^o)=(.00952/2.75)\tan^{-1}((\alpha^o-14)3/8) +(.01056/2.75)\tan^{-1}((\alpha^o-47)2/3) +(.01395/2.75)\tan^{-1}((\alpha^o-67)9/14) +(.00899/2.75)\tan^{-1}(-(\alpha^o-81)3/8)-.01862$$

$$CnNNXB0(\alpha^o)=-CnXXXB0(\alpha^o)$$

$$CnNXXB0(\alpha^o)=-CnXNXB0(\alpha^o)$$

$$CnP(\alpha^o) = (.075/\pi)\tan^{-1}((\alpha^o-17)5\pi/18) +(.04/\pi)\tan^{-1}((\alpha^o-50)10\pi/18) +(.2/\pi)\tan^{-1}(-(\alpha^o-57)100\pi/18) +(.13/\pi)\tan^{-1}((\alpha^o-62)100\pi/18) +(.09/\pi)\tan^{-1}(-(\alpha^o-73)100\pi/18) +(.1/\pi)\tan^{-1}((\alpha^o-77)100\pi/18)-.028$$

$$CnR(\alpha^o) = (.16/\pi)\tan^{-1}(-(\alpha^o-22)10\pi/18) +(.34/\pi)\tan^{-1}((\alpha^o-57)10\pi/18) +(-.1)\exp((\alpha^o-78)1/10)-.09$$

$$CnB(\alpha^o) = (.000001)[(12.7/\pi)\tan^{-1}(-(\alpha^o-13)100\pi/18) - 11.7]$$

Table 8.3b Formulas for C_n Model at M=0.6, $\delta h=-24^o$

$$CnXNNB2(\alpha^o)=(.11857/2.75)\tan^{-1}(-(\alpha^o-26.5)4/45) +(.07065/2.75)\tan^{-1}((\alpha^o-60.5)4/25) +(.02518/2.75)\tan^{-1}(-(\alpha^o-80)3/10) +(.005/2.75)\tan^{-1}(-(\alpha^o-18)2) + .020265$$

$$CnXXNB2(\alpha^o)=(.080916/2.75)\tan^{-1}(-(\alpha^o-30)3/42) +(.056/2.75)\tan^{-1}((\alpha^o-62)1/4) +(.02085/2.75)\tan^{-1}(-(\alpha^o-79)1/5) +(-.005/2.75)\tan^{-1}(-(\alpha^o-82)2) - .02221$$

$$CnNNNB2(\alpha^o)=(.120543/2.75)\tan^{-1}(-(\alpha^o-28)3/40) +(.05707/2.75)\tan^{-1}((\alpha^o-55.5)4/25) +(.03650/2.75)\tan^{-1}(-(\alpha^o-78.5)4/15) + .01202$$

$$CnNXNB2(\alpha^o)=(.063768/2.75)\tan^{-1}(-(\alpha^o-32)1/10) +(.04788/2.75)\tan^{-1}((\alpha^o-57.5)6/25) +(.03829/2.75)\tan^{-1}(-(\alpha^o-77.5)4/15) - .03288$$

$$CnXNNB0(\alpha^o)=(.02037/2.75)\tan^{-1}(-(\alpha^o-17.5)8/43) +(.00389/2.75)\tan^{-1}(-(\alpha^o-54.5)6/17) +(.01623/2.75)\tan^{-1}((\alpha^o-69.5)5/23) +(.002/2.75)\tan^{-1}(-(\alpha^o-13)2) + .02711$$

$$CnXXNB0(\alpha^o)=(.00953/2.75)\tan^{-1}((\alpha^o-15)3/8) +(.00411/2.75)\tan^{-1}(-(\alpha^o-46.5)8/15) +(.02222/2.75)\tan^{-1}((\alpha^o-71.5)4/25) - .01781$$

$$CnNNNB0(\alpha^o)=-CnXXNB0(\alpha^o)$$

$$CnNXNB0(\alpha^o)=-CnXNNB0(\alpha^o)$$

Table 8.3c Formulas for C_n Model at M=0.9, $\delta h=10.5^o$

$$CnXNX2(\alpha^o)=(.05428/2.75)\tan^{-1}(-(\alpha^o-16)3/14)$$
$$+(.05037/2.75)\tan^{-1}(-(\alpha^o-36)5/14)$$
$$+(-.003/2.75)\tan^{-1}((\alpha^o-45)1/6)$$
$$+(.060/2.75)\tan^{-1}((\alpha^o-50)1/6)$$
$$+(.005/2.75)\tan^{-1}(-(\alpha^o-8)4) + .0211$$

$$CnXXX2(\alpha^o)=(.067832/2.75)\tan^{-1}(-(\alpha^o-30)4/45)$$
$$+(.065/2.75)\tan^{-1}(-(\alpha^o-14)4/45)$$
$$+(-.04/2.75)\tan^{-1}(-(\alpha^o-14)4/45)$$
$$+(.0844/2.75)\tan^{-1}((\alpha^o-46)4/25)$$
$$+(.04085/2.75)\tan^{-1}(-(\alpha^o-100)7/20)$$
$$+(.006/2.75)\tan^{-1}(-(\alpha^o-35)) - .0352$$

$$CnNNX2(\alpha^o)=(.05428/2.75)\tan^{-1}(-(\alpha^o-22)3/14)$$
$$+(.02037/2.75)\tan^{-1}(-(\alpha^o-36)5/14)$$
$$+(-.003/2.75)\tan^{-1}((\alpha^o-45)1/6)$$
$$+(.042/2.75)\tan^{-1}((\alpha^o-47)1/6)$$
$$+(.020/2.75)\tan^{-1}(-(\alpha^o-11)4) + .0181$$

$$CnNXX2(\alpha^o)=(.067832/2.75)\tan^{-1}(-(\alpha^o-35)4/45)$$
$$+(.070/2.75)\tan^{-1}(-(\alpha^o-14)4/45)$$
$$+(-.04/2.75)\tan^{-1}(-(\alpha^o-4)4/45)$$
$$+(.0844/2.75)\tan^{-1}((\alpha^o-46)4/25)$$
$$+(.04085/2.75)\tan^{-1}(-(\alpha^o-100)7/20)$$
$$+(.006/2.75)\tan^{-1}(-(\alpha^o-35)) - .0392$$

$$CnXNX0(\alpha^o)=(.01026/2.75)\tan^{-1}(-(\alpha^o-13)3/14)$$
$$+(-.009/2.75)\tan^{-1}(-(\alpha^o-40)2/7)$$
$$+(.010/2.75)\tan^{-1}(-(\alpha^o-18)2/7)$$
$$+(-.002/2.75)\tan^{-1}(-(\alpha^o-30)2/7)$$
$$+(.022/2.75)\tan^{-1}(-(\alpha^o-49)2/7)$$
$$+(.02543/2.75)\tan^{-1}((\alpha^o-83)1/7)$$
$$+(.002/2.75)\tan^{-1}(-(\alpha^o-7)2)$$
$$+(.003/2.75)\tan^{-1}((\alpha^o-76)2) + .02769$$

$$CnXXX0(\alpha^o)=[(.01452/2.75)\tan^{-1}((\alpha^o-11)3/8)$$
$$+(-.005/2.75)\tan^{-1}((\alpha^o-22)3/8)$$
$$+(.01156/2.75)\tan^{-1}((\alpha^o-41)2/3)$$
$$+(.01205/2.75)\tan^{-1}((\alpha^o-67)9/14)$$
$$+(.00769/2.75)\tan^{-1}(-(\alpha^o-81)3/8)$$
$$- .01862](1/1.21)$$

$$CnNNX0(\alpha^o)=-CnXXX0(\alpha^o)$$

$$CnNXX0(\alpha^o)=-CnXNX0(\alpha^o)$$

Table 8.3d Formulas for C_n Model at M=0.9, δh=-24°

$$CnXNN2(\alpha^o)=(.05428/2.75)\tan^{-1}(-(\alpha^o-15)3/14) +(.05037/2.75)\tan^{-1}(-(\alpha^o-33)5/14) +(-.003/2.75)\tan^{-1}((\alpha^o-45)1/6) +(.060/2.75)\tan^{-1}((\alpha^o-46)1/6) +(.005/2.75)\tan^{-1}(-(\alpha^o-8)4)+.0241$$

$$CnXXN2(\alpha^o)=(.11091/2.75)\tan^{-1}(-(\alpha^o-25)3/42) +(-.025/2.75)\tan^{-1}(-(\alpha^o-8)3/42) +(.05600/2.75)\tan^{-1}((\alpha^o-48)1/4) +(.03385/2.75)\tan^{-1}(-(\alpha^o-100)1/5) +(-.005/2.75)\tan^{-1}(-(\alpha^o-82)2) - .03125$$

$$CnNNN2(\alpha^o)=CnXNN2(\alpha^o)$$

$$CnNXN2(\alpha^o)=(.067832/2.75)\tan^{-1}(-(\alpha^o-32)4/45) +(.063/2.75)\tan^{-1}(-(\alpha^o-14)4/45) +(-.04/2.75)\tan^{-1}(-(\alpha^o-4)4/45) +(.0844/2.75)\tan^{-1}((\alpha^o-46)4/25) +(.04085/2.75)\tan^{-1}(-(\alpha^o-90)7/20) +(.006/2.75)\tan^{-1}(-(\alpha^o-35)) -.0352$$

$$CnXNN0(\alpha^o)=(.01637/2.75)\tan^{-1}(-(\alpha^o-10)8/43) +(.00559/2.75)\tan^{-1}(-(\alpha^o-180)6/17) +(.01623/2.75)\tan^{-1}(-(\alpha^o-100)5/23) +(.002/2.75)\tan^{-1}(-(\alpha^o-13)2) +.0271$$

$$CnXXN0(\alpha^o)=(.01253/2.75)\tan^{-1}((\alpha^o-12)3/8) +(-.002/2.75)\tan^{-1}((\alpha^o-22)3/8) +(.00411/2.75)\tan^{-1}(-(\alpha^o-46.5)8/15) +(.02222/2.75)\tan^{-1}((\alpha^o-81.5)4/25) - .01161$$

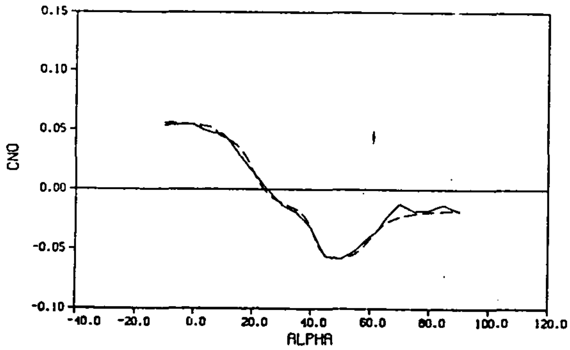
$$CnNNN0(\alpha^o)=-CnXXN0(\alpha^o)$$

$$CnNXN0(\alpha^o)=-CnXNN0(\alpha^o)$$

Analytical Model of C_n

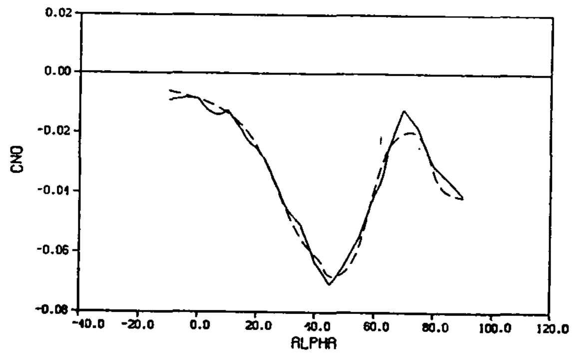
________ Wind-Tunnel ....Analytical

CNXNXB2(α)



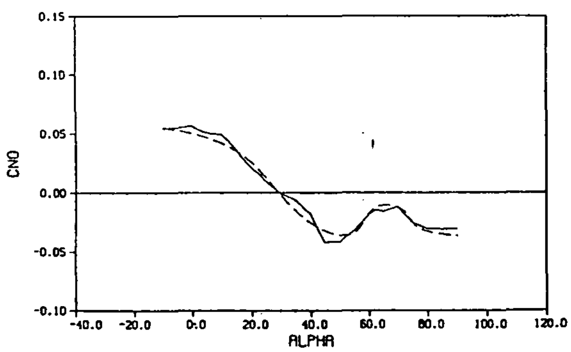
δa= 25°, δr= -30°

CNXXXB2(α)



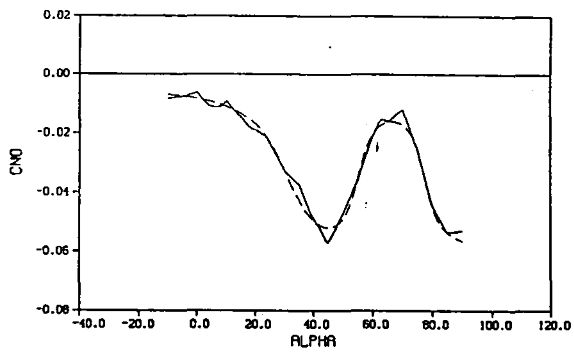
δa= 25°, δr= 30°

CNNNXB2(α)



δa= -25°, δr= -30°

CNNXXB2(α)



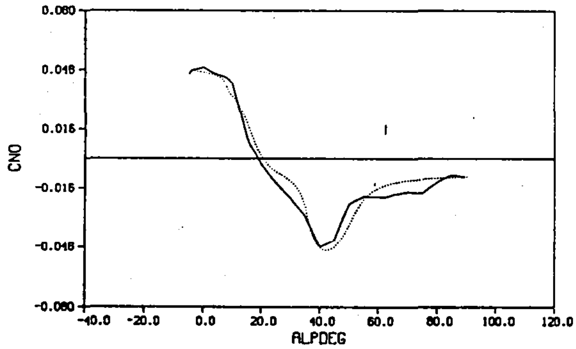
δa= -25°, δr= 30°

Figure 8.1: Comparison of Wind-Tunnel and Analytical Yawing Moment Coefficient C_{n_0} for h=15,000 feet , M=0.6, δh= 10.5° and β=20°.

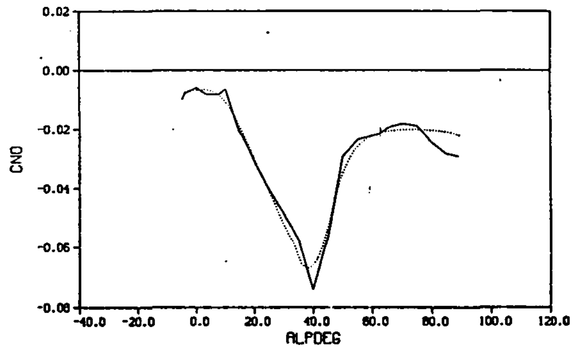
Analytical Model of C_n

_________ Wind-Tunnel ………Analytical

CNXNX2(α) CNXXX2(α)

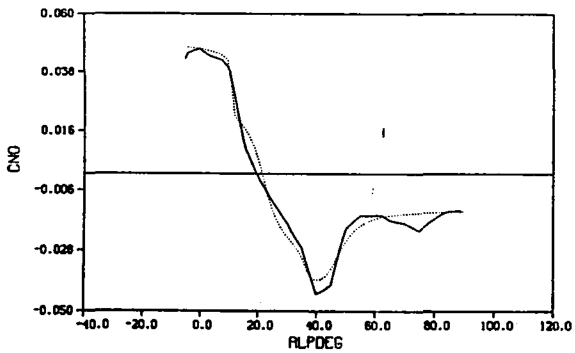


δa= 25°, δr= -30°

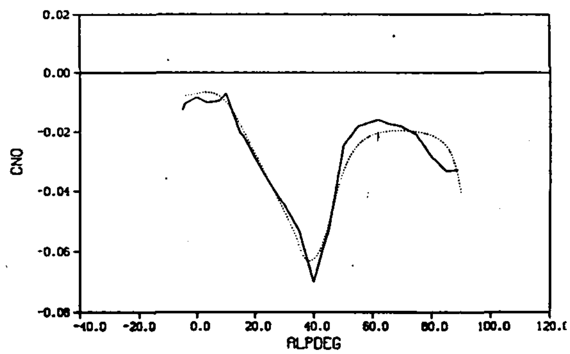


δa= 25°, δr= 30°

CNNNX2(α) CNNXX2(α)



δa= -25°, δr= -30°



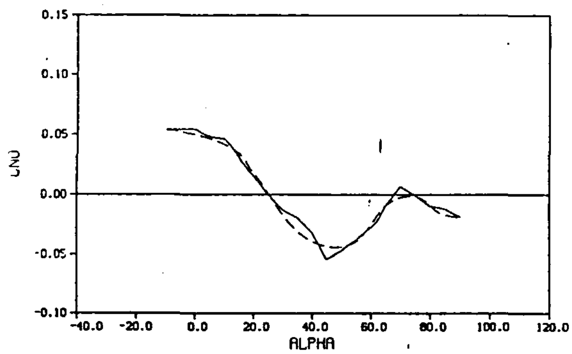
δa= -25°, δr= 30°

Figure 8.2: Comparison of Wind-Tunnel and Analytical Yawing Moment Coefficient C_{n_0} for h=15,000 feet , M=0.9, δh= 10.5° and β=20°.

Analytical Model of C_n

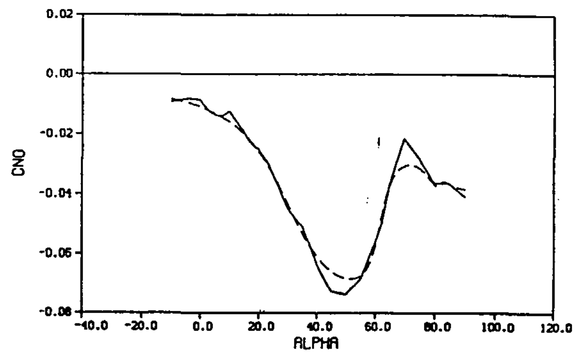
________ Wind-Tunnel ....Analytical

CNXNNB2(α)



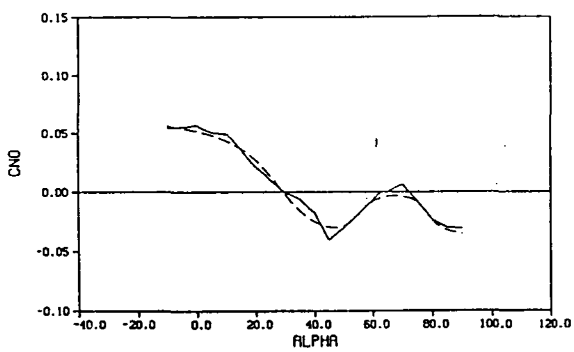
$\delta a = 25^{o}$, $\delta r = -30^{o}$

CNXXNB2(α)



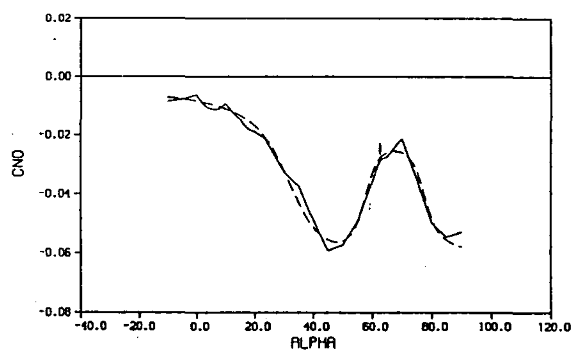
$\delta a = 25^{o}$, $\delta r = 30^{o}$

CNNNNB2(α)



$\delta a = -25^{o}$, $\delta r = -30^{o}$

CNNXNB2(α)



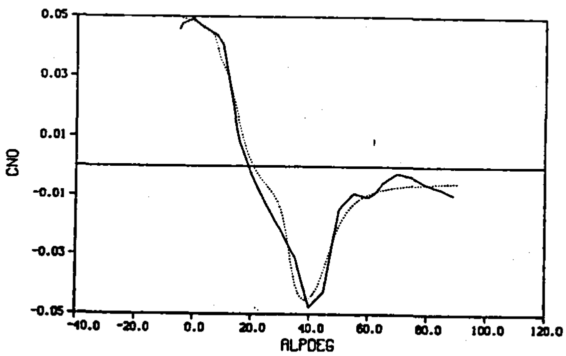
$\delta a = -25^{o}$, $\delta r = 30^{o}$

Figure 8.3: Comparison of Wind-Tunnel and Analytical Yawing Moment Coefficient C_{n_0} for h=15,000 feet , M=0.6, $\delta h = -24^{o}$ and $\beta = 20^{o}$.

Analytical Model of C_n

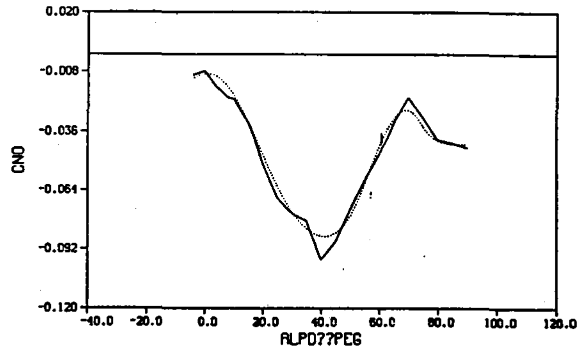
_________ Wind-Tunnel ………Analytical

CNXNN2(α)



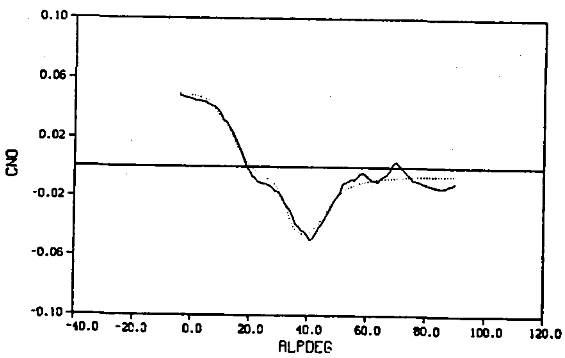
δa= 25°, δr= -30°

CNXXN2(α)



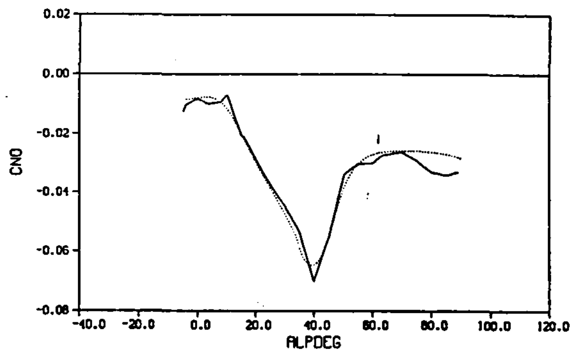
δa= 25°, δr= 30°

CNNNN2(α)



δa= -25°, δr= -30°

CNNXN2(α)



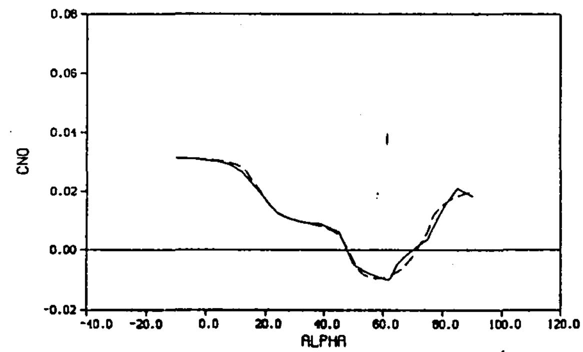
δa= -25°, δr= 30°

Figure 8.4: Comparison of Wind-Tunnel and Analytical Yawing Moment Coefficient C_{n_0} for h=15,000 feet , M=0.9, δh= -24° and β=20°.

Analytical Model of C_n

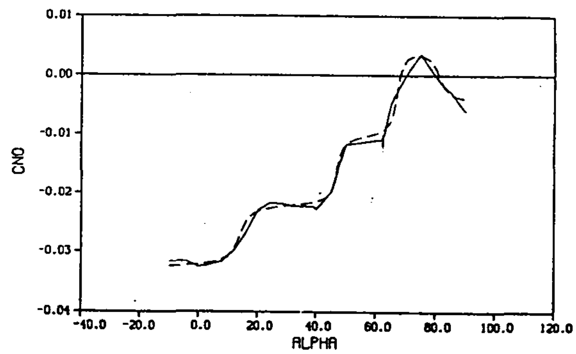
________ Wind-Tunnel ………Analytical

CNXNXB0(α)



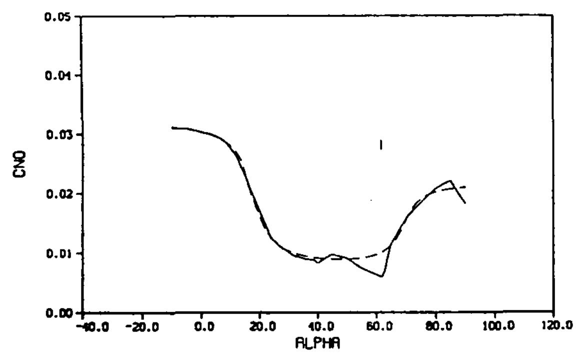
δh= 10.5°, δr= -30°

CNXXXB0(α)



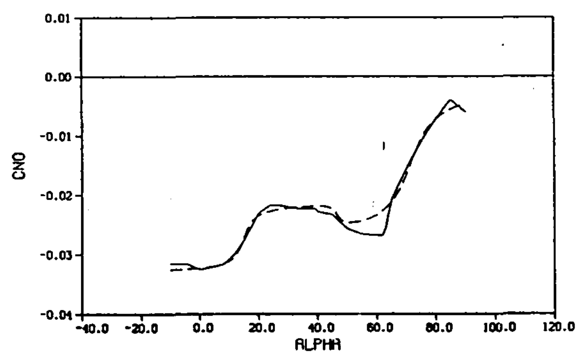
δh= 10.5°, δr= 30°

CNXNNB0(α)



δh= -24°, δr= -30°

CNXXNB0(α)



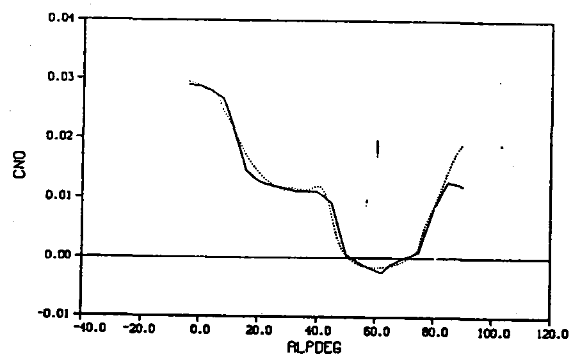
δh= -24°, δr= 30°

Figure 8.5: Comparison of Wind-Tunnel and Analytical Yawing Moment Coefficient C_{n_0} for h=15,000 feet, M=0.6, δa= 25° and β=0°.

