ENGINEERING ANALYSIS DIVISION INTERNAL NOTE

DESCRIPTION OF A COMPUTER PROGRAM WRITTEN FOR
APPROACH AND LANDING TEST POST FLIGHT DATA EXTRACTION
OF PROXIMITY SEPARATION AERODYNAMIC
COEFFICIENTS AND AERODYNAMIC DATA BASE

National Aeronautics and Space Administration
LYNDON B. JOHNSON SPACE CENTER
Houston, Texas
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OF PROXIMITY SEPARATION AERODYNAMIC COEFFICIENTS
AND AERODYNAMIC DATA BASE VERIFICATION

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SUMMARY

This report presents a description of a computer program written to calculate the proximity aerodynamic force and moment coefficients of the Orbiter/Shuttle Carrier Aircraft (SCA) vehicles based on flight instrumentation.

The Ground Reduced Aerodynamic Coefficients and Instrumentation Errors (GRACIE) program was developed as a tool to aid in flight test verification of the Orbiter/SCA separation aerodynamic data base. The program calculates the force and moment coefficients of each vehicle in proximity to the other, using the load measurement system (LMS) data, the flight instrumentation data (α, β, body rates, accelerations, etc.), and the vehicle mass properties. The uncertainty in each coefficient is determined, based on the quoted instrumentation accuracies. A subroutine, provided by McDonnell Douglas - Houston, manipulates the "Orbiter/747 Carrier Separation Aerodynamic Data Book" (reference 1) to calculate a comparable set of predicted coefficients for comparison to the calculated flight test data.

INTRODUCTION

In the Approach and Landing Test (ALT) phase of the shuttle program, one of the major problems to be considered is the separation of the Orbiter from the SCA. During mated flight, and for the first 3 sec after separation, the aerodynamics of each vehicle are influenced by the presence of the other vehicle. From past programs, it has been shown that such proximity effects are predicted with very little confidence from wind tunnel testing. Therefore, good flight test data are required to verify the adequacy of predicted separation windows and vehicle trajectories. The SCA is equipped with typical flight test instrumentation to record its absolute motion during flight. Load cells to measure the relative forces between the Orbiter and SCA are located on each of the three attach struts holding the Orbiter to the SCA during mated flight (fig. 1). Once the absolute motion of the SCA center of gravity
(measured body attitudes, rates, and accelerations) and the externally applied forces (attach forces and SCA engine thrust) are known, the aerodynamic forces and moments of each vehicle can be determined by the relationships described in the following sections.

**SYMBOLS**

[A] Transformation matrix to change from SCA body axis to orbiter body axis coordinate system, 
\[
\begin{bmatrix}
\cos i_0 & 0 & -\sin i_0 \\
0 & 1 & 0 \\
\sin i_0 & 0 & \cos i_0
\end{bmatrix}
\]

C Vehicle aerodynamic coefficients

F Vehicle forces

[G] Transformation matrix to change from body axis to stability axis, 
\[
\begin{bmatrix}
-\cos \alpha_0 & 0 & -\sin \alpha_0 \\
0 & 1 & 0 \\
\sin \alpha_0 & 0 & \cos \alpha_0
\end{bmatrix}
\]

[I] Vehicle inertia matrix, 
\[
\begin{bmatrix}
I_{xx} & 0 & -I_{xz} \\
0 & I_{yy} & 0 \\
-I_{xz} & 0 & I_{zz}
\end{bmatrix}
\] slug-ft²

i₀ Orbiter incidence angle, deg

L Attach strut forces as measured by the load measurement system, lb

L Vehicle reference length used for calculating vehicle moment coefficients, ft

M Vehicle moments

m Vehicle mass, slugs

Nₓ, Nᵧ, Nₗ Linear acceleration at vehicle center of gravity, g

p Vehicle roll rate, deg/sec

̇p Vehicle roll acceleration, deg/sec²
q  Vehicle pitch rate, deg/sec
\bar{q}  Dynamic pressure, lb/ft^2
\dot{q}  Vehicle pitch acceleration, deg/sec^2
R  Vehicle position vector
r  Vehicle yaw rate, deg/sec
\dot{r}  Vehicle yaw acceleration, deg/sec^2
s  Vehicle reference area, ft^2
T  SCA thrust, lb
V  Velocity, ft/sec
W  Vehicle weight, lb
\alpha  Vehicle angle of attack, deg
\beta  Vehicle angle of sideslip, deg
\gamma  Vehicle flight path angle, deg
\delta_{a_{I/O}}  SCA aileron (inboard/outboard) position, deg
\delta_{c_w}  SCA control wheel position, deg
\delta_{e_{I/O}}  SCA elevator (inboard/outboard) position, deg
\delta_{r_{U/L}}  SCA rudder (upper/lower) position, deg
\delta_s  SCA stabilizer position, deg
\delta_{SP}  SCA spoiler panel (outboard/middle/inboard) position, deg
\delta_{a_o}  Orbiter aileron position, deg
\delta_{e_{L/R}}  Orbiter elevon (left/right) position, deg
\delta_{r_o}  Orbiter rudder position, deg
\( \Delta N_x, \Delta N_y, \Delta N_z \) \text{ Relative load factors, } g