Analytical Model of C_n

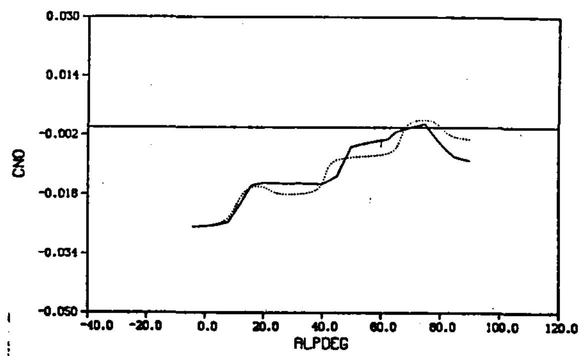
__________ Wind-Tunnel ……… Analytical

CNXNX0(α)



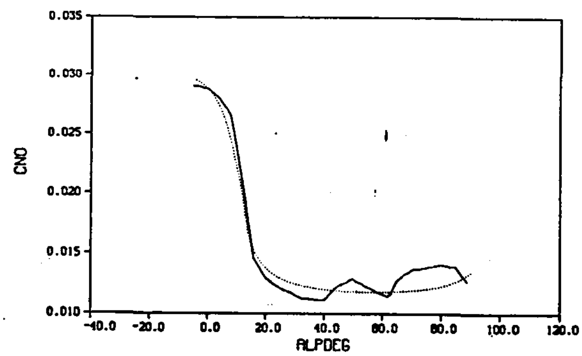
δh= 10.5°, δr= -30°

CNXXX0(α)



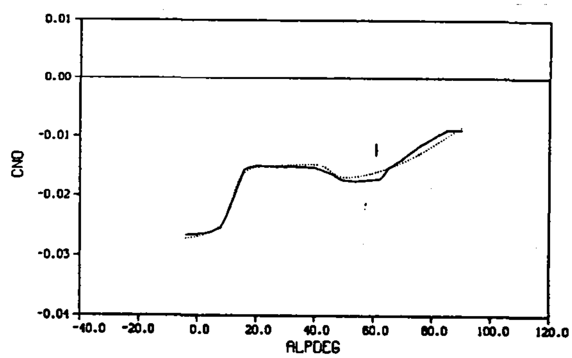
δh= 10.5°, δr= 30°

CNXNN0(α)



δh= -24°, δr= -30°

CNXXN0(α)



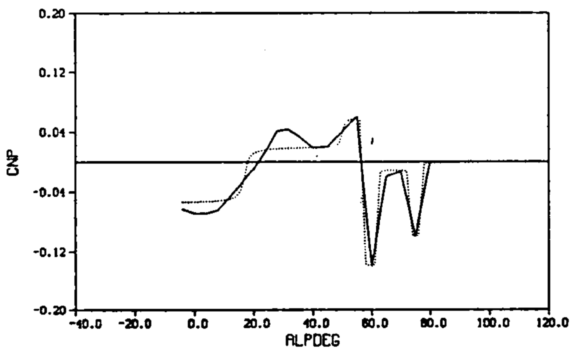
δh= -24°, δr= 30°

Figure 8.6: Comparison of Wind-Tunnel and Analytical Yawing Moment Coefficient C_{n_0} for h=15,000 feet , M=0.9, δa= 25° and β=0°.

Analytical Model of C_n

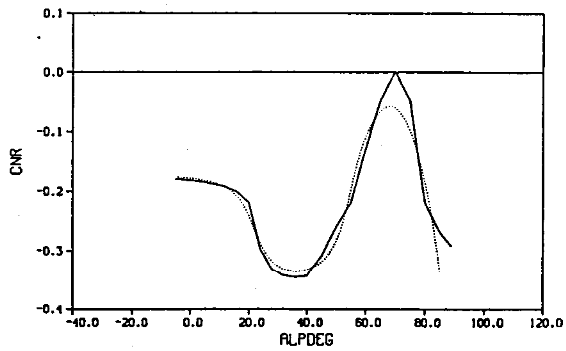
________ Wind-Tunnel ....Analytical

CnP(α) [$C_{n_p}(\alpha)$]



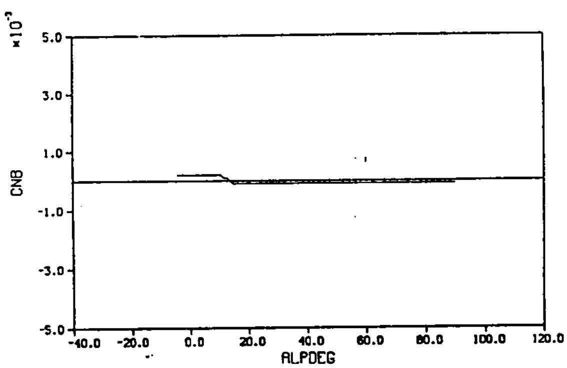
M=0.6, h=15,000 feet

CnR(α) [$C_{n_r}(\alpha)$]



M=0.6, h=15,000 feet

CnB(α) [$C_{n_\beta}(\alpha)$]



M=0.6, h=15,000 feet

Figure 8.7: Comparison of Wind-Tunnel and Analytical Yawing Moment Coefficient Derivatives C_{n_p}, C_{n_r} and C_{n_β} for h=15,000 feet and M=0.6.

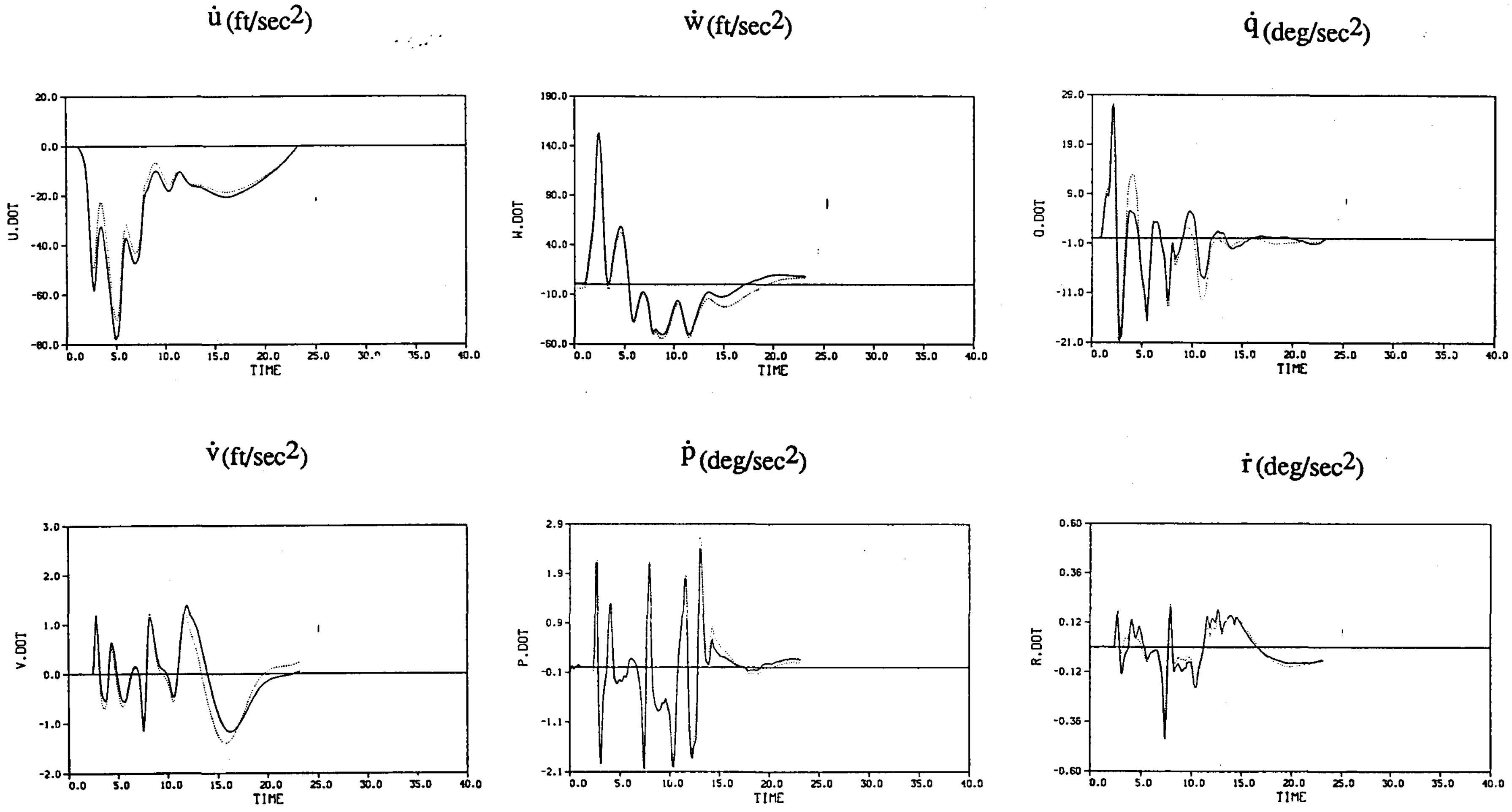
9. Time History Comparison of $\dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}$ and $\dot{r}$: Mach = 0.6

The simulation wind-tunnel model of [1] was flown in NASA's simulator by a pilot to generate some basic maneuvers at 0.6 Mach numbers such as pitch-ups, 360^{o} loaded and unloaded rolls, turn reversals, split S's and level turns. That simulator data is used here to check the validity of the 6 DOF analytical model. The accelerations

$$\dot{u},\ \dot{w},\ \dot{q},\ \dot{v},\ \dot{p},\ \dot{r}$$

are computed for the analytical model using the states and controls from the piloted simulated maneuvers. Comparisons with the accelerations from the wind-tunnel data model are shown below in Figures 9.1-9.6.

Analytical Model Simulation: Pitch Up Maneuver @ M=0.6 (Run 1, 6 October 1987)



______ Wind-Tunnel ....Analytical

Figure 9.1: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: Pitch Up Maneuver @ M=0.6 (Run 1, 6 October 1987).

$\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$

Analytical Model Simulation: 360° Loaded Roll (Trim Power) Maneuver @ M=0.6 (Run 3, 6 October 1987)

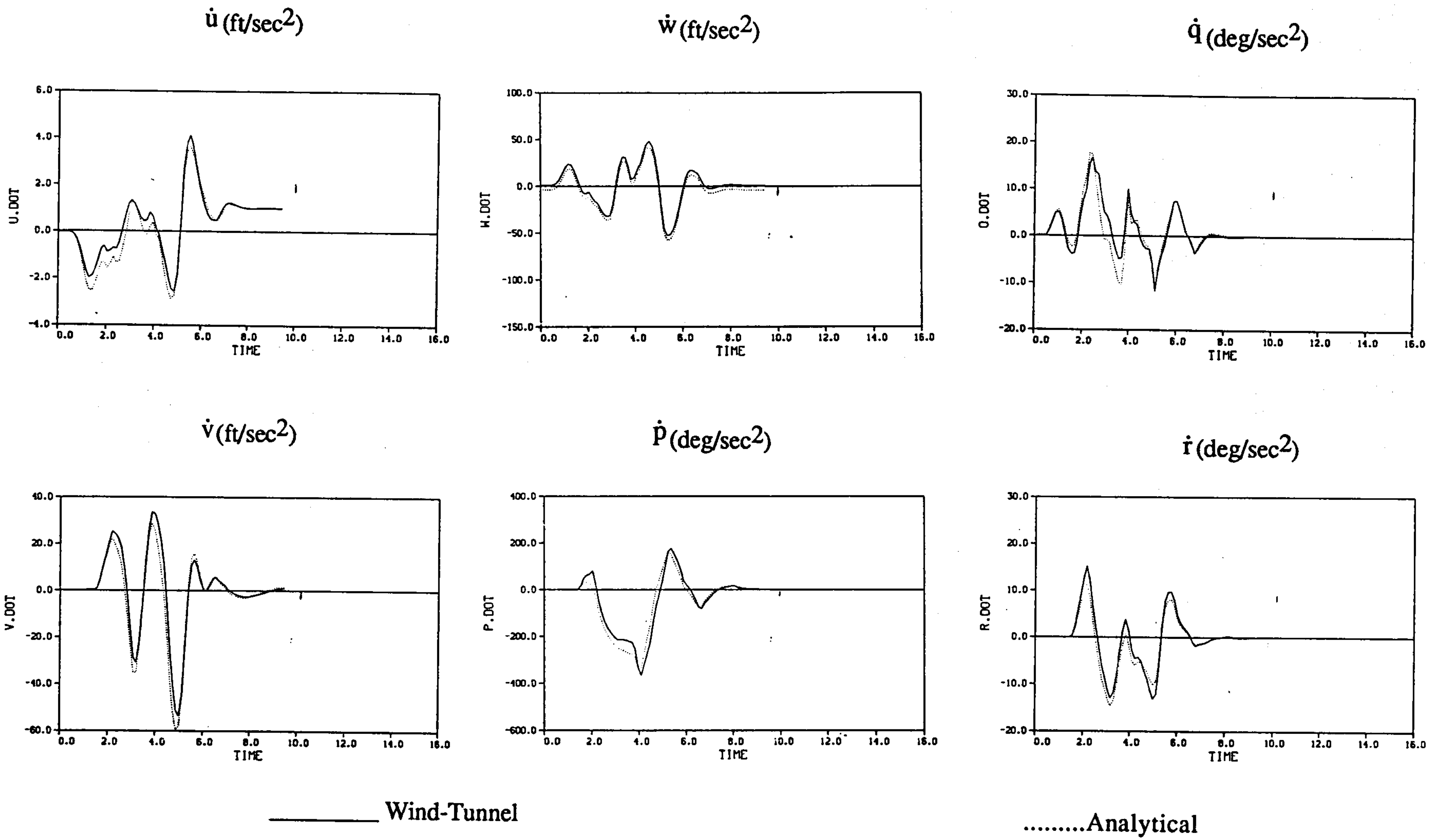
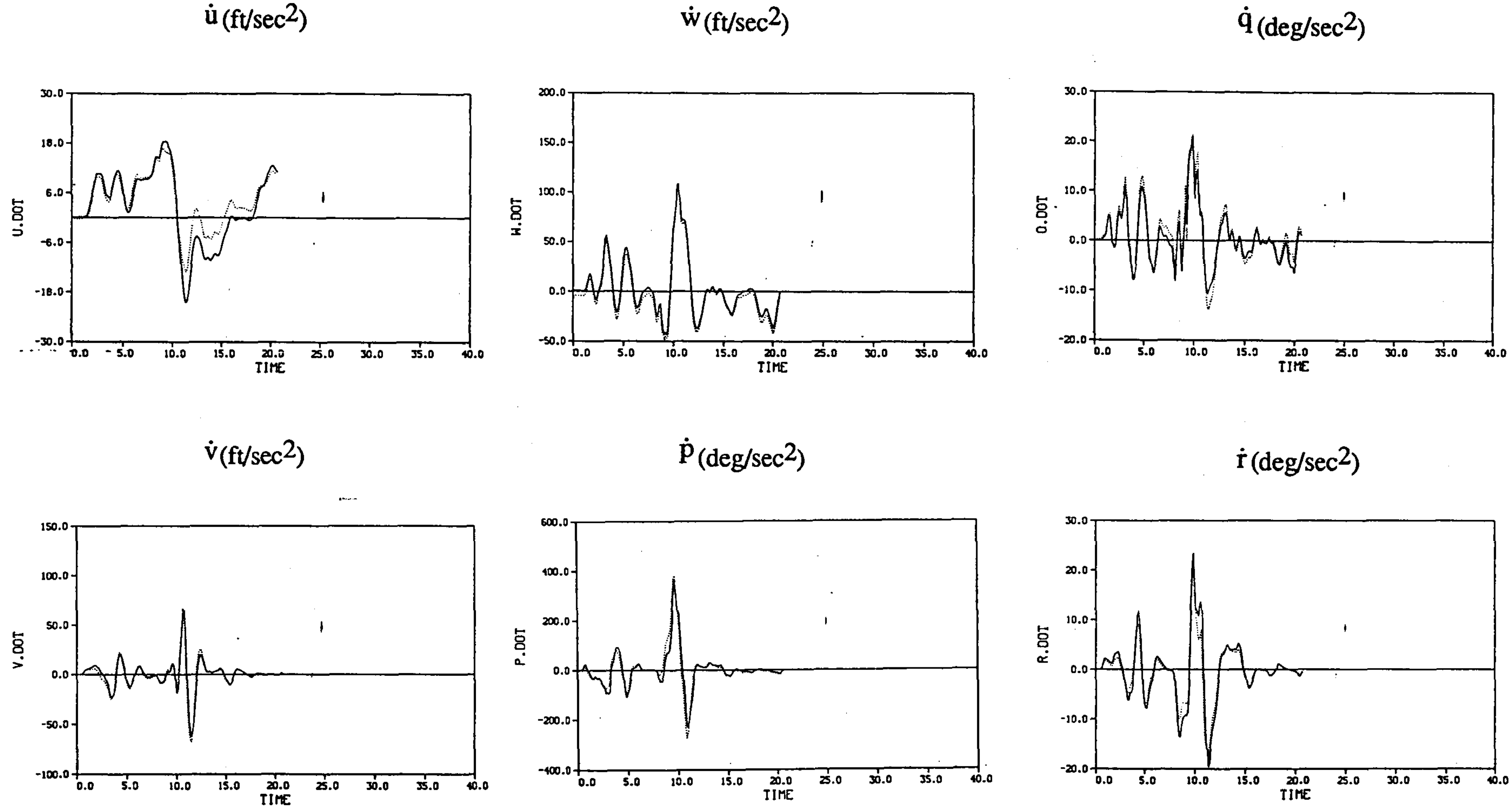


Figure 9.2: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: $\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$
360° Loaded Roll (Trim Power) Maneuver @ M=0.6 (Run 3, 6 October 1987).

Analytical Model Simulation: Turn Reversal Maneuver @ M=0.6 (Run 4, 6 October 1987)

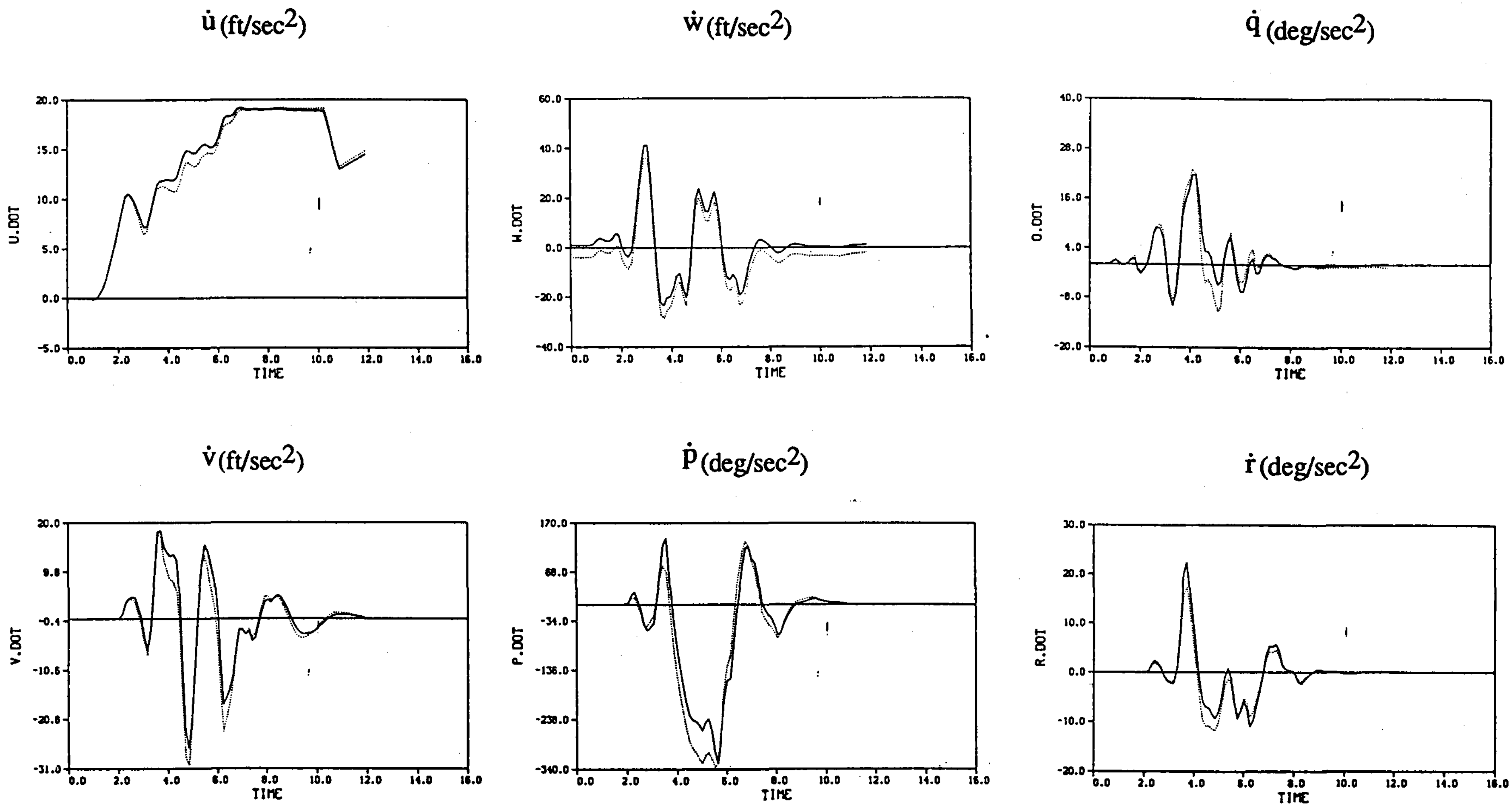


_________ Wind-Tunnel .... Analytical

Figure 9.3: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: Turn Reversal Maneuver @ M=0.6 (Run 4, 6 October 1987).

$\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$

Analytical Model Simulation: 360° Loaded Roll (AB) Maneuver @ M=0.6 (Run 5, 6 October 1987)



__________ Wind-Tunnel ....Analytical

Figure 9.4: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: $\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$
NASA's 360° Loaded Roll (AB) Maneuver @ M=0.6 (Run 5, 6 October 1987).

Analytical Model Simulation: Split S Maneuver @ M=0.6 (Run 6, 6 October 1987)

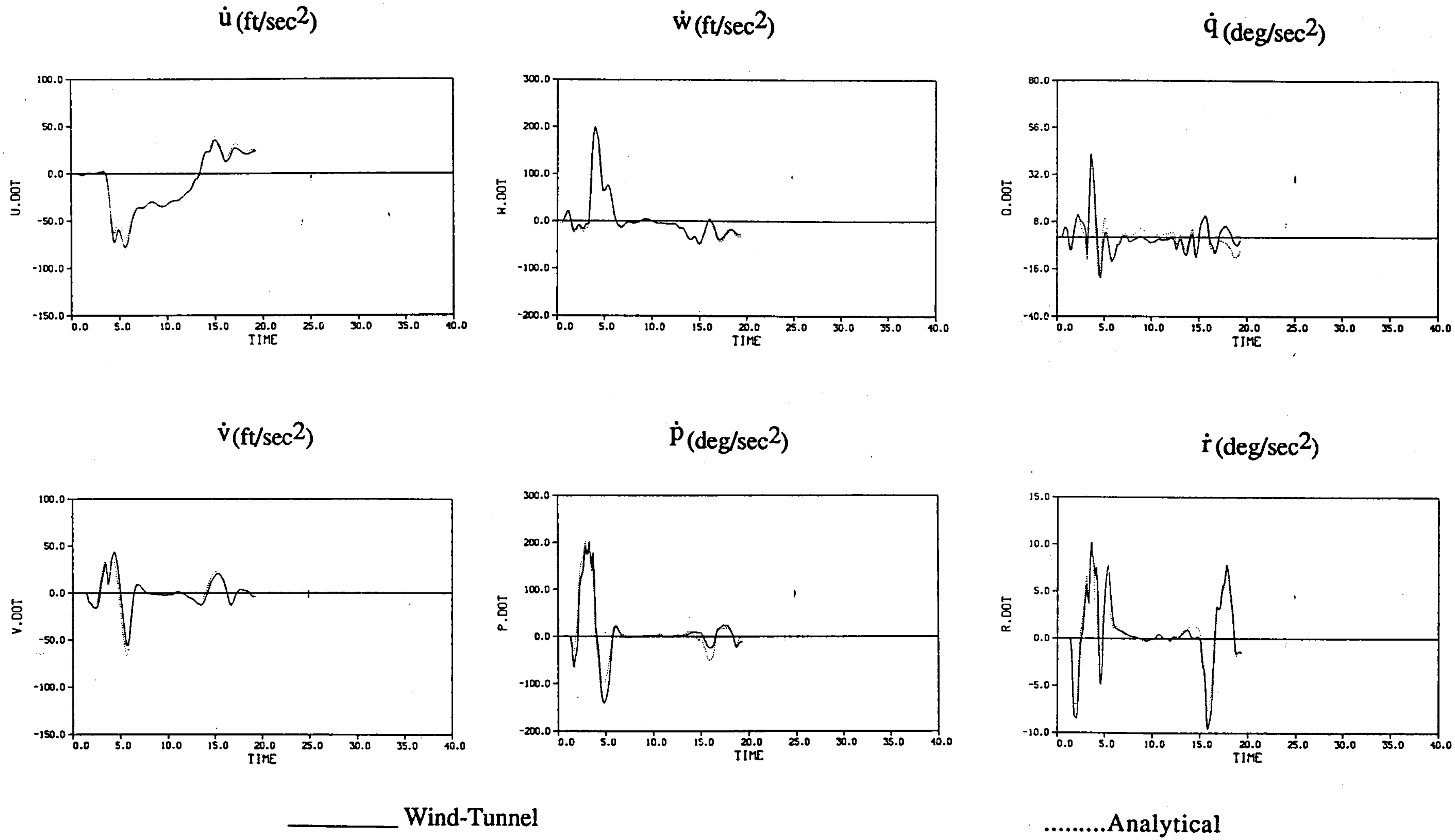
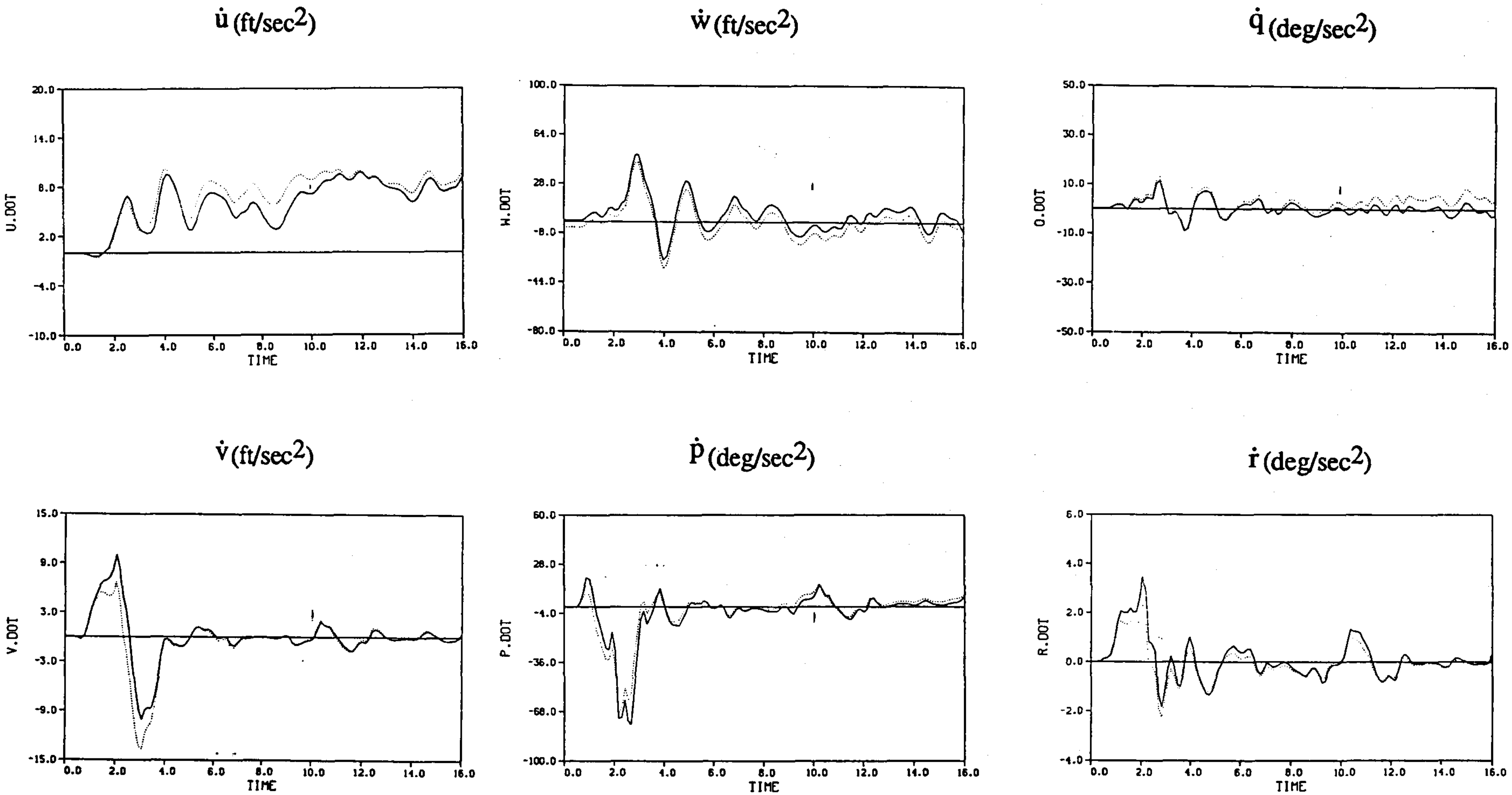


Figure 9.5: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: Split S Maneuver @ M=0.6 (Run 6, 6 October 1987).

$\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$

Analytical Model Simulation: Level Turn Maneuver @ M=0.6 (Run 7, 6 October 1987)



________ Wind-Tunnel

.........Analytical

Figure 9.6: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: Level Turn Maneuver @ M=0.6 (Run 7, 6 October 1987).

$\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$

10. Time History Comparison of $\dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}$ and $\dot{r}$: Mach = 0.9

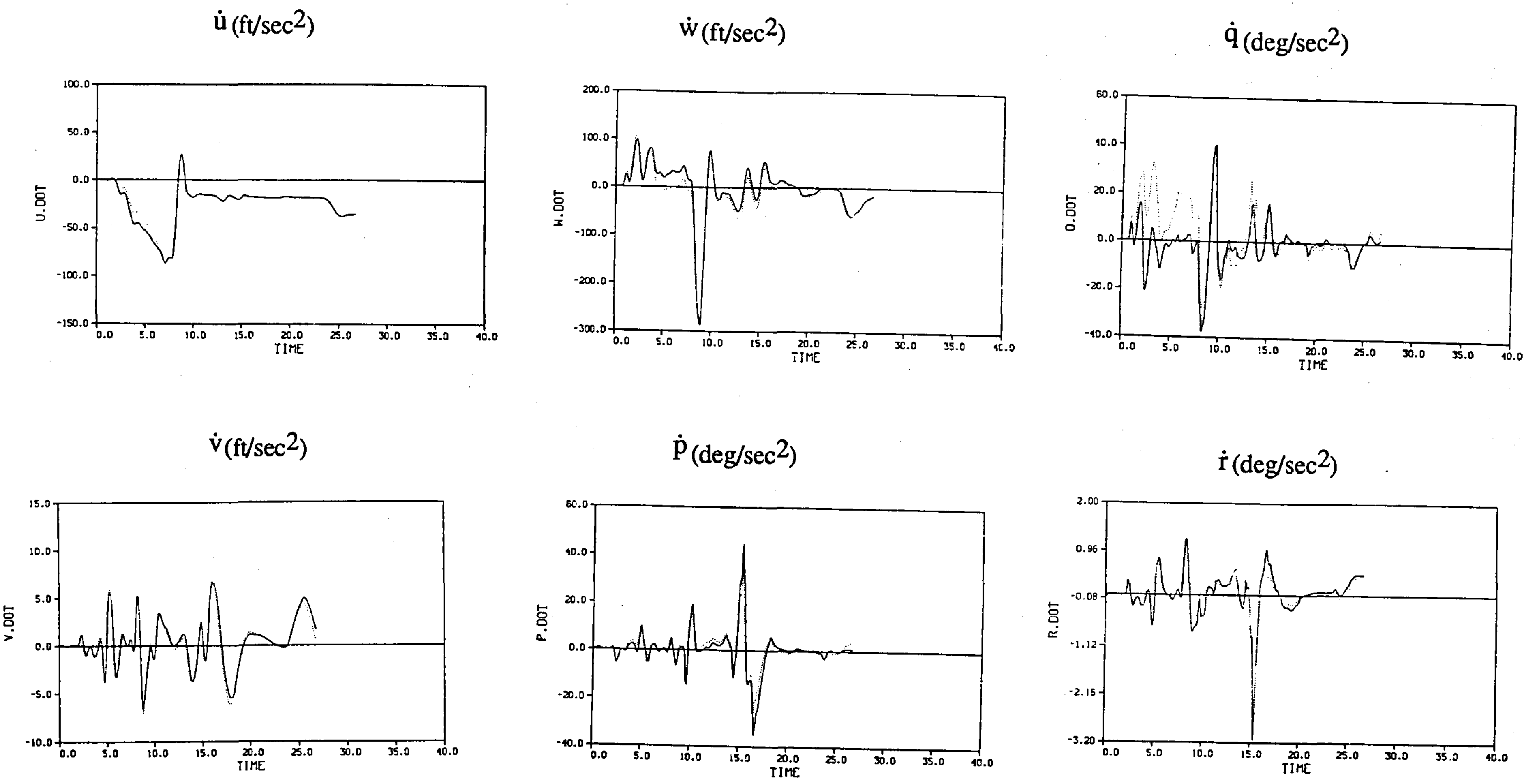
The simulation wind-tunnel model of [1] was flown in NASA's simulator by a pilot to generate some basic maneuvers at 0.9 Mach numbers such as pitch-ups, 360° loaded and unloaded rolls, turn reversals, split S's and level turns. That simulator data is used here to check the validity of the 6 DOF analytical model. The accelerations

$$\dot{u},\ \dot{w},\ \dot{q},\ \dot{v},\ \dot{p},\ \dot{r}$$

are computed for the analytical model using the states and controls from the piloted simulated maneuvers. Comparisons with the accelerations from the wind-tunnel data model are shown below in Figures 10.1-10.7.

The piloted simulated maneuvers comparison herein shows that the angular pitch accelerations from the wind-tunnel data and the analytical model have about the same shape but at times have a fairly large distance between them. We show in Appendix E that this is due to a small error in fit being multiplied by a large dynamic pressure at Mach 0.9. Therein we present some details from Run 5 (Figure 10.3) which is a turn reversal maneuver to show that the differences are due to a small difference of about 0.006 or less in the values of $C_{m_0}(t)$. As can be seen from the modeling fits shown in Figures 5.1-5.6 modeling errors of this magnitude are present in C_{m_0} at all Mach numbers. We found that the largest differences are equivalent to approximately a half degree change in stabilator deflection angle.

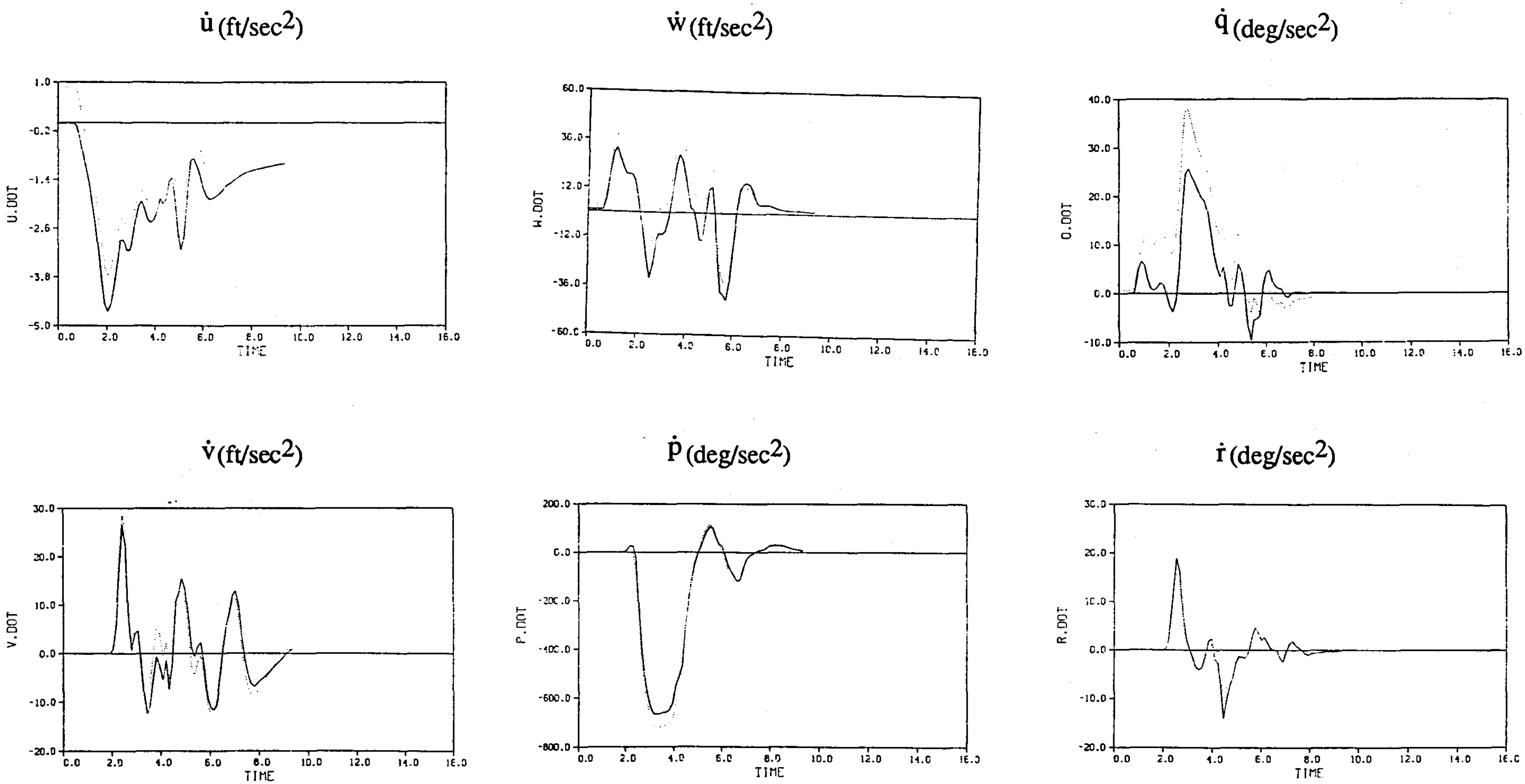
Analytical Model Simulation: Pitch Up Maneuver @ M=0.9 (Run 3, 10 October 1987)



——— Wind-Tunnel .... Analytical

Figure 10.1: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: $\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$
Pitch Up Maneuver @ M=0.9 (Run 3, 10 October 1987).

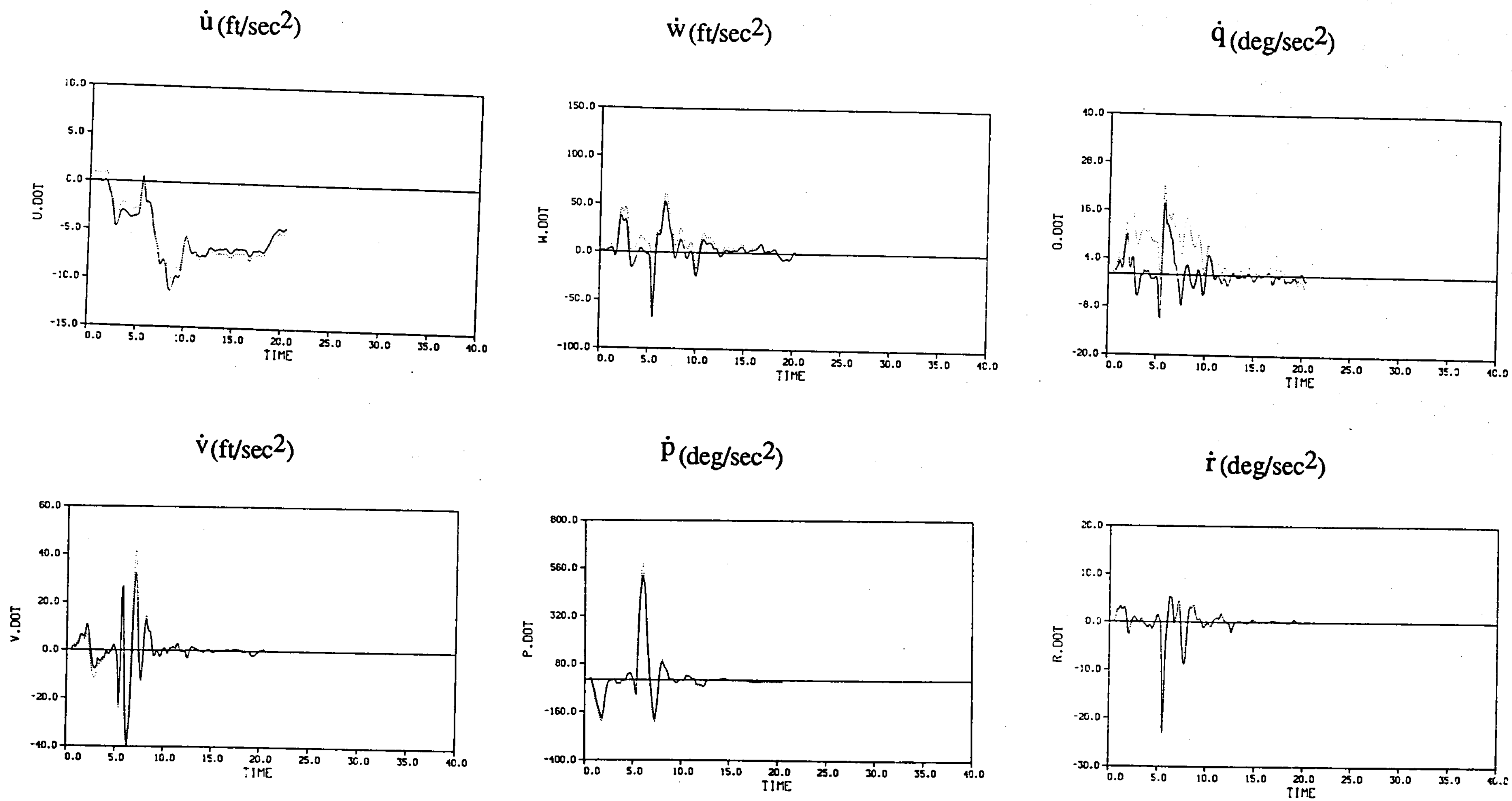
Analytical Model Simulation: 360° Loaded Roll Maneuver @ M=0.9 (Run 4, 10 October 1987)



_________ Wind-Tunnel .... Analytical

Figure 10.2: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: $\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$
360° Loaded Roll Maneuver @ M=0.9 (Run 4, 10 October 1987).

Analytical Model Simulation: Turn Reversal Maneuver @ M=0.9 (Run 5, 10 October 1987)



________ Wind-Tunnel ....Analytical

Figure 10.3: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: Turn Reversal Maneuver @ M=0.9 (Run 5, 10 October 1987).

$\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$

Analytical Model Simulation: 360° Unloaded Roll (AB) Maneuver @ M=0.9 (Run 9, 10 October 1987)

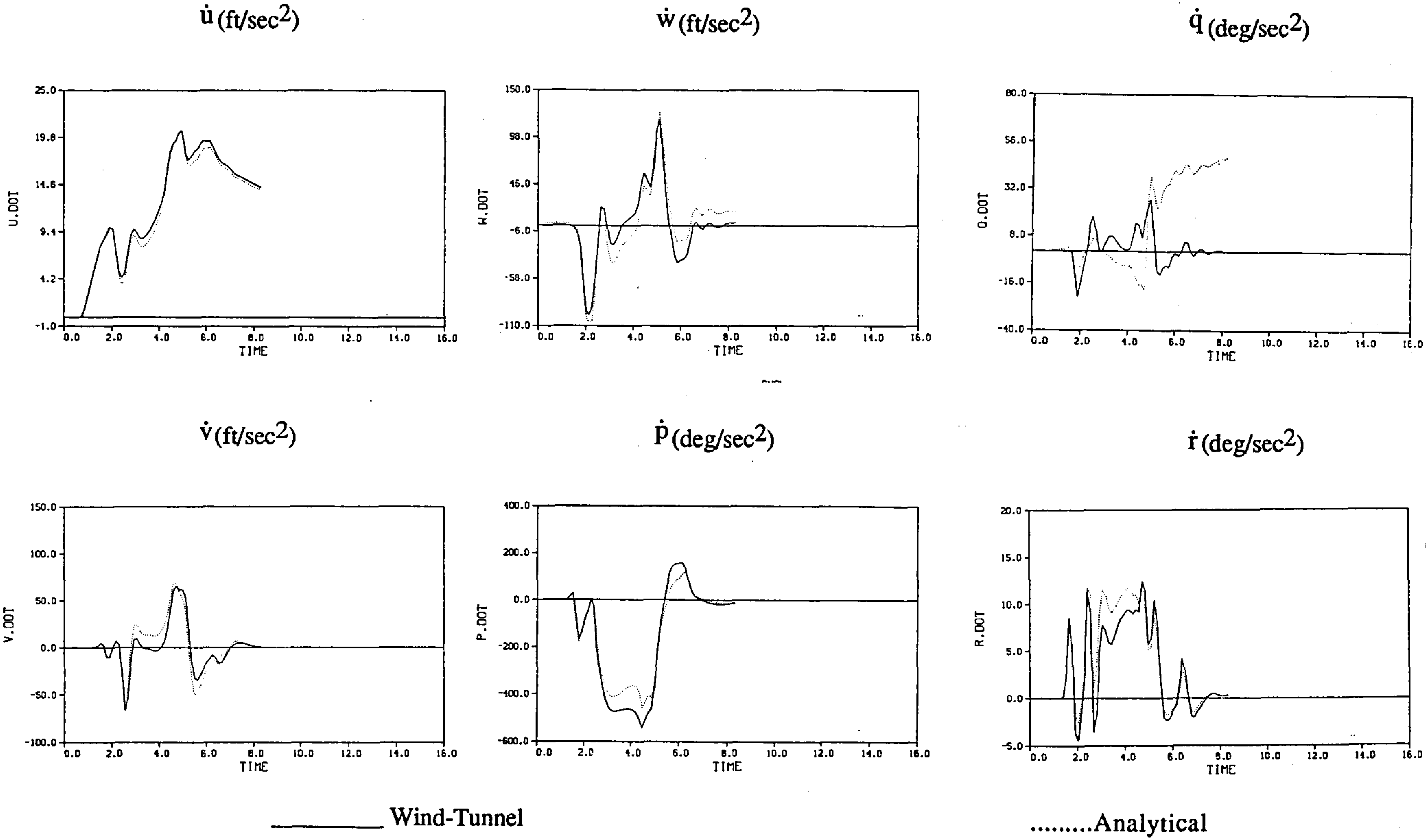
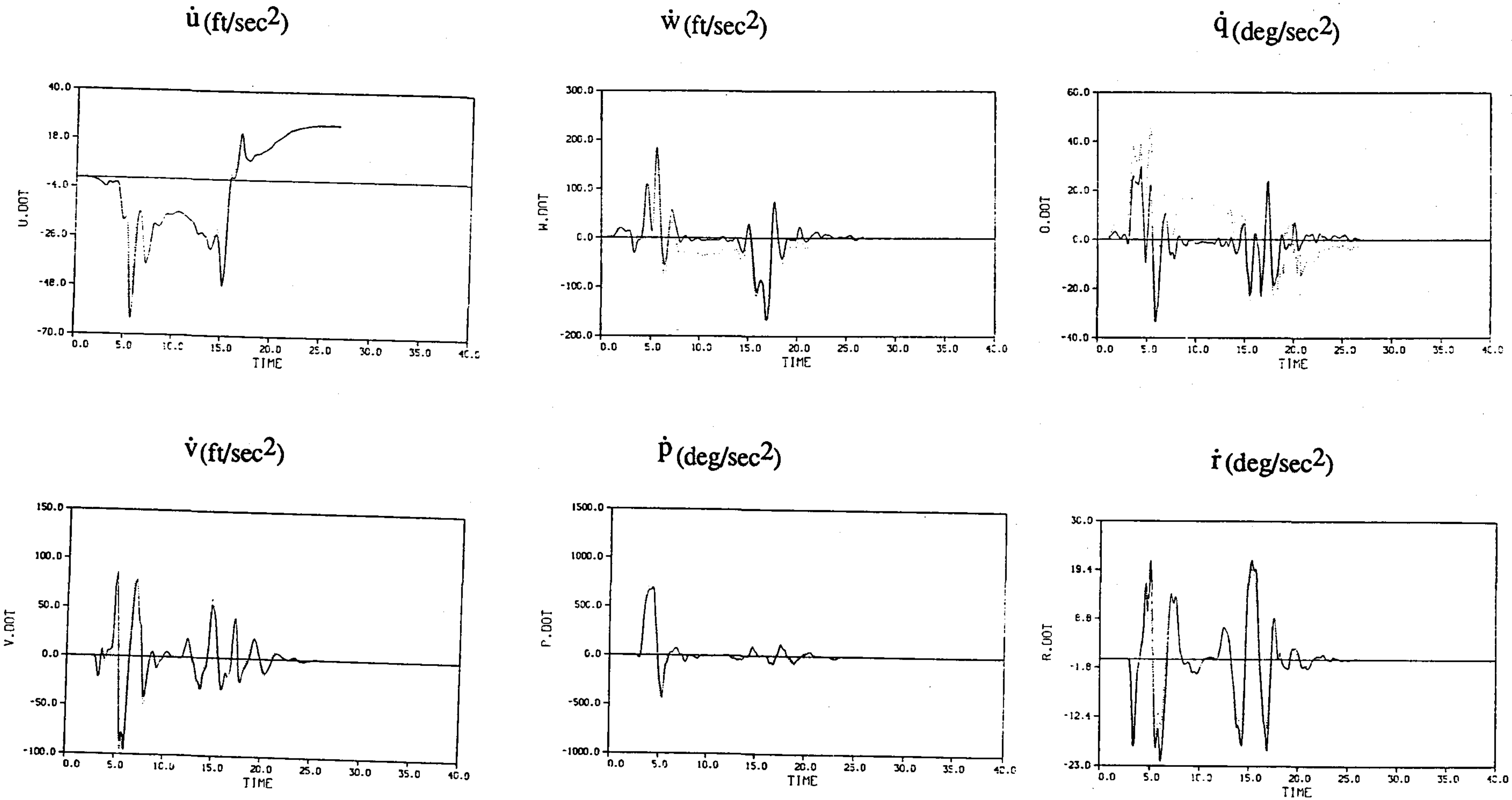


Figure 10.4: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: 360° Unloaded Roll (AB) Maneuver @ M=0.9 (Run 9, 10 October 1987).

$\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$

Analytical Model Simulation: Split S Maneuver @ M=0.9 (Run 6, 10 October 1987)



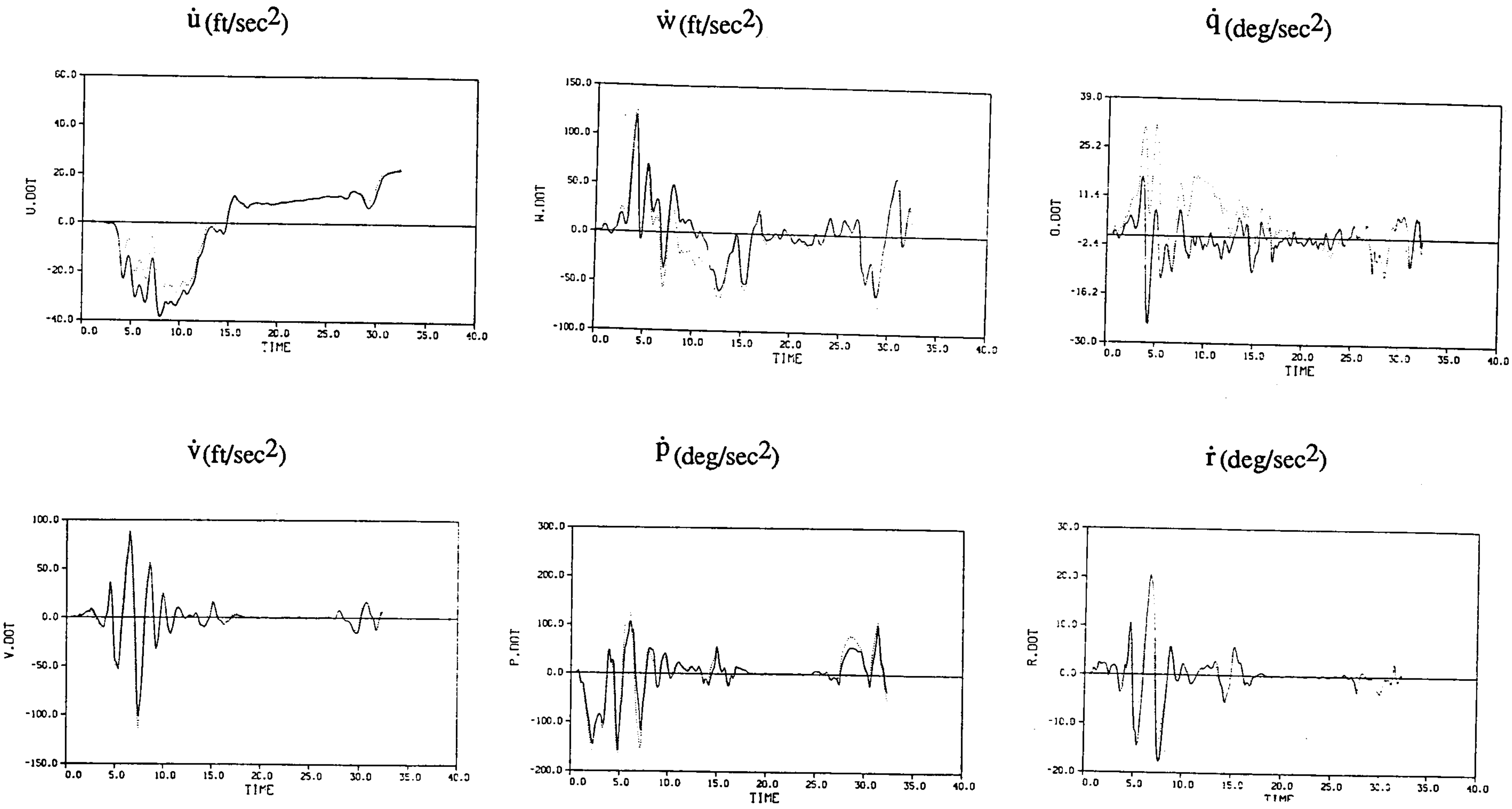
________ Wind-Tunnel

.........Analytical

Figure 10.5: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: Split S Maneuver @ M=0.9 (Run 6, 10 October 1987).

$\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$

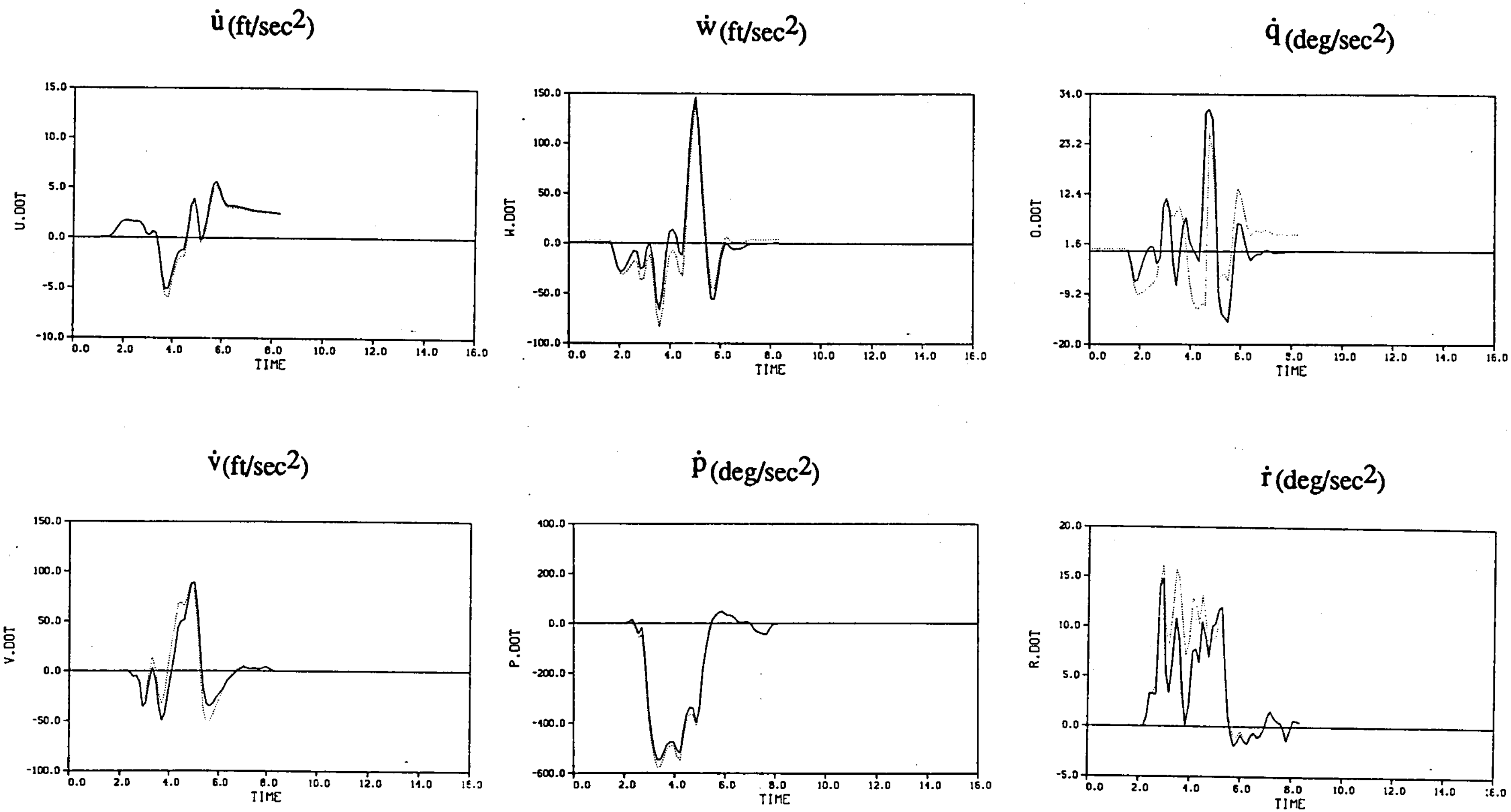
Analytical Model Simulation: Level Turn Maneuver @ M=0.9 (Run 7, 10 October 1987)



__________ Wind-Tunnel .... Analytical

Figure 10.6: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: Level Turn Maneuver @ M=0.9 (Run 7, 10 October 1987). $\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$

Analytical Model Simulation: 360° Unloaded Roll (MIL PWR) Maneuver @ M=0.9 (Run 8, 10 October 1987)



———— Wind-Tunnel ....Analytical

Figure 10.7: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: $\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$
360° Unloaded Roll (MIL PWR) Maneuver @ M=0.9 (Run 8, 10 October 1987).

11. Time History Comparison of $\dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}$ and $\dot{r}$: Mach = 0.3

The simulation wind-tunnel model of [1] was flown in NASA's simulator by a pilot to generate some basic maneuvers at 0.3 Mach numbers such as pitch-ups, 360^o loaded and unloaded rolls, turn reversals, split S's and level turns. That simulator data is used here to check the validity of the 6 DOF analytical model. The accelerations

$$\dot{u},\ \dot{w},\ \dot{q},\ \dot{v},\ \dot{p},\ \dot{r}$$

are computed for the analytical model using the states and controls from the piloted simulated maneuvers. Comparisons with the accelerations from the wind-tunnel data model are shown below in Figures 11.1-11.7.

Analytical Model Simulation: Pitch Up Maneuver @ M=0.3 (Run 11, 6 October 1987)

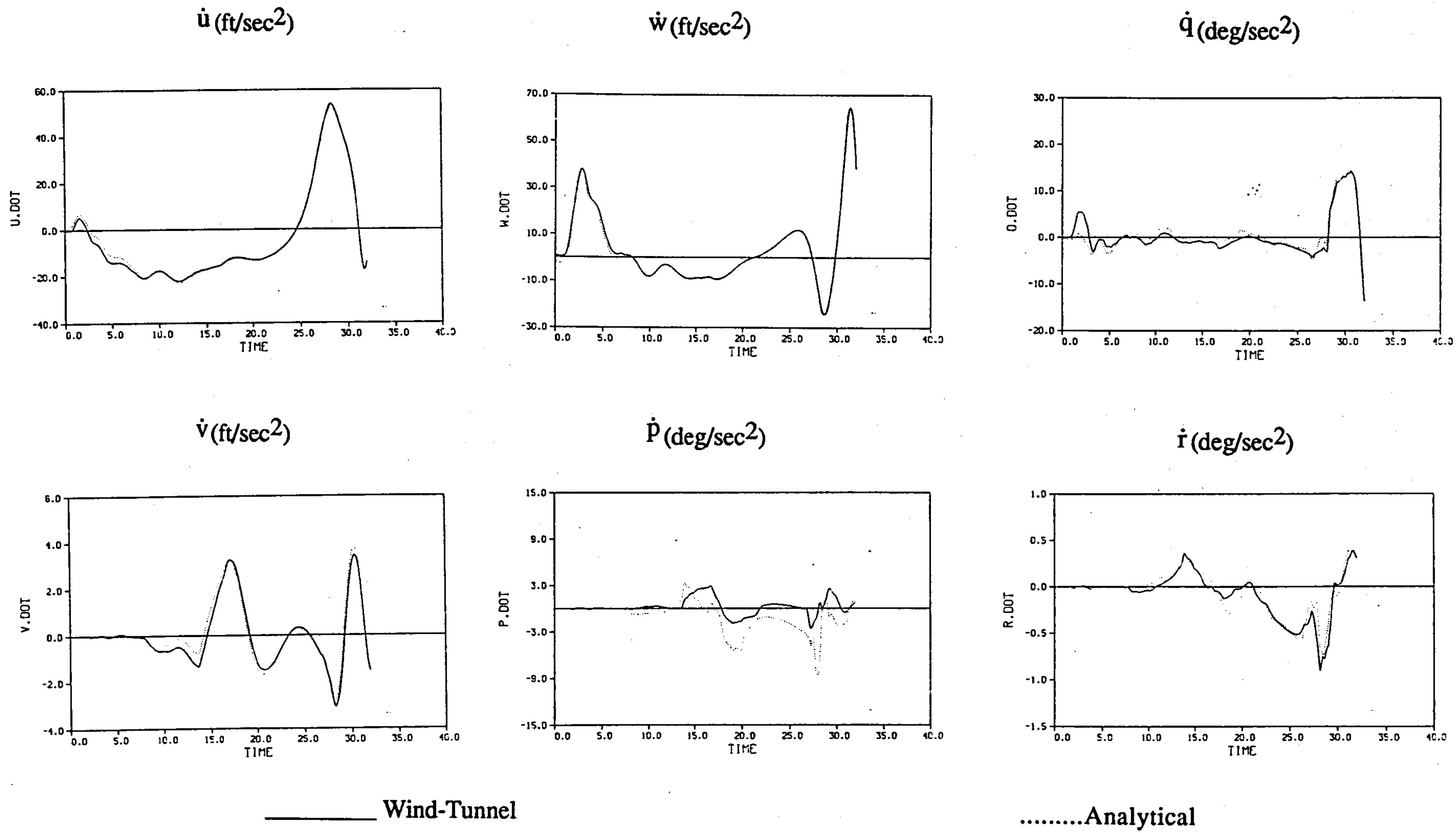


Figure 11.1: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: $\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$
Pitch Up Maneuver @ M=0.3 (Run 11, 6 October 1987).

Analytical Model Simulation: 360° Loaded Roll Maneuver @ M=0.3 (Run 13, 6 October 1987)

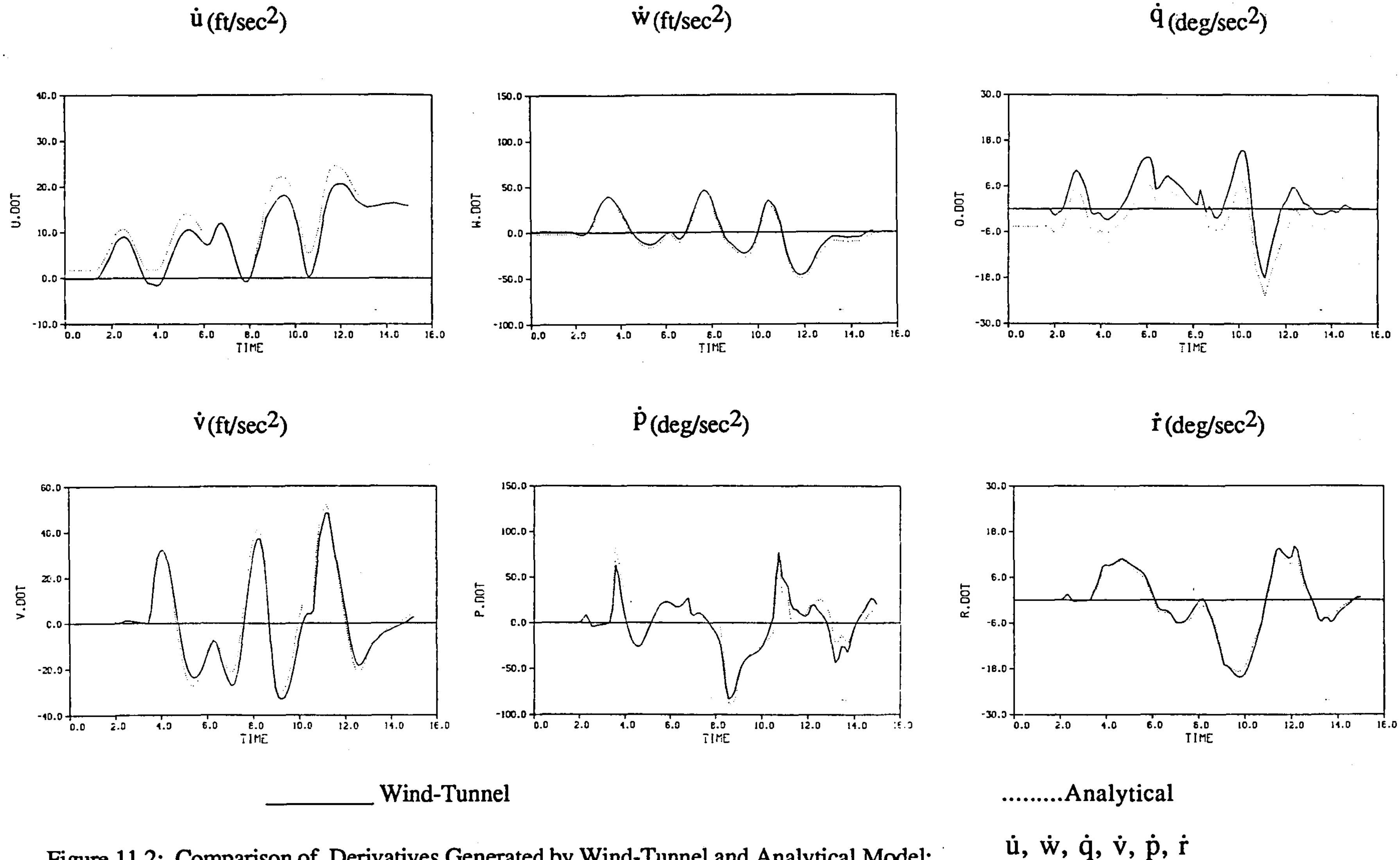
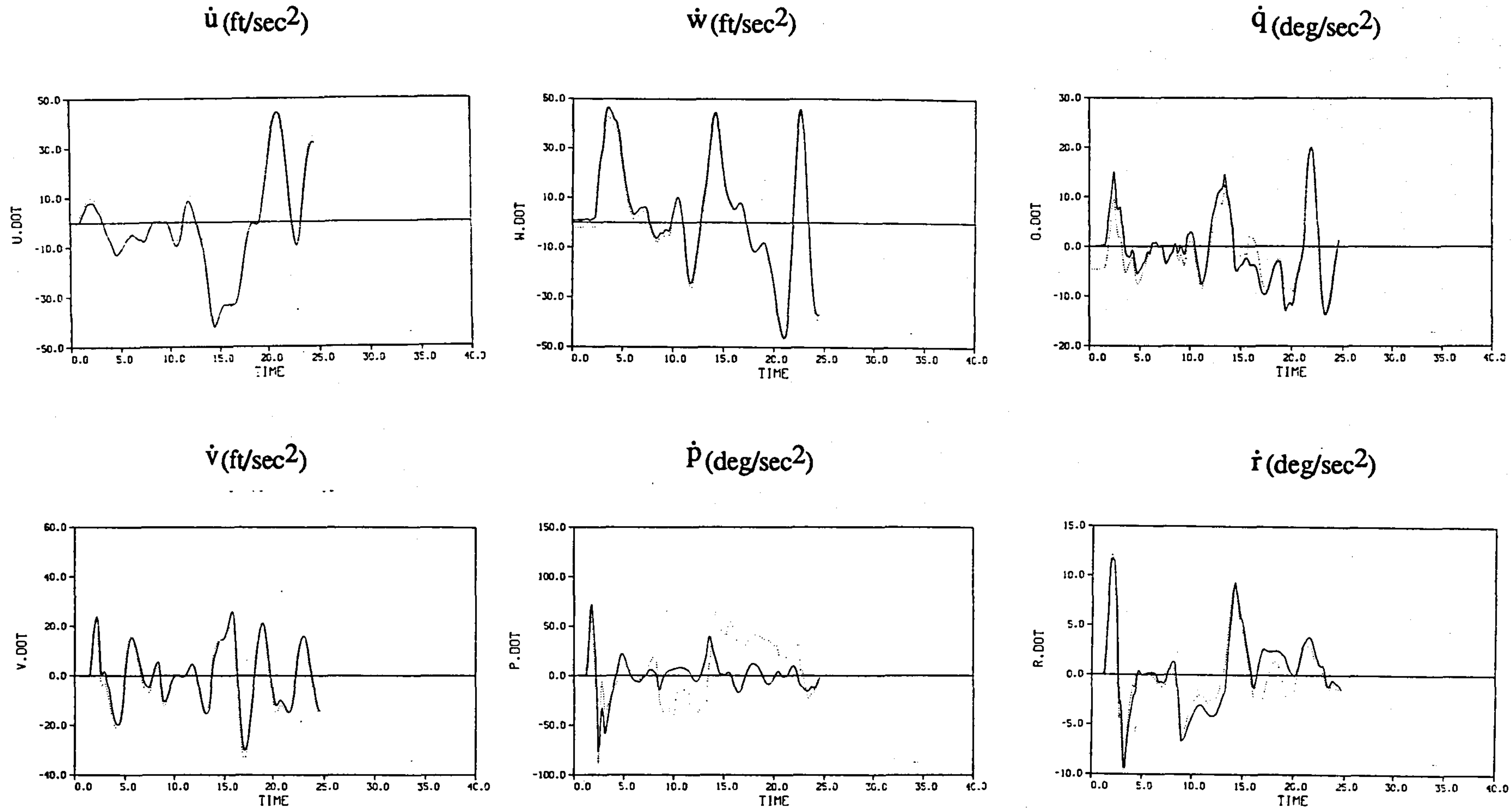


Figure 11.2: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: 360° Loaded Roll Maneuver @ M=0.3 (Run 13, 6 October 1987).

Analytical Model Simulation: Turn Reversal Maneuver @ M=0.3 (Run 15, 6 October 1987)



———— Wind-Tunnel ....Analytical

Figure 11.3: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: Turn Reversal Maneuver @ M=0.3 (Run 15, 6 October 1987). $\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$

Analytical Model Simulation: 360° Unloaded Roll Maneuver @ M=0.3 (Run 21, 6 October 1987)

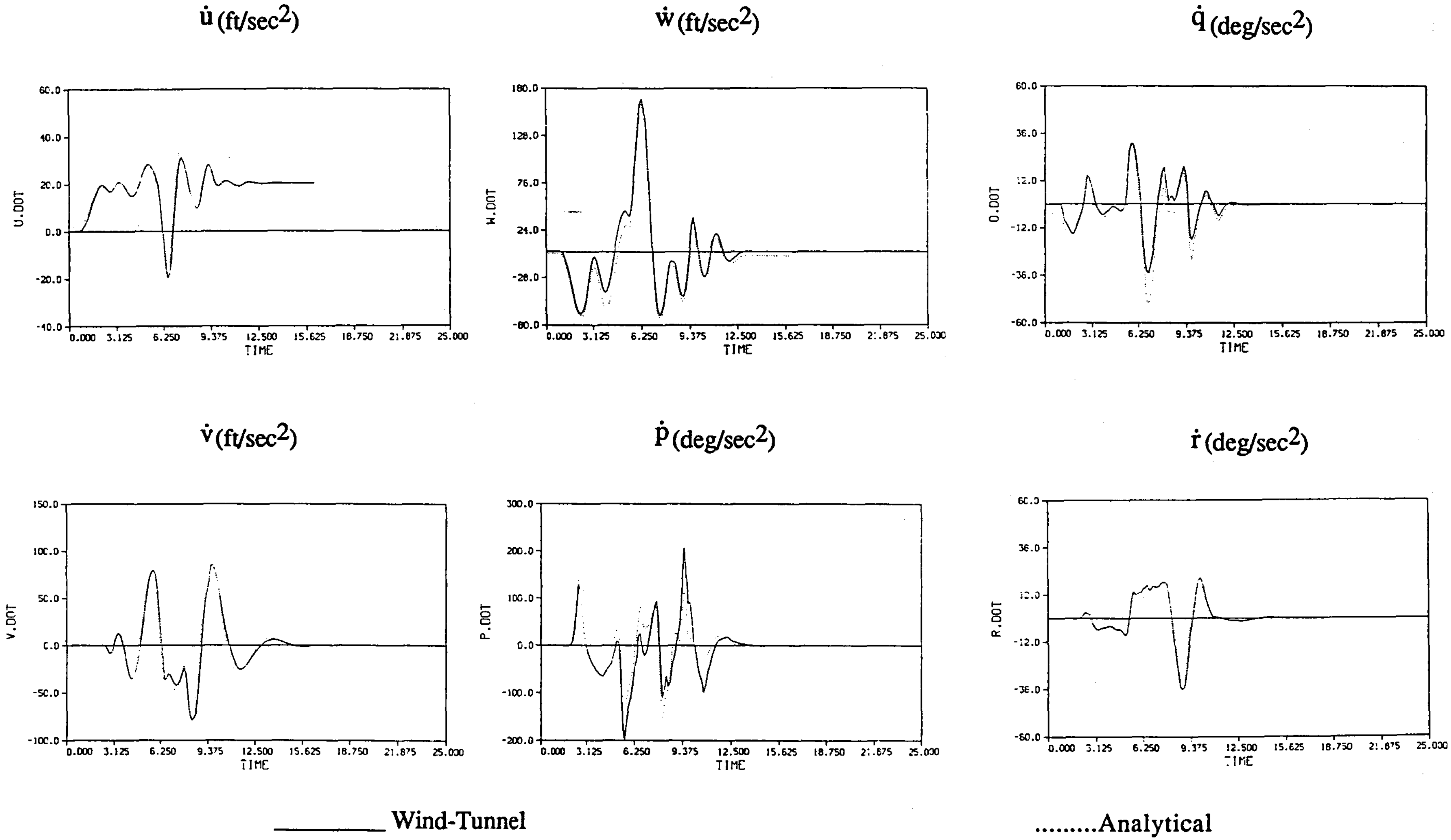
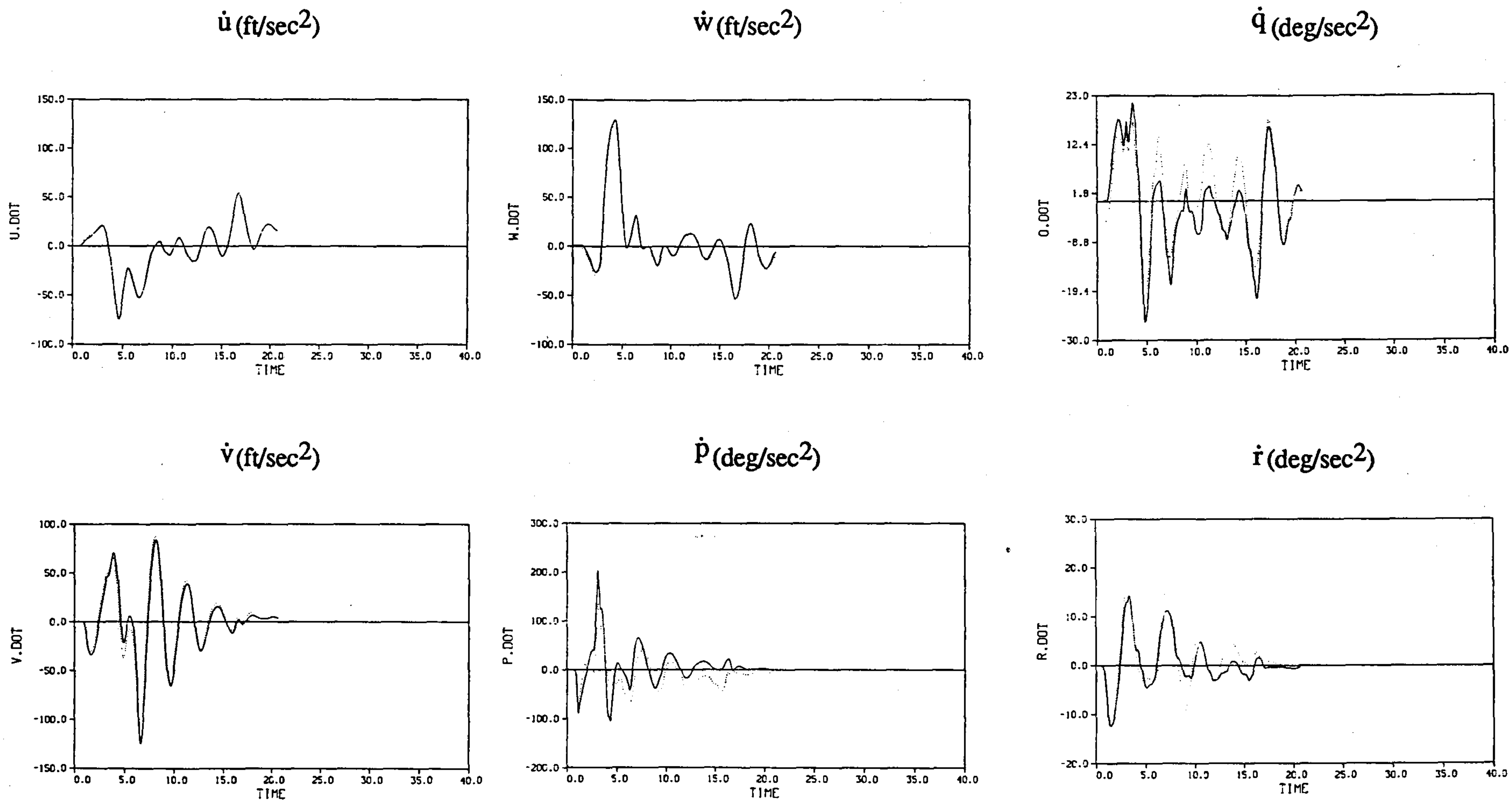


Figure 11.4: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: 360° Unloaded Roll Maneuver @ M=0.3 (Run 21, 6 October 1987).

$\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$

Analytical Model Simulation: Split S Maneuver @ M=0.3 (Run 16, 6 October 1987)



_________ Wind-Tunnel ....Analytical

Figure 11.5: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: Split S Maneuver @ M=0.3 (Run 16, 6 October 1987).

$\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$

Analytical Model Simulation: Level Turn (MAX) Maneuver @ M=0.3 (Run 20, 6 October 1987)

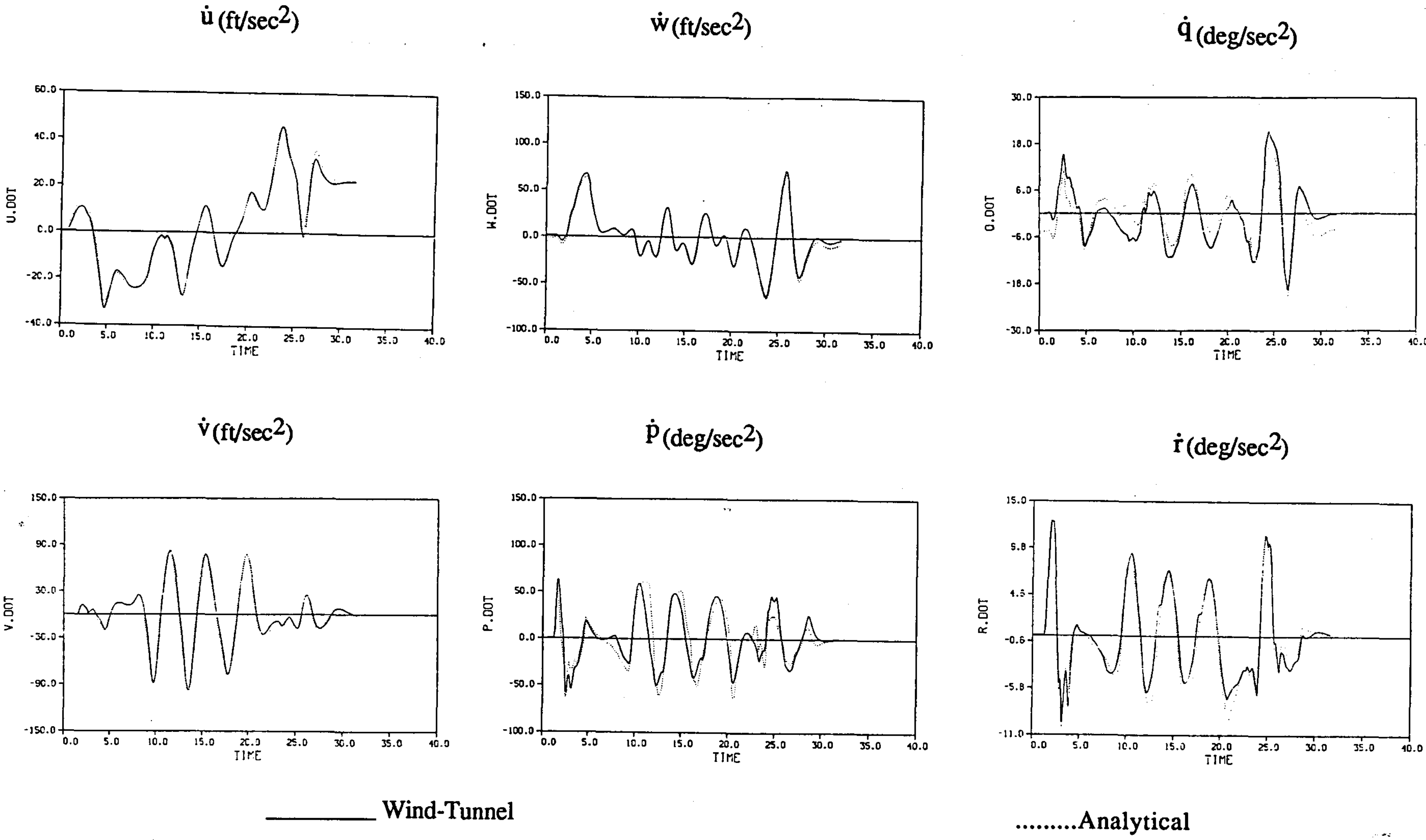
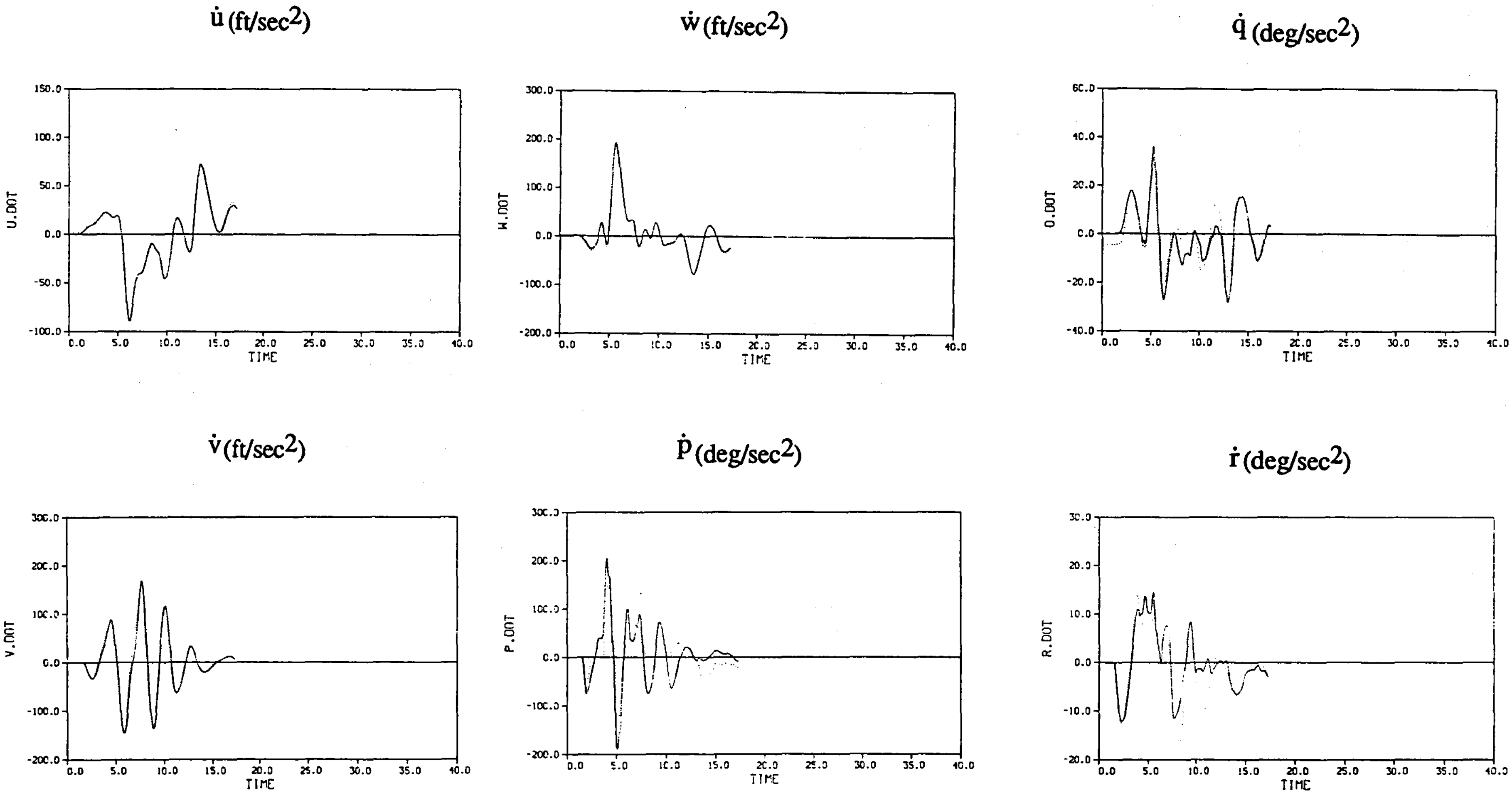


Figure 11.6: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: Level Turn (MAX) Maneuver @ M=0.3 (Run 20, 6 October 1987).

$\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$

Analytical Model Simulation: Split S Maneuver @ M=0.3 (Run 18, 6 October 1987)



———— Wind-Tunnel ……...Analytical

Figure 11.7: Comparison of Derivatives Generated by Wind-Tunnel and Analytical Model: $\dot{u}$, $\dot{w}$, $\dot{q}$, $\dot{v}$, $\dot{p}$, $\dot{r}$
Split S Maneuver @ M=0.3 (Run 18, 6 October 1987).

12. SUMMARY

A six degrees of freedom (6 DOF) analytical aerodynamic model is derived from a high angle-of-attack combat airplane wind-tunnel model, [1]. The derivation considered the altitude-Mach flight envelope centered at an altitude h = 15,000 feet and a Mach number M = 0.6. Wind-tunnel data ranging from 0.3 Mach to 0.9 Mach was used in developing the analytical models. The derived analytical models of the aerodynamic derivatives are nonlinear functions of alpha with all other states and control variables fixed. The nonlinear functions are parameterized with respect to sideslip, Mach number, roll, pitch and yaw rates and aileron deflection, rudder deflection and stabilator deflection. The lift and pitching moment coefficients have unsteady flow parts due to the time rate of change of angle of attack (alpha dot). The effects of leading edge flap, trailing edge flap, speed brake, landing gear, etc was not consided. Interpolation is required between the parameterized nonlinear functions.

Formulae for the analytical models are shown to compare well with their fits of the wind-tunnel data. The piloted simulated maneuvers comparison of Chapters 9-11 in which the analytical model is compared with the wind-tunnel data show that (1) the analytical model is a good representation of the wind-tunnel at Mach 0.6, (2) the longitudinal part of the analytical model is good for the Mach number range 0.3 to 0.9 and (3) the lateral part is good for Mach numbers between 0.6 to 0.9. Analytical models of the rolling moment coefficient were not derived using 0.3 Mach wind-tunnel data. The piloted simulated maneuvers comparison of Chapter 11 indicates that analytical models of the rolling moment coefficient should be fit at Mach 0.3 in order to better represent the wind-tunnel model there. The piloted simulated maneuvers comparison of Chapter 10 shows that the angular pitch accelerations from the wind-tunnel data and the analytical model have about the same shape but at times have a fairly large distance between them; this is due to a small C_{m_0} error of about 0.006 in fit being multiplied by a large dynamic pressure at Mach 0.9; see appendix E. We found that the largest differences are equivalent to approximately a half degree change in stabilator deflection. Such a difference should not be critical in analysis studies.

The results in this report indicate that the analytical model is a good representation of the wind-tunnel model for flight analysis in the altitude-Mach flight envelope centered at an altitude h = 15,000 feet and a Mach number M = 0.6. The storage requirement of the analytical model is about one tenth that of the wind-tunnel model and it runs twice as fast.

REFERENCES

1. Buttrill, C. S., Hoffler, K. H. AND Arbuckle, P. D. , " Simulation Model Description of a Twin Tail, High Performance Airplane," NASA LaRC TM in preparation.

2. "F/A-18 Stability and Control Data Report, Volume I: Low Angle of Attack", Report # MDC A7247, Issue data 31 August 1981, Revision date 15 November 1982, Revision letter B, McDonell Aircraft Company

3. "F/A-18 Stability and Control Data Report, Volume II: High Angle of Attack", Report # MDC A7247, Issue date 31 August 1981, McDonell Aircraft Company

4. Etkin, B., Dynamics of Atmospheric Flight, John Wiley and Sons, New York, 1972.

APPENDIX A

Computer Code for Equations of Motion

```
=============================================================
==  COMAN          THIS PROGRAM IS USED TO COMPUTE U.DOT,V.DOT    ==
==                 W.DOT,P.DOT,Q.DOT,R.DOT FOR THE HARV ANALY-    ==
==                 TICAL MODEL                                    ==
==                                                                ==
==  INPUTS:        FLIGHT_DATA FILE                               ==
==                 T           TIME                               ==
==                 MACH        MACH NUMBER                        ==
==                 HAB         ALTITUDE                           ==
==                 QBAR        DYNAMIC PRESSURE                   ==
==                 ALPDEG      ANGEL OF ATTACK                    ==
==                 BETADEG     SIDESLIP ANGEL                     ==
==                 PHID        EULER BANK ANGEL                   ==
==                 THETAD      EULER PITCH ANGEL                  ==
==                 PSID        EULER YAW ANGEL                    ==
==                 P           AIRCRAFT X-BODY AXIS ROLL RATE     ==
==                 Q           AIRCRAFT Y-BODY AXIS PITCH RATE    ==
==                 R           AIRCRAFT Z-BODY AXIS YAW RATE      ==
==                 DH          STABILATOR DEFLECTION              ==
==                 DA          AILERON DEFLECTION                 ==
==                 DR          RUDDER DEFLECTION                  ==
==                                                                ==
==  OUTPUTS:       UDT         TIME DERIVATIVE OF U               ==
==                 VDT         TIME DERIVATIVE OF V               ==
==                 WDT         TIME DERIVATIVE OF W               ==
==                 PDT         TIME DERIVATIVE OF P               ==
==                 QDT         TIME DERIVATIVE OF Q               ==
==                 RDT         TIME DERIVATIVE OF R               ==
==                                                                ==
==                                                                ==
==                                                                ==
==  AUTHER        JICHANG CAO                                     ==
==                GRADUATE RESEARCH ASSISTANT                     ==
==                SCHOOL OF AEROSPACE ENGINEERING                 ==
==                GEORGIA INSTITUTE OF TECHNOLOGY                 ==
==                ATLANTA,GEORGIA 30332                           ==
==                                                                ==
==  DATA         JUNE,1990                                        ==
==                                                                ==
=============================================================
      PROGRAM COMLAT
      PARAMETER (N=129)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      REAL*8  MACH ,MASS ,NZ ,IAS ,HAB
      REAL*8  AU(N) ,AV(N) ,AW(N) ,AP(N) ,AQ(N) ,AR(N)
      REAL*8  APHID(N) ,ATHETA(N) ,APSID(N) ,AALP(N) ,ABET(N)
      REAL*8  TIME(N) ,AMACH(N) ,AHAB(N) ,AQBAR(N) ,AVTOTAL(N)
      REAL*8  ADH(N) ,ADA(N) ,ADR(N)
      REAL*8  UDT(N) ,VDT(N) ,WDT(N) ,PDT(N) ,QDT(N) ,RDT(N)
      REAL*8  ATNETL(N),ATNETR(N) ,LXE ,LYE ,LZE
      CHARACTER*80  HEADER
      CHARACTER  AA1*15,AA2*15,AA3*15,AA4*15,AA5*15,BB*50
      OPEN (UNIT=5,FILE='MACH03')
      OPEN (UNIT=6,FILE='DATA_ANAL')
      -------------------------------------------------------------
      GENERAL CONSTANTS
      -------------------------------------------------------------
      G   =32.174
      DTR =ACOS(-1.)/180.
      -------------------------------------------------------------
      AIRCRAFT CONSTANTS
      -------------------------------------------------------------
      MASS   =1035.308
      XI     =23000.
      YI     =151293.
      ZI     =169945.
```

```
      XZI     =-2971.
      B       =37.42
      CBAR    =11.52
      S       =400.
      XL      =-3.56/12.
      YL      =0.
      ZL      =2.8/12.
      THZ     =0.0

      LXE     =-232.5/12.
      LYE     =0.0
      LZE     =2.8/12.

      CSTAR   =XI*ZI/(XI*ZI-XZI**2)
      C41     =CSTAR*XZI*(ZI+XI-YI)/(XI*ZI)
      C42     =CSTAR*(ZI*(YI-ZI)-XZI**2)/(XI*ZI)
      C43     =CSTAR*XZI/XI
      C51     =(ZI-XI)/YI
      C52     =XZI/YI
      C61     =CSTAR*(XI*(XI-YI)+XZI**2)/(XI*ZI)
      C62     =CSTAR*XZI*(YI-ZI-XI)/(XI*ZI)
      C63     =CSTAR*XZI/ZI
      ------------------------------------------------------------------
      FLIGHT CONDITION
      ------------------------------------------------------------------
      READ (5,5) NUMBER
      DO 99 I=2,13
      READ (5,15) AA1 ,AA2 ,AA3 ,AA4 ,AA5
   99 CONTINUE
      READ (5,25) BB
    5 FORMAT (I4)
   15 FORMAT (5A15)
   25 FORMAT (A50)

      DO 400 I=1,N
      READ FLIGHT DATA FILE
      READ (5,10) T ,MACH ,HAB ,QBAR ,ALPDEG ,BETADEG ,PSID ,THETAD
      READ (5,10) PHID ,PDEG ,QDEG ,RDEG ,VTOTAL,AX ,AY ,GZ
      READ (5,10) DLADEG.DLADDEG,DLSDEG,DLHDDEG,DLNDEG,DLNDDEG,
     1            DLFDEG.DLFDDEG
      READ (5,20) DLRDEG ,DLRDDEG ,TNETL ,TNETR
*******************************************************************
      T       ---  TIME
      MACH    ---  MACH NUMBER
      HAB     ---  ALTITUDE
      QBAR    ---  DYNAMIC PRESSURE
      ALPDEG  ---  ANGEL OF ATTACK
      BETADEG ---  SIDESLIP ANGEL
      PSID    ---  EULER BANK ANGEL
      THETAD  ---  EULER PITCH ANGEL
      PHID    ---  EULER YAW ANGEL
      PDEG    ---  AIRCRAFT X-BODY AXIS ROLL RATE
      QDEG    ---  AIRCRAFT Y-BODY AXIS PITCH RATE
      RDEG    ---  AIRCRAFT Z-BODY AXIS YAW RATE
      VTOTAL  ---  VELOCITY
      DLADEG  ---  AILERON DEFLECTION (AVERAGE)
      DLRDEG  ---  RUDDER DEFLECTION (AVERAGE)
      DLSDEG  ---  STABILATOR DEFLECTION (AVERAGE)
      TNETL   ---  THRUST OF LEFT ENGINE
      TNETR   ---  THRUST OF RIGHT ENGINE
*******************************************************************
   10 FORMAT (8E10.4)
   20 FORMAT (4E10.4)

      U      = VTOTAL*DCOS(ALPDEG*DTR)*DCOS(BETADEG*DTR)
      V      = VTOTAL*DSIN(BETADEG*DTR)
```

```
      W      = VTOTAL*DSIN(ALPDEG*DTR)*DCOS(BETADEG*DTR)

      AVTOTAL(I)  = VTOTAL
      AU(I)  = U
      AV(I)  = V
      AW(I)  = W

      AP(I)  = PDEG
      AQ(I)  = QDEG
      AR(I)  = RDEG

      APHID(I)   =PHID
      ATHETA(I)  =THETAD
      APSID(I)   =PSID

      AALP(I)    =ALPDEG
      ABET(I)    =BETADEG
      AHAB(I)    =HAB
      TIME(I)    =T
      AQBAR(I)   =QBAR
      AMACH(I)   =MACH

      ADH(I)     =DLSDEG
      ADA(I)     =DLADEG
      ADR(I)     =DLRDEG

      ATNETL(I)  =TNETL
      ATNETR(I)  =TNETR

  400 CONTINUE

      DO 410 I=1,N
      BO2VT   = B/(2*AVTOTAL(I))
      CO2VT   = CBAR/(2*AVTOTAL(I))
      ALPHA   =AALP(I)
      BETA    =ABET(I)
      MACH    =AMACH(I)
      ALT     =AHAB(I)
      DH      =ADH(I)
      DA      =ADA(I)/2.
      DR      =ADR(I)
      QBAR    =AQBAR(I)
      TNETL   =ATNETL(I)
      TNETR   =ATNETR(I)

      P       =AP(I)*DTR
      Q       =AQ(I)*DTR
      R       =AR(I)*DTR

      CALL NAEROC1  (CLO  ,CLQ  ,CLAD,CMO  ,CMQ  ,CMAD,
     *                CDO  ,
     *              =F (
     *                ALPHA,MACH,DH,ALT)

      CALL NAEROC2  (CYO  ,C1O  ,CNO  ,CYB  ,C1B  ,CNB  ,
     *                CYR  ,C1R  ,CNR  ,CYP  ,C1P  ,CNP  ,
     *              =F (
     *                ALPHA  ,BETA  ,MACH  ,DA  ,DR  ,DH  ,P  ,R  ,ALT  )


      U       =AU(I)
      V       =AV(I)
      W       =AW(I)

      PHID   =APHID(I)*DTR
      THET   =ATHETA(I)*DTR
```

```
      PSID  =APSID(I)*DTR

      AA    =ALPHA*DTR
      BT    =BETA*DTR

      THX   =(TNETL+TNETR)*COS(1.98*DTR)
      THY   = TNETR*SIN(-1.98*DTR)+TNETL*SIN(1.98*DTR)

      FD    = QBAR*S*CDO/MASS

      CB    = QBAR*S*CO2VT*CLAD/(U*U+W*W)/MASS
      BQ    = 1+CB*DCOS(AA)*U-CB*DCOS(AA)*W*(CB*DSIN(AA)*U)
     *        /(1+CB*DSIN(AA)*W)
      FU    = R*V-Q*W-G*DSIN(THET)-FD*DCOS(AA)+THX/MASS
     *        +QBAR*S*DSIN(AA)*(CLO+CO2VT*CLQ*Q)/MASS
      FW    = Q*U-P*V+G*DCOS(THET)*DCOS(PHID)-FD*DSIN(AA)
     *        -QBAR*S*DCOS(AA)*(CLO+CO2VT*CLQ*Q)/MASS+THZ/MASS
      WDT(I)= (FW+CB*DCOS(AA)*W*FU/(1+CB*DSIN(AA)*W))/BQ
      UDT(I)= (FU+CB*DSIN(AA)*U*WDT(I))/(1+CB*DSIN(AA)*W)
      DALFA = (U*WDT(I)-W*UDT(I))/(U*U+W*W)

      CL    = CLO+CO2VT*(CLQ*Q+CLAD*DALFA)
      CM    = CMO+CO2VT*(CMQ*Q+CMAD*DALFA)

      C1    = C1O+C1B*BT+BO2VT*(C1P*P+C1R*R)
      CY    = CYO+CYB*BT+BO2VT*(CYP*P+CYR*R)
      CN    = CNO+CNB*BT+BO2VT*(CNP*P+CNR*R)

      FL    = QBAR*S*CL/MASS

      FX    = -FD*DCOS(AA)+FL*DSIN(AA)
      FY    = QBAR*S*CY/MASS
      FZ    = -FD*DSIN(AA)-FL*DCOS(AA)

      FP    = QBAR*S*B*C1/XI+MASS*(YL*FZ-ZL*FY)/XI
      FQ    = QBAR*S*CBAR*CM/YI+MASS*(ZL*FX-XL*FZ)/YI
      FR    = QBAR*S*B*CN/ZI+MASS*(XL*FY-YL*FX)/ZI

      VDT(I) = P*W-R*U+G*COS(THET)*SIN(PHID)+FY+THY/MASS

      YY1    = C41*P*Q+C42*Q*R+C43*FR+CSTAR*FP+C43*LXE*THY/ZI
     1         -C43*LYE*THX/ZI
     1         +CSTAR*(LYE*THZ-LZE*THY)/XI

      YY2    = C51*P*R+C52*(R*R-P*P)+FQ+(LZE*THX-LXE*THZ)/YI

      YY3    = C61*P*Q+C62*Q*R+C63*FP+CSTAR*FR+C63/XI*(LYE*THZ-LZE*THY)
     1         +CSTAR/ZI*LXE*THY
     1         -CSTAR*LYE*THX/ZI

      PDT(I) =YY1/DTR
      QDT(I) =YY2/DTR
      RDT(I) =YY3/DTR

  410 CONTINUE

      M=N-2
      DO 710 I=1,M
      WRITE (6,910) TIME(I) ,UDT(I) ,VDT(I) ,WDT(I) ,PDT(I) ,QDT(I),
     1              RDT(I)
  710 CONTINUE
  910 FORMAT(7E10.4)
      STOP
      END
```

APPENDIX B

Computer Code for Longitudinal Analytical Model

```
C-------------------------------------------------------------------==
C-------------------------------------------------------------------==
C    PURPOSE: THIS SUBROUTINE WILL BE CALLED TO CALCULATE 7 AERODY-   ==
C             NAMIC COEFFICIENTS WHICH ARE THE OUTPUTS OF THIS SUB-   ==
C             ROUTINE.(LONGITUDINAL COEFFICIENTS)                     ==
C                                                                     ==
C    INPUTS:                                                          ==
C              ALPDEG  ANGLE OF ATTACK        (DEG)                   ==
C              MACH    MACH NUMBER                                    ==
C              ALT     ALTITUDE               (FEET)
C              DH      STABILATOR DEFLECTION  (DEG)                   ==
C                                                                     ==
C    OUTPUTS:                                                         ==
C              CLO ,CLQ ,CLAD                                         ==
C              CMO ,CMQ ,CMAD                                         ==
C              CDO                                                    ==
C                                                                     ==
C    THOSE COEFFICIENTS ARE USED  IN THE FOLLOWING FORMULAS           ==
C                                                                     ==
C          CL = CLO+CO2VT*(CLQ*Q+CLAD*ALPDEG)                         ==
C          CM = CMO+CO2VT*(CMQ*Q+CMAD*ALPDEG)                         ==
C          CD = CDO                                                   ==
C                                                                     ==
C          CL       LIFT FORCE COEFFICIENT ALONG Z_WIND AXIS          ==
C          CM       PITCH MOMENT COEFFICIENT ABOUT Y_WIND AXIS        ==
C          CD       SIDE FORCE COEFFICIENT ABOUT X_WIND AXIS          ==
C          CREF     REFERENCE WINGSPAN                                ==
C          V        AIRCRAFT TOTAL AIRSPEED                           ==
C                                                                     ==
C    AUTHER:   JICHANG CAO                                            ==
C              GRADUATE RESEARCH ASSISTANT                            ==
C              GEORGIA INSTITUTE OF TECHNOLOGY                        ==
C              ATLANTA, GA30332                                       ==
C                                                                     ==
C=====================================================================
      SUBROUTINE NAEROC1 (CLO ,CLQ ,CLAD,CMO ,CMQ ,CMAD,
     *                    CDO ,
C                        =F (
     *                    ALPDEG,MACH,DH,ALT)
C
      IMPLICIT REAL(C)
      REAL     ALFA,MACH,DH,ALT,ALPDEG,A,
     *         DHN,DHX,PI
C
C---------------------------------------------------------------------
C    CONVERSION OF ALFA
C---------------------------------------------------------------------
C
      IF (DH.LT.-24.)  DH=-24.
      IF (DH.GT.10.5)  DH=10.5
C---------------------------------------------------------------------
      A      = ALPDEG
      PI     =ACOS(-1.)
      SI     =2.75
C---------------------------------------------------------------------
C    EXTREMAL VALUES OF CONTROL SURFACES DEFLECTION
C---------------------------------------------------------------------
      DHN    = -24.
      DHX    = 10.5
C---------------------------------------------------------------------
C    COMPUTATION OF COEFFICIENTS
C---------------------------------------------------------------------
      CLOX6  = 0.86/SI*ATAN(-(A+5.)*1./100.)
     *         +2.19/SI*ATAN((A-5.)*1./7.)
     *         +0.90/SI*ATAN((A-24.)*1./17.)
     *         +1.71/SI*ATAN(-(A-53.)*2./25.)
```

```
     *          +.41/SI*ATAN(-(A-70.)*2./7.)
     *          -.1+.05
C
      CLON6  = 1.06/SI*ATAN(-(A+5.)*1./100.)
     *          +1.79/SI*ATAN((A-5.)*1./7.)
     *          +2.50/SI*ATAN((A-15.)*1./22.)
     *          +2.71/SI*ATAN(-(A-59.)*1./50.)
     *          +1.21/SI*ATAN(-(A-70.)*1./20.)
     *          -.80+.08
C
      CMOX6  = 0.26/SI*ATAN(-(A-5.)*1./10.)
     *          -0.39/SI*ATAN((A-1.)*1./8.)
     *          +0.80/SI*ATAN((A-5.)*1./13.)
     *          +0.70/SI*ATAN(-(A-10.)*1./65.)
     *          +1.20/SI*ATAN((A-49.)*1./15.)
     *          +2.10/SI*ATAN(-(A-69.)*1/15.)
     *          -0.45/SI*ATAN(-(A-77.)*1./2.)
     *          -.408+.01
C
      CMOO6  = 0.36/SI*ATAN(-(A-5.)*1./30.)
     *          -0.29/SI*ATAN((A-1.)*1./15.)
     *          +0.90/SI*ATAN((A-5.)*1./35.)
     *          +0.80/SI*ATAN(-(A-48.)*1./75.)
     *          +0.90/SI*ATAN((A-52.)*1./10.)
     *          +2.10/SI*ATAN(-(A-69.)*1/15.)
     *          -0.45/SI*ATAN(-(A-77.)*1./2.)
     *          -.45-.007
C
      CMOZ6  = 0.26/SI*ATAN(-(A-5.)*1./60.)
     *          -0.39/SI*ATAN((A-1.)*1./14.0)
     *          +0.80/SI*ATAN((A-5.)*1./42.)
     *          +0.80/SI*ATAN(-(A-20.)*1./55.)
     *          +1.80/SI*ATAN((A-65.)*1./60.)
     *          +2.40/SI*ATAN(-(A-69.)*1/20.)
     *          -0.45/SI*ATAN(-(A-79.)*1./2.)
     *          -.138-.02
C
      CMOX26  = 0.26/SI*ATAN(-(A-2.)*1./10.)
     *          -0.39/SI*ATAN((A-1.)*1./10.)
     *          +1.00/SI*ATAN((A-3.)*1./11.)
     *          +0.85/SI*ATAN(-(A-7.)*1./20.)
     *          +1.35/SI*ATAN((A-51.)*1./19.)
     *          +2.20/SI*ATAN(-(A-69.)*1/15.)
     *          -0.45/SI*ATAN(-(A-77.)*1./2.)
     *          -.3-.01
C
      CMOX56  = 0.26/SI*ATAN(-(A-5.)*1./10.)
     *          -0.39/SI*ATAN((A-1.)*1./12.)
     *          +0.90/SI*ATAN((A-5.)*1./15.)
     *          +0.85/SI*ATAN(-(A-10.)*1./30.)
     *          +1.35/SI*ATAN((A-49.)*1./19.)
     *          +2.20/SI*ATAN(-(A-69.)*1/15.)
     *          -0.45/SI*ATAN(-(A-77.)*1./2.)
     *          -.348-.02
C
      CMON6  = 0.26/SI*ATAN(-(A-5.)*1./60.)
     *          -0.39/SI*ATAN((A-1.)*1./30.)
     *          +0.80/SI*ATAN((A-5.)*1./45.)
     *          +0.80/SI*ATAN(-(A-10.)*1./65.)
     *          +1.80/SI*ATAN((A-49.)*1./45.)
     *          +2.80/SI*ATAN(-(A-69.)*1/23.)
     *          -0.45/SI*ATAN(-(A-79.)*1./2.)
     *          -.138-.01
C
      CMON56  = 0.26/SI*ATAN(-(A-5.)*1./30.)
     *          -0.39/SI*ATAN((A-1.)*1./30.0)
```

```
     *          +1.20/SI*ATAN((A-5.)*1./40.)
     *          +0.60/SI*ATAN(-(A-8.)*1./23.)
     *          +1.30/SI*ATAN(-(A-60.)*1./65.)
     *          +2.80/SI*ATAN((A-72.)*1./55.)
     *          +2.30/SI*ATAN(-(A-73.)*1/19.)
     *          -0.45/SI*ATAN(-(A-77.)*1./2.)
     *          -.168-.02
C
      CMON6  = 0.26/SI*ATAN(-(A-5.)*1./60.)
     *          -0.39/SI*ATAN((A-1.)*1./30.)
     *          +0.80/SI*ATAN((A-5.)*1./45.)
     *          +0.80/SI*ATAN(-(A-10.)*1./65.)
     *          +1.80/SI*ATAN((A-51.)*1./45.)
     *          +2.80/SI*ATAN(-(A-69.)*1/23.)
     *          -0.45/SI*ATAN(-(A-79.)*1./2.)
     *          -.138-.01
C ****************************************************************
      CDOX   =  0.40/SI*ATAN((A*78./80.+7.)*1./30.)
     *          +0.60/SI*ATAN(-(A*78./80.+2.)*1./8.)
     *          -0.30/SI*ATAN(-(A*78./80.+5.)*1./90.)
     *          -0.20/SI*ATAN(-(A*78./80.-6.)*1./5.)
     *          +1.95/SI*ATAN((A*78./80.-28.)*1./15.)
     *          +2.20/SI*ATAN((A*78./80.-58.)*1./40.)
     *          +1.40/SI*ATAN(-(A*78./80.-73.)*1./30.)
     *          +2.30/SI*ATAN(-(A*78./80.-138.)*1/20.)
     *          -.147
C
      CDOZ   = (0.60/SI*ATAN((A*77./80.+6.)*1./30.)
     *          +0.60/SI*ATAN(-(A*77./80.+1.)*1./8.)
     *          -0.30/SI*ATAN(-(A*77./80.+4.)*1./90.)
     *          -0.20/SI*ATAN(-(A*77./80.-7.)*1./10.)
     *          +1.95/SI*ATAN((A*77./80.-29.)*1./15.)
     *          +2.20/SI*ATAN((A*77./80.-59.)*1./40.)
     *          +1.55/SI*ATAN(-(A*77./80.-74.)*1./30.)
     *          +2.30/SI*ATAN(-(A*77./80.-139.)*1/20.)
     *          -.2635-.0199)*2.17/2.1+.0199
C
      CDON5  =  0.32/SI*ATAN((A*80./85.+8.)*1./30.)
     *          +0.60/SI*ATAN(-(A*80./85.+3.5)*1./6.5)
     *          -0.30/SI*ATAN(-(A*80./85.+7.)*1./90.)
     *          -0.20/SI*ATAN(-(A*80./85.-4.)*1./15.)
     *          +1.95/SI*ATAN((A*80./85.-28.)*1./15.)
     *          +2.25/SI*ATAN((A*80./85.-68.)*1./40.)
     *          +1.664/SI*ATAN(-(A*80./85.-90.)*1./30.)
     *          +2.35/SI*ATAN(-(A*80./85.-140.)*1/20.)
     *          -.246
C
      CDON   =  0.50/SI*ATAN((A+5.)*1./30.)
     *          +0.60/SI*ATAN(-(A+0.)*1./6.)
     *          -0.25/SI*ATAN(-(A+3.)*1./90.)
     *          -0.15/SI*ATAN(-(A-4.)*1./40.)
     *          +1.85/SI*ATAN((A-30.)*1./28.)
     *          +2.30/SI*ATAN((A-60.)*1./40.)
     *          +1.15/SI*ATAN(-(A-85.)*1./30.)
     *          +2.30/SI*ATAN(-(A-140.)*1/20.)
     *          -.2425
C  ***************************************************************
      CMON3  = 0.26/SI*ATAN(-(A-5.)*1./60.)
     *          -0.39/SI*ATAN((A-1.)*1./30.)
     *          +0.80/SI*ATAN((A-5.)*1./45.)
     *          +0.80/SI*ATAN(-(A-10.)*1./65.)
     *          +1.80/SI*ATAN((A-49.)*1./40.)
     *          +2.80/SI*ATAN(-(A-69.)*1/23.)
     *          -0.45/SI*ATAN(-(A-79.)*1./2.)
     *          -.138
C
```

```
      CMONZ3  = 0.26/SI*ATAN(-(A-5.)*1./60.)
     *          -0.39/SI*ATAN((A-1.)*1./14.0)
     *          +0.85/SI*ATAN((A-5.)*1./42.)
     *          +0.80/SI*ATAN(-(A-50.)*1./60.)
     *          +1.80/SI*ATAN((A-70.)*1./54.)
     *          +2.40/SI*ATAN(-(A-69.)*1/25.)
     *          -0.45/SI*ATAN(-(A-79.)*1./2.)
     *          -.138-.02
C
      CMON53  =CMON56
C
      CMOX03  = CMO06
      CMOX23  = CMOX26
C
      CMOX53 = CMOX56
C
      CMOX3  = 0.26/SI*ATAN(-(A-5.)*1./10.)
     *          -0.39/SI*ATAN((A-1.)*1./8.)
     *          +0.75/SI*ATAN((A-5.)*1./13.)
     *          +0.70/SI*ATAN(-(A-10.)*1./65.)
     *          +1.20/SI*ATAN((A-49.)*1./15.)
     *          +2.10/SI*ATAN(-(A-69.)*1/15.)
     *          -0.45/SI*ATAN(-(A-77.)*1./2.)
     *          -.408+.01
C     ========================================================
      CMOX8  = 0.26/SI*ATAN(-(A-5.)*1./15.)
     *          -0.33/SI*ATAN((A-1.)*1./7.)
     *          +0.72/SI*ATAN((A-5.)*1./15.)
     *          +0.70/SI*ATAN(-(A-35.)*1./75.)
     *          +1.13/SI*ATAN((A-51.)*1./11.)
     *          +2.08/SI*ATAN(-(A-67.)*1/17.)
     *          -0.45/SI*ATAN(-(A-78.)*1./4.)
     *          -.440
C
      CMOX58  = 0.26/SI*ATAN(-(A-5.)*1./10.)
     *          -0.39/SI*ATAN((A-1.)*1./12.)
     *          +0.70/SI*ATAN((A-5.)*1./15.)
     *          +0.85/SI*ATAN(-(A-20.)*1./40.)
     *          +1.45/SI*ATAN((A-52.)*1./15.)
     *          +2.20/SI*ATAN(-(A-69.)*1/15.)
     *          -0.45/SI*ATAN(-(A-77.)*1./3.4)
     *          -.318-.02
C
      CMOX28  = 0.36/SI*ATAN(-(A-5.)*1./35.)
     *          -0.29/SI*ATAN((A-1.)*1./30.)
     *          +1.00/SI*ATAN((A-15.)*1./90.)
     *          +0.75/SI*ATAN(-(A-48.)*1./110.)
     *          +0.90/SI*ATAN((A-52.)*1./9.)
     *          +2.10/SI*ATAN(-(A-69.)*1/17.)
     *          -0.45/SI*ATAN(-(A-77.)*1./3.)
     *          -.38-.007
C
      CMOX08  = 0.36/SI*ATAN(-(A-5.)*1./35.)
     *          -0.29/SI*ATAN((A-1.)*1./30.)
     *          +1.00/SI*ATAN((A-15.)*1./90.)
     *          +0.80/SI*ATAN(-(A-48.)*1./90.)
     *          +0.90/SI*ATAN((A-52.)*1./9.)
     *          +2.10/SI*ATAN(-(A-69.)*1/17.)
     *          -0.45/SI*ATAN(-(A-77.)*1./3.)
     *          -.38-.007
C
      CMON58  = 0.36/SI*ATAN(-(A-5.)*1./35.)
     *          -0.29/SI*ATAN((A-1.)*1./30.)
     *          +1.30/SI*ATAN((A-15.)*1./95.)
     *          +0.80/SI*ATAN(-(A-47.)*1./35.)
     *          +1.00/SI*ATAN((A-53.)*1./10.)
```

```
     *          +2.15/SI*ATAN(-(A-69.)*1/18.)
     *          -0.45/SI*ATAN(-(A-78.)*1./2.)
     *          -.36-.007
C
      CMONZ8  = 0.36/SI*ATAN(-(A-5.)*1./35.)
     *          -0.29/SI*ATAN((A-1.)*1./30.)
     *          +1.25/SI*ATAN((A-15.)*1./95.)
     *          +0.80/SI*ATAN(-(A-47.)*1./28.)
     *          +1.00/SI*ATAN((A-53.)*1./10.)
     *          +2.25/SI*ATAN(-(A-69.)*1/18.)
     *          -0.45/SI*ATAN(-(A-78.)*1./2.)
     *          -.31-.007
C
      CMON8   = 0.26/SI*ATAN(-(A-5.)*1./40.)
     *          -0.45/SI*ATAN((A-4.)*1./30.)
     *          +0.70/SI*ATAN((A-2.)*1./40.)
     *          +0.80/SI*ATAN(-(A-37.)*1./25.)
     *          +1.90/SI*ATAN((A-52.)*1./25.)
     *          +2.70/SI*ATAN(-(A-69.)*1/20.)
     *          -0.45/SI*ATAN(-(A-79.)*1./2.)
     *          -.188-.01
C
C    ==========================================================
      CLOX9   = 0.86/SI*ATAN(-(A+5.)*1./100.)
     *          +2.59/SI*ATAN((A-3.)*1./7.)
     *          +1.60/SI*ATAN((A-20.)*1./22.)
     *          +3.41/SI*ATAN(-(A-57.)*1./30.)
     *          +.41/SI*ATAN(-(A-70.)*1./20.)
     *          -.65
C
      CLON9   = 1.06/SI*ATAN(-(A+5.)*1./100.)
     *          +1.79/SI*ATAN((A-5.)*1./7.)
     *          +2.50/SI*ATAN((A-13.)*1./22.)
     *          +2.71/SI*ATAN(-(A-59.)*1./50.)
     *          +1.21/SI*ATAN(-(A-70.)*1./20.)
     *          -.80
C
      CMOX9   = 0.26/SI*ATAN(-(A-5.)*1./10.)
     *          -0.39/SI*ATAN((A-0.)*1./10.)
     *          +1.00/SI*ATAN((A-3.)*1./25.)
     *          +0.70/SI*ATAN(-(A-7.)*1./25.)
     *          +1.30/SI*ATAN((A-50.)*1./16.)
     *          +2.10/SI*ATAN(-(A-69.)*1/15.)
     *          -0.45/SI*ATAN(-(A-76.)*1./3.5)
     *          -.433
C
      CMOX59  = 0.26/SI*ATAN(-(A-5.)*1./4.)
     *          -0.39/SI*ATAN((A+2.)*1./5.)
     *          +1.00/SI*ATAN((A-1.)*1./15.)
     *          +0.60/SI*ATAN(-(A-18.)*1/13.)
     *          +1.30/SI*ATAN((A-51.)*1./14.)
     *          +2.15/SI*ATAN(-(A-69.)*1/15.)
     *          -0.45/SI*ATAN(-(A-76.)*1./3.5)
     *          -.490
C
      CMOX29  = 0.26/SI*ATAN(-(A-5.)*1./10.)
     *          -0.39/SI*ATAN((A+4.)*1./7.)
     *          +1.33/SI*ATAN((A-1.)*1./40.)
     *          +0.60/SI*ATAN(-(A-19.)*1/17.)
     *          +0.90/SI*ATAN((A-51.)*1./9.)
     *          +2.05/SI*ATAN(-(A-69.)*1/15.)
     *          -0.45/SI*ATAN(-(A-76.)*1./3.5)
     *          -.450
C
      CMOX09  = 0.26/SI*ATAN(-(A-5.)*1./10.)
     *          -0.39/SI*ATAN((A+2.)*1./10.)
```

```
     *          +1.30/SI*ATAN((A-1.)*1.1/40.)
     *          +0.60/SI*ATAN(-(A-19.)*1/15.)
     *          +0.90/SI*ATAN((A-51.)*1./9.)
     *          +2.11/SI*ATAN(-(A-69.)*1/15.)
     *          -0.45/SI*ATAN(-(A-76.)*1./3.5)
     *          -.490
C
      CMON59  = 0.26/SI*ATAN(-(A-5.)*1./11.)
     *          -0.39/SI*ATAN((A+2.)*1./10.)
     *          +1.50/SI*ATAN((A-1.)*1.1/48.)
     *          +0.60/SI*ATAN(-(A-19.)*1/15.)
     *          +0.80/SI*ATAN((A-51.)*1./10.)
     *          +2.32/SI*ATAN(-(A-70.)*1/20.)
     *          -0.45/SI*ATAN(-(A-78.)*1./3.5)
     *          -.490
C
      CMONZ9  = 0.26/SI*ATAN(-(A-5.)*1./7.)
     *          -0.39/SI*ATAN((A+0.)*1./10.)
     *          +1.60/SI*ATAN((A-5.)*1./50.)
     *          +0.60/SI*ATAN(-(A-32.)*1/11.)
     *          +0.80/SI*ATAN((A-51.)*1./11)
     *          +2.23/SI*ATAN(-(A-69.)*1/19.)
     *          -0.45/SI*ATAN(-(A-78.)*1./3.5)
     *          -.410
C
C
      CMON9  = 0.16/SI*ATAN(-(A-5.)*1./40.)
     *          -0.39/SI*ATAN((A-3.)*1./8.)
     *          +1.20/SI*ATAN((A-15.)*1./120.)
     *          +0.70/SI*ATAN(-(A-25.)*1./50.)
     *          +2.00/SI*ATAN((A-52.)*1./75.)
     *          +2.00/SI*ATAN(-(A-69.)*1/20.)
     *          -0.42/SI*ATAN(-(A-79.)*1./4.)
     *          -.068
C
      CLQ    = 0.26/SI*ATAN(-(A-5.)*1./10.)
     *          -2.39/SI*ATAN((A-6.)*1./3.)
     *          +2.40/SI*ATAN((A-15.5)*1./3.)
     *          +2.00/SI*ATAN(-(A-20.)*1./5.)
     *          +4.30/SI*ATAN((A-37.)*1./4.5)
     *          +2.20/SI*ATAN(-(A-45.)*1/15.)
     *          +2.20/SI*ATAN(-(A-80.)*1/15.)
     *          -0.45/SI*ATAN(-(A-76.)*1./3.5)
     *          +4.2
C
      CLAD   = 1.32/PI*ATAN(50.*PI/180.*(-A+5.))+1.8
     *         -0.75*ATAN(1.*(A-45.)/2)
C
      CMQ    =-0.82/PI*ATAN(20.*PI/180.*(-A+5.))-5.8
     *         +2.00*ATAN((-A+32)/6.)
     *         +4.55*ATAN((A-43.)*3.5)
     *         -3.50*ATAN((A-57.)/5.)
C
      CMAD   =-0.02/PI*ATAN(50.*PI/180.*(-A+1.))-0.9
     *         +0.50*ATAN((A-6.)*5)
     *         -0.80*ATAN((A-18.)/2)
     *         +0.90*ATAN((A-45.)/2)
C   ================================================
      A1 =CLOX6
      A2 =CLON6
      A11=(A1-A2)/(10.5-(-24))*(DH-(-24))+A2
      A3 =CLOX9
      A4 =CLON9
      A12=(A3-A4)/(10.5-(-24))*(DH-(-24))+A4
      CLO = A11 +(A12-A11)*(MACH-.6)/0.3
C ----------------------------------------------------------
```

```
C     CLO=A11  IF MACH NUMBER =.6
C     CLO=A12  IF MACH NUMBER =.9
C  ---------------------------------------------------------
      IF (DH.GE.5.) THEN
          B10 =(CMOX3-CMOX53)*(DH-5.)/5.5+CMOX53
          B11 =(CMOX6-CMOX56)*(DH-5.)/5.5+CMOX56
          B12 =(CMOX8-CMOX58)*(DH-5.)/5.5+CMOX58
          B13 =(CMOX9-CMOX59)*(DH-5.)/5.5+CMOX59
          GO TO 200
      ELSE
          GO TO 5
      END IF
    5 CONTINUE
      IF (DH.GE.2.) THEN
          B10 =(CMOX53-CMOX23)*(DH-2.)/3.+CMOX23
          B11 =(CMOX56-CMOX26)*(DH-2.)/3.+CMOX26
          B12 =(CMOX58-CMOX28)*(DH-2.)/3.+CMOX28
          B11 =(CMOX59-CMOX29)*(DH-2.)/3.+CMOX29
          GO TO 200
      ELSE
          GO TO 8
      END IF
    8 CONTINUE
      IF (DH.GE.0.) THEN
          B10 =(CMOX23-CMOX03)*DH/2.+CMOX03
          B11 =(CMOX26-CMO06)*DH/2.+CMO06
          B12 =(CMOX28-CMOX08)*DH/2.+CMOX08
          B13 =(CMOX29-CMOX09)*DH/2.+CMOX09
          GO TO 200
      ELSE
          GO TO 10
      END IF
   10 CONTINUE
      IF (DH.GE.-5.) THEN
          B10 =(CMOX03-CMON53)*(DH+5.)/5.+CMON53
          B11 =(CMO06-CMON56)*(DH+5.)/5.+CMON56
          B12 =(CMOX08-CMON58)*(DH+5.)/5.+CMON58
          B13 =(CMOX09-CMON59)*(DH+5.)/5.+CMON59
          GO TO 200
      ELSE
          GO TO 20
      END IF
   20 CONTINUE
      IF (DH.GE.-12.5) THEN
          B10 =(CMON53-CMONZ3)*(DH+12.5)/7.5+CMONZ3
          B11 =(CMON56-CMOZ6)*(DH+12.5)/7.5+CMOZ6
          B12 =(CMON58-CMONZ8)*(DH+12.5)/7.5+CMONZ8
          B13 =(CMON59-CMONZ9)*(DH+12.5)/7.5+CMONZ9
          GO TO 200
      ELSE
          GO TO 30
      END IF
   30 CONTINUE
      IF (DH.GE.-24.) THEN
          B10 =(CMONZ3-CMON3)*(DH+24.)/11.5+CMON3
          B11 =(CMOZ6-CMON6)*(DH+24.)/11.5+CMON6
          B12 =(CMONZ8-CMON8)*(DH+24.)/11.5+CMON8
          B13 =(CMONZ9-CMON9)*(DH+24.)/11.5+CMON9
      ELSE
          GO TO 200
      END IF
  200 CONTINUE
C  ---------------------------------------------------------
      IF (MACH.LE.0.6) THEN
         CMO = B10+(B11-B10)*(MACH-.3)/0.3
         GO TO 250
```

```
      ELSE
         GO TO 210
      END IF
  210 CONTINUE
      IF (MACH.LE.0.8) THEN
      CMO = B11 +(B12-B11)*(MACH-.6)/0.2
         GO TO 250
      ELSE
         GO TO 220
      END IF
  220 CONTINUE
      IF (MACH.LT.1.) THEN
      CMO = B12 +(B13-B12)*(MACH-.8)/0.1
      ELSE
         GO TO 250
      END IF
  250 CONTINUE
C
C   ----------------------------------------------------------
C     CMO = B10   IF MACH NUMBER =.3
C     CMO = B11   IF MACH NUMBER =.6
C     CMO = B12   IF MACH NUMBER =.9
C   ----------------------------------------------------------
      IF (DH.GE.0.) THEN
         CDO =(CDOX-CDOZ)*(DH+0.)/10.5+CDOZ
C     PRINT *,'DH IS LAGER THAN 0.'
         GO TO 300
      ELSE
         GO TO 50
      END IF
   50 CONTINUE
      IF (DH.GE.-5.) THEN
         CDO =(CDOZ-CDON5)*(DH+5.)/5.+CDON5
C     PRINT *,'DH IS LAGER THAN -5.'
         GO TO 300
      ELSE
         GO TO 60
      END IF
   60 CONTINUE
      IF (DH.GE.-24.) THEN
         CDO =(CDON5-CDON)*(DH+24.)/19.+CDON
      END IF
  300 CONTINUE
C############################################################
C end of interpolations
C############################################################
      RETURN
      END
```

APPENDIX C

Computer Code for Lateral Analytical Model

```
C----------------------------------------------------------------------==
C----------------------------------------------------------------------==
C    PURPOSE: THIS SUBROUTINE WILL BE CALLED TO CALCULATE 12 AERODY-   ==
C             NAMIC COEFFICIENTS WHICH ARE THE OUTPUTS OF THIS SUB-    ==
C             ROUTINE(LATERAL COEFFICIENTS)                            ==
C                                                                      ==
C    INPUTS:                                                           ==
C              ALPDEG  ANGLE OF ATTACK         (DEG)                   ==
C              BETDEG  SIDESLIP ANGLE          (DEG)                   ==
C              MACH    MACH NUMBER                                     ==
C              DA      AILERON DEFLECTION      (DEG)                   ==
C              DR      RUDDER DEFLECTION       (DEG)                   ==
C              DH      STABILATOR DEFLECTION   (DEG)                   ==
C              P       AIRCRAFT X_BODY AXIS ROLL RATE   (RAD/SEC)      ==
C              R       AIRCRAFT Z_BODY AXIS YAW RATE    (RAD/SEC)      ==
C                                                                      ==
C    OUTPUTS:                                                          ==
C              CRO ,CYB ,CYP ,CYR                                      ==
C              C1O ,C1B ,C1P ,C1R                                      ==
C              CNO ,CNB ,CNP ,CNR                                      ==
C                                                                      ==
C    THOSE COEFFICIENTS ARE USED IN AEROLAT IN THE FOLLOWING FORMULAS  ==
C                                                                      ==
C          CY = CYO+CYB*BETDEG+BO2VT*(CYP*P+CYR*R)                     ==
C          C1 = C1O+C1B*BETDEG+BO2VT*(C1P*P+C1R*R)                     ==
C          CN = CNO+CNB*BETDEG+BO2VT*(CNP*P+CNR*R)                     ==
C                                                                      ==
C          BO2VT = BREF/(2*V)                                          ==
C          CY      SIDE FORCE COEFFICIENT ALONG Y_WIND AXIS            ==
C          C1      ROLL MOMENT COEFFICIENT ABOUT X_WIND AXIS           ==
C          CN      YAW MOMENT COEFFICIENT ABOUT Z_WIND AXIS            ==
C          BREF    REFERENCE WINGSPAN                                  ==
C          V       AIRCRAFT TOTAL AIRSPEED                             ==
C                                                                      ==
C    AUTHER:   JICHANG CAO                                             ==
C              GRADUATE RESEARCH ASSISTANT                             ==
C              GEORGIA INSTITUTE OF TECHNOLOGY                         ==
C              ATLANTA, GA30332                                        ==
C                                                                      ==
C======================================================================
      SUBROUTINE NAEROC2 (CYO ,C1O ,CNO ,CYB ,C1B ,CNB ,
     *                    CYR ,C1R ,CNR ,CYP ,C1P ,CNP ,
C                        =F (
     *                    ALPDEG,BETDEG,MACH,DA,DR,DH,P,R,ALT)
C
      IMPLICIT REAL(C)
      REAL     ALFA,BETA,MACH,DA,DR,DH,P,R,ALT,ALPDEG,BETDEG,A,
     *         DAN,DAX,DRN,DRX,DHN,DHX,PI,HC1P,LC1P
C
C-----------------------------------------------------------------------
C    CONVERSION OF ALFA AND BETA
C-----------------------------------------------------------------------
C
      IF  (DA.LT.-25.) DA=-25.
      IF  (DA.GT.25.)  DA=25.
      IF  (DR.LT.-30.)  DR=-30.
      IF  (DR.GT.30.)   DR= 30.
      IF  (DH.LT.-24.)  DH=-24.
      IF  (DH.GT.10.5)  DH=10.5
C-----------------------------------------------------------------------
      A      = ALPDEG
      PI     =ACOS(-1.)
      SI     =2.75
C-----------------------------------------------------------------------
C    EXTREMAL VALUES OF CONTROL SURFACES DEFLECTION
C-----------------------------------------------------------------------
```

```
      DAN    = -25.
      DAX    = -DAN
      DRN    = -30.
      DRX    = -DRN
      DHN    = -24.
      DHX    = 10.5
C------------------------------------------------------------------------
C     COMPUTATION OF COEFFICIENTS
C------------------------------------------------------------------------
      CYOXXBO  = .01216/SI*ATAN(A*3./4.)
     *            +.03247/SI*ATAN(-(A-13.)/4.)
     *            +.00891/SI*ATAN((A-29.5)*2./3.)
     *            +.03058/SI*ATAN((46.-A)*2./5.)
     *            +.02759/SI*ATAN((75.-A)*3./40.)
     *            +.03477
C
      CYOXXB2  = .06/PI*ATAN(A/3.)
     *            +.09/PI*ATAN((A-31.)*5./8.)
     *            +.06/PI*ATAN(-(A-46.)*3./10.)
     *            +.03/PI*ATAN((A-63.)*3./7.)
     *            +.09/PI*ATAN((75.-A)*3./5.)
     *            +.04/PI*ATAN((A-85.)*4./5.)
     *            -0.285
C
      CYOXNBO  = 0.029624*ATAN((A-20.)*4./25.)
     *            -0.0020868*ATAN((12.-A)*5.)
     *            +6.99*EXP(-(A+17.6))
     *            -0.075535
C
      CYOXNB2  = .232/PI*ATAN(110*PI/180.*(A-16.))-.394
C
      CYONXBO  = -CYOXNBO
C
      CYONXB2  = .047/PI*ATAN(A/2.)
     *            +.021/PI*ATAN((17.-A)*5./4.)
     *            +.037/PI*ATAN((A-32.)*5./3.)
     *            +.06/PI*ATAN((76.-A)*5./4.)
     *            +.043/PI*ATAN(A-85.)
     *            -.248
C
      CYONNBO  = -CYOXXBO
C
      CYONNB2  = .219544/PI*ATAN((A-21.)*5./56.)
     *            +.0636375/PI*ATAN(-(A-74.)/4.)
     *            +.0709125/PI*ATAN((A-85.)*3./10.)
     *            -.36444
C
      C1OXXBO  = .04226/SI*ATAN(-(A-20.)*2./7.)
     *            +.00831/SI*ATAN(-(A-53.)*4./7.)
     *            +.00997/SI*ATAN((A-65.)*4./5.)
     *            +.0101/SI*ATAN(-(A-77.5)*8./15.)
     *            -.002/PI*ATAN(-(A-8.)*10.)
     *            +.0286
C
      C1OXXB2  = .02771/SI*ATAN(-(A-2.)/5.)
     *            +.06763/SI*ATAN(-(A-19.)/4.)
     *            +.006/SI*ATAN((A-22.)*2.)
     *            +.00081
C
      C1OXNBO  = .0041/SI*ATAN((A-4.)*2./3.)
     *            +.003/SI*ATAN(-(A-20.)/3.)
     *            +.011/SI*ATAN(-(A-59.)*2./5.)
     *            -.00144/SI*ATAN(-(A+1.)*8.)
     *            +.01793
C
      C1OXNB2  = .085/SI*ATAN(-(A-15.)*8./92.)-.0065
```

```
C
      C1ONXBO  = -C1OXNBO
C
      C1ONXB2  = .0395/SI*ATAN(-(A-5.)*3./13.)
     *           +.0295/SI*ATAN((A-25.)*3./7.)
     *           +.0126/SI*ATAN(-(A-38.)*4./3.)
     *           +.0114/SI*ATAN((A-42.)*2.)
     *           +.0082/SI*ATAN(-(A-51.)/2.)
     *           +.0132/SI*ATAN((A-70.)*2./5.)
     *           -.0479
C
      C1ONNBO  = -C1OXXBO
C
      C1ONNB2  = .0344/SI*ATAN(-(A-5.)*3./13.)
     *           +.037/SI*ATAN((A-24.)*2./5.)
     *           +.011/SI*ATAN(-(A-38.)*2.)
     *           +.012/SI*ATAN((A-42.)*7./4.)
     *           +.011/SI*ATAN(-(A-52.)*3./8.)
     *           +.0176/SI*ATAN((A-73.)*3./13.)
     *           -.0553
C
      C1OXXO  = (.04226/SI*ATAN(-(A-8.5)*2./7.)
     *           +.01031/SI*ATAN(-(A-35.)*4./7.)
     *           +.00997/SI*ATAN((A-65.)*4./5.)
     *           +.0131/SI*ATAN(-(A-77.5)*8./15.)
     *           -.002/PI*ATAN(-(A-8.)*10.)
     *           +.0286)/1.8
C
      CLOXX2  = .085/SI*ATAN(-(A-15.)*8./92.)-.0198
C
      C1OXNO  =(.0041/SI*ATAN((A-8.)*2./3.)
     *          +.012/SI*ATAN(-(A-11.)/3.)
     *          +.010/SI*ATAN(-(A-15.)/3.)
     *          +.012/SI*ATAN(-(A-35.)/3.)
     *          +.005/SI*ATAN(-(A-100.)*2./5.)
     *          -.00144/SI*ATAN(-(A-2.)*8.)
     *          +.01793)/2.-.0032
C
      C1OXN2  =  .048/SI*ATAN(-(A-18.)*8./92.)
     *           +.030/SI*ATAN(-(A-23.)*8./92.)
     *           +.045/SI*ATAN((A-80.)*8./92.)
     *           -.0105
C
      C1ONXO  = -C1OXNO
C
      C1ONX2  = 0.0295/SI*ATAN(-(A-25.)*3./13.)
     *          +0.0295/SI*ATAN((A-42.5)*3./7.)
     *          +.0086/SI*ATAN(-(A-15.)*4./3.)
     *          +.0014/SI*ATAN((A-42.)*2.)
     *          +.0162/SI*ATAN(-(A-51.)/2.)
     *          +.0012/SI*ATAN((A-70.)*2./5.)
     *          -.0479+.0013
C
      C1ONNO  = -C1OXXO
C
      C1ONN2  =-(0.0544/SI*ATAN(-(A-7.)*3./13.)
     *          +0.087/SI*ATAN((A-17.)*2./7.)
     *          +.008/SI*ATAN(-(A-25.)*2.)
     *          +.019/SI*ATAN((A-28.)*7./4.)
     *          +.051/SI*ATAN(-(A-42.)*3./8.)
     *          +.0096/SI*ATAN((A-55.)*3./13.)
     *          -.0553)/2.6-0.074
C
      CNXXXBO  = .00952/SI*ATAN((A-14.)*3./8.)
     *           +.01056/SI*ATAN((A-47.)*2./3.)
     *           +.01395/SI*ATAN((A-67.)*9./14.)
```

```
     *          +.00899/SI*ATAN(-(A-81.)*3./8.)
     *          -.01862
C
      CNXXXB2 = .077832/SI*ATAN(-(A-27.5)*4./45.)
     *          +.0744/SI*ATAN((A-58.5)*4./25.)
     *          +.02885/SI*ATAN(-(A-79.)*7./20.)
     *          +.006/SI*ATAN(-(A-43.))
     *          -.022
C
      CNXXNBO = .00953/SI*ATAN((A-15.)*3./8.)
     *          +.00411/SI*ATAN(-(A-46.5)*8./15.)
     *          +.02222/SI*ATAN((A-71.5)*4./25.)
     *          -.01781
C
      CNXXNB2 = .080916/SI*ATAN(-(A-30.)*3./42.)
     *          +.056/SI*ATAN((A-62.)/4.)
     *          +.02085/SI*ATAN(-(A-79.)/5.)
     *          -.005/SI*ATAN(-(A-82.)*2.)
     *          -.02221
C
      CNXNXBO = .02026/SI*ATAN(-(A-19.)*3./14.)
     *          +.022/SI*ATAN(-(A-49.)*2./7.)
     *          +.03393/SI*ATAN((A-73.)/7.)
     *          +.002/SI*ATAN(-(A-14.)*2.)
     *          +.003/SI*ATAN((A-76.)*2.)
     *          +.02769
C
      CNXNXB2 = .06482/SI*ATAN(-(A-20.)*3./14.)
     *          +.04937/SI*ATAN(-(A-41.)*5./14.)
     *          +.053/SI*ATAN((A-60.)/6.)
     *          +.005/SI*ATAN(-(A-8.)*4.)
     *          +.0211
C
      CNXNNBO = .02037/SI*ATAN(-(A-17.5)*8./43.)
     *          +.00389/SI*ATAN(-(A-54.5)*6./17.)
     *          +.01623/SI*ATAN((A-69.5)*5./23.)
     *          +.002/SI*ATAN(-(A-13.)*2.)
     *          +.02711
C
      CNXNNB2 = .11857/SI*ATAN(-(A-26.5)*4./45.)
     *          +.07065/SI*ATAN((A-60.5)*4./25.)
     *          +.02518/SI*ATAN(-(A-80.)*3./10.)
     *          +.005/SI*ATAN(-(A-18.)*2.)
     *          +.020265
C
      CNNXXBO = -CNXNXBO
C
      CNNXXB2 = .06132/SI*ATAN(-(A-31.)/10.)
     *          +.05521/SI*ATAN((A-55.)*2./9.)
     *          +.04659/SI*ATAN(-(A-77.5)*4./15.)
     *          -.03235
C
      CNNXNBO = -CNXNNBO
C
      CNNXNB2 = .063768/SI*ATAN(-(A-32.)/10.)
     *          +.04788/SI*ATAN((A-57.5)*6./25.)
     *          +.03829/SI*ATAN(-(A-77.5)*4./15.)
     *          -.03288
C
      CNNNXBO = -CNXXXBO
C
      CNNNXB2 = .11977/SI*ATAN(-(A-28.5)*3.5/51.)
     *          +.04303/SI*ATAN((A-58.5)*4./13.)
     *          +.02532/SI*ATAN(-(A-74.)*2./5.)
     *          +.01184
C
```

```
      CNNNNBO  = -CNXXNBO
C
      CNNNNB2  = .120543/SI*ATAN(-(A-28.)*3./40.)
     *           +.05707/SI*ATAN((A-55.5)*4./25.)
     *           +.03650/SI*ATAN(-(A-78.5)*4./15.)
     *           +.01202
C
      CNXXXO =( .01452/SI*ATAN((A-11.)*3./8.)
     *          -.005/SI*ATAN((A-22.)*3./8.)
     *          +.01156/SI*ATAN((A-41.)*2./3.)
     *          +.01205/SI*ATAN((A-67.)*9./14.)
     *          +.00769/SI*ATAN(-(A-81.)*3./8.)
     *          -.01862)/1.21
C
      CNXXX2 = .067832/SI*ATAN(-(A-30.)*4./45)
     *          +.065/SI*ATAN(-(A-14.)*4./45.)
     *          -.04/SI*ATAN(-(A-4.)*4./45.)
     *          +.0844/SI*ATAN((A-46.)*4./25.)
     *          +.04085/SI*ATAN(-(A-100.)*7./20.)
     *          +.006/SI*ATAN(-(A-35.))
     *          -.0352
C
      CNXXNO =  .01253/SI*ATAN((A-12.)*3./8.)
     *          -.00200/SI*ATAN((A-22.)*3./8.)
     *          +.00411/SI*ATAN(-(A-46.5)*8./15.)
     *          +.02222/SI*ATAN((A-81.5)*4./25.)
     *          -.01161
C
      CNXXN2 =  .11091/SI*ATAN(-(A-25.)*3./42.)
     *          -.025/SI*ATAN(-(A-8.)*3./42.)
     *          +.05600/SI*ATAN((A-48.)/4.)
     *          +.03385/SI*ATAN(-(A-100.)/5.)
     *          -.005/SI*ATAN(-(A-82.)*2.)
     *          -.03125
C
      CNXNXO = .01026/SI*ATAN(-(A-13.)*3./14.)
     *          -.009/SI*ATAN(-(A-40.)*2./7.)
     *          +.010/SI*ATAN(-(A-18.)*2./7.)
     *          -.002/SI*ATAN(-(A-30.)*2./7.)
     *          +.022/SI*ATAN(-(A-49.)*2./7.)
     *          +.02543/SI*ATAN((A-83.)/7.)
     *          +.002/SI*ATAN(-(A-7.)*2.)
     *          +.003/SI*ATAN((A-76.)*2.)
     *          +.02769
C
      CNXNX2 = .05428/SI*ATAN(-(A-16.)*3./14.)
     *          +.05037/SI*ATAN(-(A-36.)*5./14.)
     *          -.003/SI*ATAN((A-45.)/6.)
     *          +.060/SI*ATAN((A-50.)/6.)
     *          +.005/SI*ATAN(-(A-8.)*4.)
     *          +.0211
C
      CNXNNO = .01637/SI*ATAN(-(A-10.)*8./43.)
     *          +.00559/SI*ATAN(-(A-180.)*6./17.)
     *          +.01623/SI*ATAN((A-100.)*5./23.)
     *          +.002/SI*ATAN(-(A-13.)*2.)
     *          +.0271
C
      CNXNN2 = .05428/SI*ATAN(-(A-15.)*3./14.)
     *          +.05037/SI*ATAN(-(A-33.)*5./14.)
     *          -.003/SI*ATAN((A-45.)/6.)
     *          +.062/SI*ATAN((A-46.)/6.)
     *          +.005/SI*ATAN(-(A-8.)*4.)
     *          +.0241
C
      CNNXXO = -CNXNXO
```

```
C
      CNNXX2 = .067832/SI*ATAN(-(A-32.)*4./45)
     *          +.063/SI*ATAN(-(A-14.)*4./45.)
     *          -.04/SI*ATAN(-(A-4.)*4./45.)
     *          +.0844/SI*ATAN((A-46.)*4./25.)
     *          +.04085/SI*ATAN(-(A-90.)*7./20.)
     *          +.006/SI*ATAN(-(A-35.))
     *          -.0352
C
      CNNXNO = -CNXNNO
C
      CNNXX2 = .067832/SI*ATAN(-(A-35.)*4./45)
     *          +.070/SI*ATAN(-(A-14.)*4./45.)
     *          -.04/SI*ATAN(-(A-4.)*4./45.)
     *          +.0844/SI*ATAN((A-46.)*4./25.)
     *          +.04085/SI*ATAN(-(A-100.)*7./20.)
     *          +.006/SI*ATAN(-(A-35.))
     *          -.0392
C
      CNNNXO = -CNXXXO
C
      CNNNX2 = .05428/SI*ATAN(-(A-22.)*3./14.)
     *          +.02037/SI*ATAN(-(A-36.)*5./14.)
     *          -.003/SI*ATAN((A-45.)/6.)
     *          +.042/SI*ATAN((A-47.)/6.)
     *          +.020/SI*ATAN(-(A-11.)*4.)
     *          +.0181
C
      CNNNNO = -CNXXNO
C
      CNNNN2 = CNXNN2
C
      CYB    = .206*E-3
C
      CYP    = .086/PI*ATAN(100.*PI/180.*A)
     *        +.096/PI*ATAN(100.*PI/180.*(-A+23.))
     *        +.22/PI*ATAN(100.*PI/180.*(-A+45.))
     *        +.256/PI*ATAN(100.*PI/180.*(A-54.))-.047
C
      CYR    = .17/PI*ATAN(100.*PI/180.*(A-4.))
     *        +.55/PI*ATAN(100.*PI/180.*(-A+20.))
     *        +.54/PI*ATAN(100.*PI/180.*(A-45.))
     *        +.26/PI*ATAN(100.*PI/180.*(-A+61.))+.07
C
      C1B    = 1.E-4*(6.32/PI*ATAN(1000.*PI/180.*(-A+13.))+3.26)
C
      LC1P    = .15/PI*ATAN(100.*PI/180.*(A-12))
     *        +.25/PI*ATAN(1000.*PI/180.*(-A+28.))
     *        +.55/PI*ATAN(1000.*PI/180.*(A-41.))
     *        +.33/PI*ATAN(100.*PI/180.*(-A+50.))-.341
C
      HC1P    = .28/PI*ATAN(100.*PI/180.*(A-10.))
     *         +.25/PI*ATAN(1000.*PI/180.*(-A+41.))
     *         +.55/PI*ATAN(1000.*PI/180.*(A-41.))
     *         +.33/PI*ATAN(100.*PI/180.*(-A+50.))-.471
C ------------------------------------------------------------
      C1P    = LC1P + (HC1P-LC1P)*(MACH-.6)/0.3
C ------------------------------------------------------------
      C1R    = .304/PI*ATAN(100.*PI/180.*(A-3.))
     *        +.22/PI*ATAN(20.*PI/180.*(50.-A))
     *        -.026*EXP((A-85.)/100.)+.018
C
      CNB    = 1.E-6*(12.7/PI*ATAN(1000.*PI/180.*(-A+13.))-11.7)
C
      CNP    = .075/PI*ATAN(50.*PI/180.*(A-17.))
     *        +.04/PI*ATAN(100.*PI/180.*(A-50.))
```

```
     *       +.2/PI*ATAN(1000.*PI/180.*(-A+57.))
     *       +.13/PI*ATAN(1000.*PI/180.*(A-62.))
     *       +.09/PI*ATAN(1000.*PI/180.*(-A+73.))
     *       +.1/PI*ATAN(1000.*PI/180.*(A-77.))-.028
C
      CNR    = .16/PI*ATAN(100.*PI/180.*(-A+22.))
     *       +.34/PI*ATAN(100.*PI/180.*(A-57.))
     *       -.1*EXP((A-78.)/10.)-.09
C
C####################################################################
      A1=BETDEG/20*CYOXXB2+(20-BETDEG)/20*CYOXXBO
      A2=BETDEG/20*CYONXB2+(20-BETDEG)/20*CYONXBO
      A11=(A1-A2)/(25-(-25))*(DA-(-25))+A2
      A3=BETDEG/20*CYOXNB2+(20-BETDEG)/20*CYOXNBO
      A4=BETDEG/20*CYONNB2+(20-BETDEG)/20*CYONNBO
      A12=(A3-A4)/(25-(-25))*(DA-(-25))+A4
      A13=(A11-A12)/(30-(-30))*(DR-(-30))+A12
C   ---------------------------------------------------
C     CYO=A13
C   -----------------------------------------------------
      D1=BETDEG/20*CNXXXB2+(20-BETDEG)/20*CNXXXBO
      D2=BETDEG/20*CNXXNB2+(20-BETDEG)/20*CNXXNBO
      D3=BETDEG/20*CNXNXB2+(20-BETDEG)/20*CNXNXBO
      D4=BETDEG/20*CNXNNB2+(20-BETDEG)/20*CNXNNBO
      D5=BETDEG/20*CNNXXB2+(20-BETDEG)/20*CNNXXBO
      D6=BETDEG/20*CNNXNB2+(20-BETDEG)/20*CNNXNBO
      D7=BETDEG/20*CNNNXB2+(20-BETDEG)/20*CNNNXBO
      D8=BETDEG/20*CNNNNB2+(20-BETDEG)/20*CNNNNBO
      D11=(D1-D2)/(10.5-(-24))*(DH-(-24))+D2
      D13=(D3-D4)/(10.5-(-24))*(DH-(-24))+D4
      D15=(D5-D6)/(10.5-(-24))*(DH-(-24))+D6
      D17=(D7-D8)/(10.5-(-24))*(DH-(-24))+D8
      D21=(D11-D13)/(30-(-30))*(DR-(-30))+D13
      D22=(D15-D17)/(30-(-30))*(DR-(-30))+D17
      D31=(D21-D22)/(25-(-25))*(DA-(-25))+D22
C   -----------------------------------------------------------
C     CNO=D31   IF MACH NUMBER =.6
C   -----------------------------------------------------------
      DD1=BETDEG/20*CNXXX2+(20-BETDEG)/20*CNXXXO
      DD2=BETDEG/20*CNXXN2+(20-BETDEG)/20*CNXXNO
      DD3=BETDEG/20*CNXNX2+(20-BETDEG)/20*CNXNXO
      DD4=BETDEG/20*CNXNN2+(20-BETDEG)/20*CNXNNO
      DD5=BETDEG/20*CNNXX2+(20-BETDEG)/20*CNNXXO
      DD6=BETDEG/20*CNNXN2+(20-BETDEG)/20*CNNXNO
      DD7=BETDEG/20*CNNNX2+(20-BETDEG)/20*CNNNXO
      DD8=BETDEG/20*CNNNN2+(20-BETDEG)/20*CNNNNO
      DD11=(DD1-DD2)/(10.5-(-24))*(DH-(-24))+DD2
      DD13=(DD3-DD4)/(10.5-(-24))*(DH-(-24))+DD4
      DD15=(DD5-DD6)/(10.5-(-24))*(DH-(-24))+DD6
      DD17=(DD7-DD8)/(10.5-(-24))*(DH-(-24))+DD8
      DD21=(DD11-DD13)/(30-(-30))*(DR-(-30))+DD13
      DD22=(DD15-DD17)/(30-(-30))*(DR-(-30))+DD17
      DD31=(DD21-DD22)/(25-(-25))*(DA-(-25))+DD22
C   -----------------------------------------------------------
C     CNO = DD31   IF MACH NUMBER =.9
C   -----------------------------------------------------------
      CNO = D31 +(DD31-D31)*(MACH-.6)/0.3
C   -----------------------------------------------------------
C     cn=cn0+cnb*betdeg+bo2vt*(cnr*r+cnp*p)
C   -----------------------------------------------------------
      B1=BETDEG/20*C10XXB2+(20-BETDEG)/20*C10XXBO
      B2=BETDEG/20*C10NXB2+(20-BETDEG)/20*C10NXBO
      B11=(B1-B2)/(25-(-25))*(DA-(-25))+B2
      B3=BETDEG/20*C10XNB2+(20-BETDEG)/20*C10XNBO
      B4=BETDEG/20*C10NNB2+(20-BETDEG)/20*C10NNBO
      B12=(B3-B4)/(25-(-25))*(DA-(-25))+B4
```

```
      B13=(B11-B12)/(30-(-30))*(DR-(-30))+B12
C ----------------------------------------------------
C     C10=B13   WHEN MACH NUMBER = .6
C ----------------------------------------------------
      IF (BETDEG.LT.-12.) BETDEG=-12.
      IF (BETDEG.GT.12.)  BETDEG= 12.
C
      BB1=BETDEG/12*C10XX2+(12-BETDEG)/12*C10XX0
      BB2=BETDEG/12*C10NX2+(12-BETDEG)/12*C10NX0
      BB11=(BB1-BB2)/(25-(-25))*(DA-(-25))+BB2
      BB3=BETDEG/12*C10XN2+(12-BETDEG)/12*C10XN0
      BB4=BETDEG/12*C10NN2+(12-BETDEG)/12*C10NN0
      BB12=(BB3-BB4)/(25-(-25))*(DA-(-25))+BB4
      BB13=(BB11-BB12)/(30-(-30))*(DR-(-30))+BB12
C ----------------------------------------------------
C     C10 = BB13   IF MACH NUMBER = .9
C ----------------------------------------------------
      C10 = B13 +(BB13-B13)*(MACH-.6)/0.3
C###############################################################
C end of interpolations
C###############################################################
      RETURN
      END
```

APPENDIX D

Computer Code for Simulation Comparison

```
=================================================================
==  COMMOD_N       THIS PROGRAM IS USED TO COMPUTE U.DOT,V.DOT,   ==
==                 W.DOT,P.DOT,R.DOT USING THE HARV WIND-TUNNEL   ==
==                 MODEL.                                         ==
==                                                                ==
==  INPUTS:      FLIGHT_DATA FILE                                 ==
==               T         TIME                                   ==
==               MACH      MACH NUMBER                            ==
==               HAB       ALTITUDE                               ==
==               QBAR      DYNAMIC PRESSURE                       ==
==               ALPDEG    ANGEL OF ATTACK                        ==
==               BETADEG   SIDESLIP ANGEL                         ==
==               PHID      EULER BANK ANGEL                       ==
==               THETAD    EULER PITCH ANGEL                      ==
==               PSID      EULER YAW ANGEL                        ==
==               P         AIRCRAFT X-BODY AXIS ROLL RATE         ==
==               Q         AIRCRAFT Y-BODY AXIS PITCH RATE        ==
==               R         AIRCRAFT Z-BODY AXIS YAW RATE          ==
==               DH        STABILATOR DEFLECTION                  ==
==               DA        AILERON DEFLECTION                     ==
==               DR        RUDDER DEFLECTION                      ==
==                                                                ==
==  OUTPUTS:                                                      ==
==                 UDT         TIME DERIVATIVE OF U               ==
==                 VDT         TIME DERIVATIVE OF V               ==
==                 WDT         TIME DERIVATIVE OF W               ==
==                 PDT         TIME DERIVATIVE OF P               ==
==                 QDT         TIME DERIVATIVE OF Q               ==
==                 RDT         TIME DERIVATIVE OF R               ==
==                                                                ==
==                                                                ==
==  AUTHER          JICHANG CAO                                   ==
==                  GRADUATE RESEARCH ASSISTANT                   ==
==                  SCHOOL OF AEROSPACE ENGINEERING               ==
==                  GEORGIA INSTITUTE OF TECHNOLOGY               ==
==                  ATLANTA,GEORGIA 30332                         ==
==                                                                ==
==  DATA         JUNE,1990                                        ==
==                                                                ==
=================================================================
      PROGRAM COMLAT
      PARAMETER (N=129)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      REAL*8  MACH ,MASS ,NZ ,IAS ,HAB
      REAL*8  AU(N) ,AV(N) ,AW(N) ,AP(N) ,AQ(N) ,AR(N)
      REAL*8  APHID(N) ,ATHETA(N) ,APSID(N) ,AALP(N) ,ABET(N)
      REAL*8  TIME(N) ,AMACH(N) ,AHAB(N) ,AQBAR(N)
      REAL*8  ADH(N) ,ADA(N) ,ADR(N) ,ADSB(N)
      REAL*8  UDT(N) ,VDT(N) ,WDT(N) ,PDT(N) ,QDT(N) ,RDT(N)
      REAL*8  ATNETL(N),ATNETR(N) ,LXE ,LYE ,LZE
      CHARACTER*80  HEADER
      CHARACTER  AA1*15,AA2*15,AA3*15,AA4*15.AA5*15,BB*50
      OPEN (UNIT=5,FILE='MACH03')
      OPEN (UNIT=6,FILE='DATA_N4')
      ---------------------------------------------------------------
      GENERAL CONSTANTS
      ---------------------------------------------------------------
      G   =32.174
      DTR =ACOS(-1.)/180.
      ---------------------------------------------------------------
      AIRCRAFT CONSTANTS
      ---------------------------------------------------------------
      CBAR   =11.52
      MASS   =1035.308
      XI     =23000.
      YI     =151293.
```

```
      ZI      =169945.
      XZI     =-2971.
      B       =37.42
      CBAR    =11.52
      S       =400.
      XL      =-3.56/12.
      YL      =0.
      ZL      =2.8/12.
      THZ     =0.0

      LXE     =-232.5/12.
      LYE     =0.
      LZE     =2.8/12.
      DT      =130.

      CSTAR   =XI*ZI/(XI*ZI-XZI**2)
      C41     =CSTAR*XZI*(ZI+XI-YI)/(XI*ZI)
      C42     =CSTAR*(ZI*(YI-ZI)-XZI**2)/(XI*ZI)
      C43     =CSTAR*XZI/XI
      C51     =(ZI-XI)/YI
      C52     =XZI/YI
      C61     =CSTAR*(XI*(XI-YI)+XZI**2)/(XI*ZI)
      C62     =CSTAR*XZI*(YI-ZI-XI)/(XI*ZI)
      C63     =CSTAR*XZI/ZI
      -------------------------------------------------------------------
      FLIGHT CONDITION
      -------------------------------------------------------------------
      READ (5,5) NUMBER
      DO 99 I=2,13
      READ (5,15) AA1 ,AA2 ,AA3 ,AA4 ,AA5
   99 CONTINUE
      READ (5,25) BB
    5 FORMAT (I4)
   15 FORMAT (5A15)
   25 FORMAT (A50)
      ---------------------------------------------------------------------
      ---------------------------------------------------------------------
      DO 400 I=1,N
      READ FLIGHT DATA FILE
      READ (5,10) T ,MACH ,HAB ,QBAR ,ALPDEG ,BETADEG ,PSID ,THETAD
      READ (5,10) PHID ,PDEG ,QDEG ,RDEG ,VTOTAL,AX ,AY ,GZ
      READ (5,10) DLADEG,DLADDEG,DLSDEG,DLHDDEG,DLNDEG,DLNDDEG,
     1            DLFDEG,DLFDDEG
      READ (5,20) DLRDEG ,DLRDDEG ,TNETL ,TNETR
*********************************************************************
      T       ---  TIME
      MACH    ---  MACH NUMBER
      HAB     ---  ALTITUDE
      QBAR    ---  DYNAMIC PRESSURE
      ALPDEG  ---  ANGEL OF ATTACK
      BETADEG ---  SIDESLIP ANGEL
      PSID    ---  EULER BANK ANGEL
      THETAD  ---  EULER PITCH ANGEL
      PHID    ---  EULER YAW ANGEL
      PDEG    ---  AIRCRAFT X-BODY AXIS ROLL RATE
      QDEG    ---  AIRCRAFT Y-BODY AXIS PITCH RATE
      RDEG    ---  AIRCRAFT Z-BODY AXIS YAW RATE
      VTOTAL  ---  VELOCITY
      DLADEG  ---  AILERON DEFLECTION (AVERAGE)
      DLRDEG  ---  RUDDER DEFLECTION (AVERAGE)
      DLSDEG  ---  STABILATOR DEFLECTION (AVERAGE)
      TNETL   ---  THRUST OF LEFT ENGINE
      TNETR   ---  THRUST OF RIGHT ENGINE
******************************************************************
   10 FORMAT (8E10.4)
   20 FORMAT (4E10.4)
```

```
      U       = VTOTAL*COS(ALPDEG*DTR)*COS(BETADEG*DTR)
      V       = VTOTAL*SIN(BETADEG*DTR)
      W       = VTOTAL*SIN(ALPDEG*DTR)*COS(BETADEG*DTR)

      AU(I) = U
      AV(I) = V
      AW(I) = W

      AP(I) = PDEG
      AQ(I) = QDEG
      AR(I) = RDEG

      APHID(I)   =PHID
      ATHETA(I)  =THETAD
      APSID(I)   =PSID

      AALP(I)    =ALPDEG
      ABET(I)    =BETADEG
      TIME(I)    =T
      AQBAR(I)   =QBAR
      AMACH(I)   =MACH
      AHAB(I)    =HAB

      ADH(I)     =DLSDEG
      ADA(I)     =DLADEG
      ADR(I)     =DLRDEG
      ADSB(I)    =DLSBDEG

      ATNETL(I)  =TNETL
      ATNETR(I)  =TNETR

  400 CONTINUE

      CALL IAERO  (HEADER)
      CALL IENG   (HEADER)

      DO 410 I=1,N
      ALPHA   =AALP(I)
      BETA    =ABET(I)
      MACH    =AMACH(I)
      HAB     =AHAB(I)
      DH      =ADH(I)
      DA      =ADA(I)/2.
      DR      =ADR(I)
      DSB     =ADSB(I)
      QBAR    =AQBAR(I)
      TNETL   =ATNETL(I)
      TNETR   =ATNETR(I)

      CALL F18M3   ( CDO   ,CYO   ,CLO   ,CIO   ,CMO   ,CNO   ,
     1               CLAD  ,CMAD  ,CLQ   ,CMQ   ,TH    ,TX    ,
     2               CYB   ,CYR   ,CYP   ,CIB   ,CIR   ,CIP   ,
     3               CNB   ,CNR   ,CNP   ,BO2VT,CO2VT,
                    =F (
     4               ALPHA ,BETA ,MACH ,HAB ,
     5               DH    , DA   ,DR    ,DSB   ,DT )


      U       =AU(I)
      V       =AV(I)
      W       =AW(I)

      P       =AP(I)*DTR
      Q       =AQ(I)*DTR
      R       =AR(I)*DTR
```

```
      PHID  =APHID(I)*DTR
      THET  =ATHETA(I)*DTR
      PSID  =APSID(I)*DTR

      AA    =ALPHA*DTR
      BT    =BETA*DTR

      THX   =(TNETL+TNETR)*COS(1.98*DTR)
      THY   = TNETR*SIN(-1.98*DTR)+TNETL*SIN(1.98*DTR)

      FD    = QBAR*S*CDO/MASS

      CB    = QBAR*S*CO2VT*CLAD/(U*U+W*W)/MASS
      BQ    = 1+CB*COS(AA)*U-CB*COS(AA)*W*(CB*SIN(AA)*U)
     X        /(1+CB*SIN(AA)*W)
      FU    = R*V-Q*W-G*SIN(THET)-FD*COS(AA)+THX/MASS
     X        +QBAR*S*SIN(AA)*(CLO+CO2VT*CLQ*Q)/MASS
      FW    = Q*U-P*V+G*COS(THET)*COS(PHID)-FD*SIN(AA)
     X        -QBAR*S*COS(AA)*(CLO+CO2VT*CLQ*Q)/MASS
*     WDT(I)= (FW+CB*COS(AA)*W*FU/(1+CB*SIN(AA)*W))+THZ/MASS
      UDT(I)= (FU+CB*SIN(AA)*U*WDT(I))/(1+CB*SIN(AA)*W)
      DALFA = (U*WDT(I)-W*UDT(I))/(U*U+W*W)

      CL    = CLO+CO2VT*(CLQ*Q+CLAD*DALFA)
      CM    = CMO+CO2VT*(CMQ*Q+CMAD*DALFA)

      C1    = C10+C1B*BT+BO2VT*(C1P*P+C1R*R)
      CY    = CYO+CYB*BT+BO2VT*(CYP*P+CYR*R)
      CN    = CNO+CNB*BT+BO2VT*(CNP*P+CNR*R)

      FL    = QBAR*S*CL/MASS

      FX    = -FD*COS(AA)+FL*SIN(AA)
      FY    = QBAR*S*CY/MASS
      FZ    = -FD*SIN(AA)-FL*COS(AA)

      FP    = QBAR*S*B*C1/XI+MASS*(YL*FZ-ZL*FY)/XI
      FQ    = QBAR*S*CBAR*CM/YI+MASS*(ZL*FX-XL*FZ)/YI
      FR    = QBAR*S*B*CN/ZI+MASS*(XL*FY-YL*FX)/ZI

      VDT(I) = P*W-R*U+G*COS(THET)*SIN(PHID)+FY+THY/MASS

      YY1   = C41*P*Q+C42*Q*R+C43*FR+CSTAR*FP+C43*LXE*THY/ZI
     1        -C43*LYE*THX/ZI
     1        +CSTAR*(LYE*THZ-LZE*THY)/XI
      YY2   = C51*P*R+C52*(R*R-P*P)+FQ+(LZE*THX-LXE*THZ)/YI
      YY3   = C61*P*Q+C62*Q*R+C63*FP+CSTAR*FR+C63/XI*(LYE*THZ-LZE*THY)
     1        +CSTAR/ZI*LXE*THY
     1        -CSTAR*LYE*THX/ZI

      PDT(I) =YY1/DTR
      QDT(I) =YY2/DTR
      RDT(I) =YY3/DTR

  410 CONTINUE

      M=N-2
      DO 710 I=1,M
      WRITE (6,910) TIME(I) ,UDT(I) ,VDT(I) ,WDT(I) ,PDT(I) ,QDT(I),
     1              RDT(I)
  710 CONTINUE
  910 FORMAT(7E10.4)
      STOP
      END
```

APPENDIX E

Comparison of $C_{m_0}(t)$ for Run 5, Mach 9 Flight Trajectory

The piloted simulated maneuvers comparison of Chapter 10 shows that the angular pitch accelerations from the wind-tunnel data and the analytical model have about the same shape but at times have a fairly large distance between them; this is due to a small error in fit being multiplied by a large dynamic pressure at Mach 0.9. We found that the largest differences are equivalent to approximately a half degree change in stabilator deflection. In this appendix we present some details from Run 5 which is a turn reversal maneuver to show that the differences are due to a small difference of about 0.006 or less in the values of $C_{m_0}(t)$. As can be seen from the modeling fits shown in Figures 5.1-5.6 modeling errors of this magnitude are present in C_{m_0} at all Mach numbers.

The time history of C_m is p otted in Figure E.1(a) for Run 5 showing maximum differences of about 0.01 magnitude. Removing the effect of dynamic pressure we note that the maximum difference in is about 0.006 as shown in Figure E.1(b). The time histories of the angle of attack and the stabilator angle values are presented in Figures E.1 (c) and (d), respectively. The angle of attack has values between 1 and 5 degrees and the stabilator angle has values between 1 degree and -3.0 degrees. Consequently, the analytical models of Chapter 5 governing Run 5 are CM0X29(α), CM0X9(α) and CM0N59(α) presented in Figures 5.5,5.6 and 5.8.

As can be seen from Figures E.1(b) and E.1(c) the small difference 0.006 can be made up by small changes in the stabilator angle. Such a small difference in the stabilator angle would have negligible bearing on analysis study results using the analytical models as compared to those obtained using the wind-tunnel data.

Comparison of $C_{m0}(t)$: Turn Reversal Maneuver @ M=0.9 (Run 5, 10 October 1987)

(a) C_m

(b) C_{m0}

(c) Angle of Attack (Deg)

(d) Stabilator Deflection Angle (Deg)

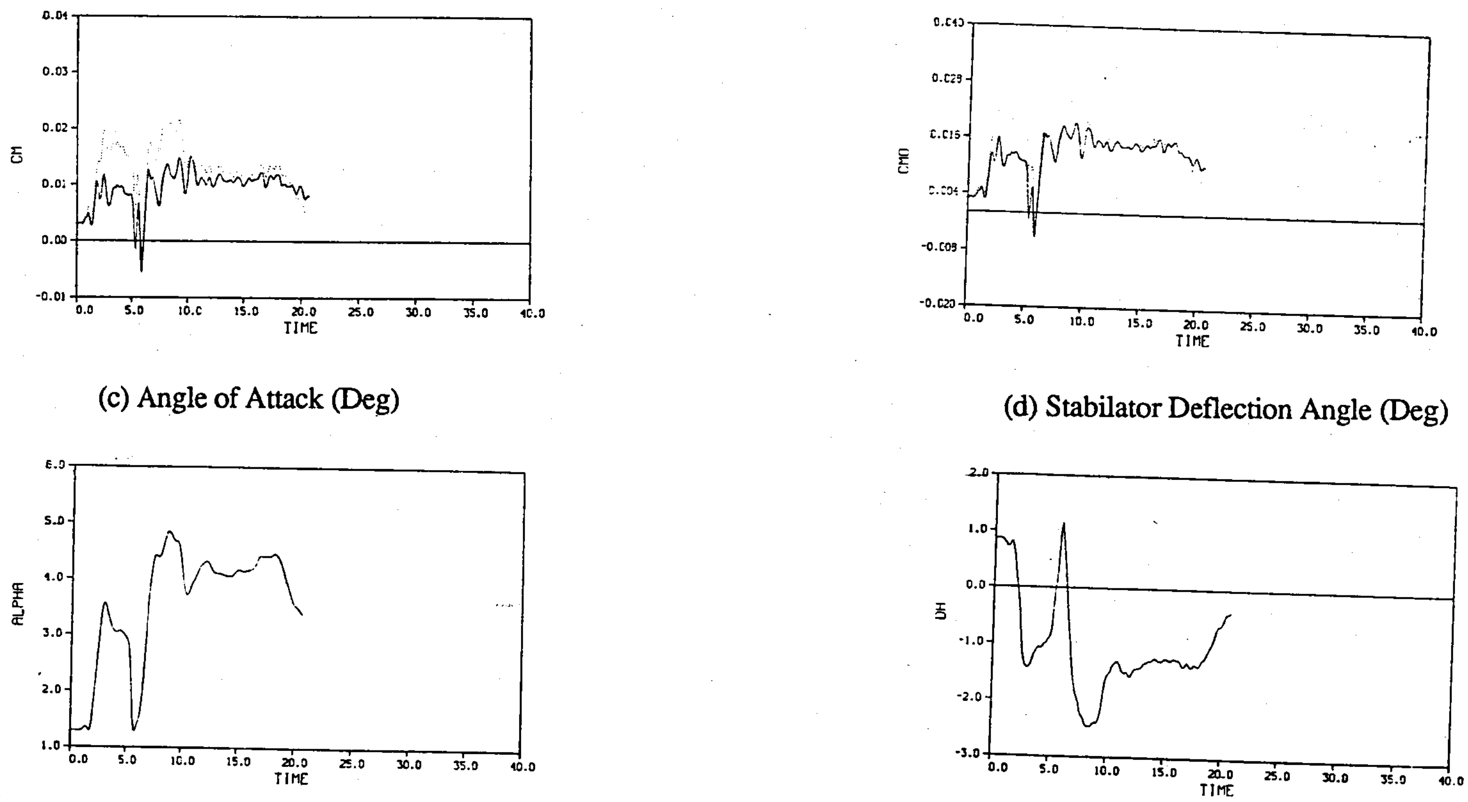


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Figure E.1: Comparison of $C_{m0}(t)$: Turn Reversal Maneuver @ M=0.9 (Run 5, 10 October 1987)

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16. Abstract

A 6 DOF analytical aerodynamic model of a high alpha research vehicle is derived. The derivation is based on wind-tunnel model data valid in the altitude-Mach flight envelope centered at 15,000 ft altitude and 0.6 Mach number with Mach range between 0.3 and 0.9. The analytical models of the aerodynamics coefficients are nonlinear functions of alpha with all control variable and other states fixed. Interpolation is required between the parameterized nonlinear functions. The lift and pitching moment coefficients have unsteady flow parts due to the time rate of change of angle-of-attack (alpha dot).

The analytical models are plotted and compared with their corresponding wind-tunnel data. Piloted simulated maneuvers of the wind-tunnel model are used to evaluate the analytical model. The maneuvers considered are pitch-ups, 360 degrees loaded and unloaded rolls, turn reversals, split S's and level turns. The evaluation finds that (1) the analytical model is a good representation at Mach 0.6, (2) the longitudinal part is good for the Mach range 0.3 to 0.9 and (3) the lateral part is good for Mach numbers between 0.6 and 0.9.

The computer simulations show that the storage requirement of the analytical model is about one tenth that of the wind-tunnel model and it runs twice as fast.

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