\( \theta \) \text{ Vehicle pitch angle, deg}

\( \dot{\theta} \) \text{ Orbiter instantaneous pitch acceleration, deg/sec}^2

\( \lambda \) \text{ Tilt angle of forward strut}

\( \rho \) \text{ C.G. relative position vector } (\Delta x, \Delta y, \Delta z), \text{ ft}

\( \rho \) \text{ C.G. to attach strut moment arm}

\( \phi \) \text{ Vehicle roll angle, deg}

\( \psi \) \text{ Vehicle yaw angle, deg}

\( \omega \) \text{ Vehicle angular velocity vector } - p, q, r

\( \dot{\omega} \) \text{ Vehicle angular acceleration vector } - \dot{p}, \dot{q}, \dot{r}

\text{SUBSCRIPTS}

\( c \) \text{ SCA vehicle}

\( F \) \text{ Forward}

\( L \) \text{ Left}

\( M \) \text{ Mated vehicle}

\( O \) \text{ Orbiter vehicle}

\( R \) \text{ Right}

\text{PROGRAM DESCRIPTION AND ASSUMPTIONS}

GRACIE is a program that uses flight test data to determine aerodynamic coefficients and their corresponding uncertainties for comparison with wind tunnel predicted values. The program manipulates LMS forces, SCA body motions, vehicle configurations, and vehicle mass properties to output tabulated and plotted time histories of Orbiter proximity, SCA proximity, and mated vehicle aerodynamic force and moment coefficients, as well as, relative normal load factor (\( \Delta N_z \)) and Orbiter instantaneous pitch acceleration (\( \dot{\theta} \)). The LMS data, the SCA body motion data, and the vehicle configuration are obtained from a ground recorded telemetry data tape to which all instrumentation calibrations have been applied. The vehicle mass properties and the SCA thrust data time
histories are input through subroutines, since they require post flight calculations and are not recorded on the data tape.

The program performs three basic operations utilizing the flight test data. The equations of motion and the aerodynamic uncertainty calculations are made using data retrieved from flight test instrumentation, while the predicted values of the coefficients are determined using the algorithms and data presented in reference 1. The following sections describe these operations.

Equations of Motion

As a basis for this evaluation, the mated vehicle is assumed to be a rigid body in motion with respect to a fixed coordinate system XYZ (fig. 2).

![Figure 2. - Vehicle coordinate system](Image)

Affixing a second set of axes to the carrier aircraft, with the origin (C) located at the carrier c.g. and observing its motion, allows evaluation of the motion of any other point in the mated configuration, namely the Orbiter c.g., as well as the mated c.g. For example, the acceleration of the Orbiter c.g. (O) can be determined by knowing the relative position (η), the linear acceleration (\( \ddot{R}_O \)), angular rates (\( \omega \)), and angular accelerations (\( \dot{\omega} \)) of the carrier c.g. (C),

\[
\ddot{R}_O = \ddot{R}_C + \dot{\omega}_C \times \omega + \omega \times (\omega \times \phi) + \alpha_{o/xyz} + 2\omega \times \nu_{o/xyz},
\]
but since the mated vehicle is assumed to be a rigid body

\[
\mathbf{a}_{o/xyz} = \mathbf{v}_{o/xyz} = 0
\]

Therefore,

\[
\ddot{\mathbf{R}}_o = \ddot{\mathbf{R}}_c + \dot{\mathbf{w}}_c \times \mathbf{\omega} + \mathbf{\omega} \times (\mathbf{\omega} + \mathbf{\omega}).
\]

The total resultant or applied forces on either vehicle are then:

\[
\mathbf{F}_{c\text{TOTAL}}^{\text{APPLIED}} = m_c \ddot{\mathbf{R}}_c
\]

\[
\mathbf{F}_{o\text{TOTAL}}^{\text{APPLIED}} = m_o \ddot{\mathbf{R}}_o
\]

and

\[
\mathbf{F}_{m\text{TOTAL}}^{\text{APPLIED}} = m_m \ddot{\mathbf{R}}_m
\]

Similar use of kinematics provides the equations for calculating the resultant moments (\(\mathbf{M}\)) on each vehicle, i.e.

\[
\mathbf{M}_{c\text{TOTAL}}^{\text{APPLIED}} = [I]_c \dot{\mathbf{\omega}}_c + \mathbf{\omega}_c \times [I]_c \mathbf{\omega}_c,
\]

\[
\mathbf{M}_{o\text{TOTAL}}^{\text{APPLIED}} = [I]_o \dot{\mathbf{\omega}}_o + \mathbf{\omega}_o \times [I]_o \mathbf{\omega}_o,
\]

and

\[
\mathbf{M}_{m\text{TOTAL}}^{\text{APPLIED}} = [I]_m \dot{\mathbf{\omega}}_m + \mathbf{\omega}_m \times [I]_m \mathbf{\omega}_m.
\]

where,

\[
\mathbf{\omega}_o = [A] \mathbf{\omega}_c, \quad \mathbf{\dot{\omega}}_o = [A]_c \mathbf{\dot{\omega}}
\]
and

\[ \omega_m = \omega_c, \dot{\omega}_m = \dot{\omega}_c \]

From figure 3, the load cell outputs, expressed in the carrier body axis coordinate system, are as follows:

\[ F_{F_Y} = \text{Forward side force} \]

\[ F_{F_Z} = \text{Forward vertical force (parallel to strut axis)} \]

\[ F_{F_X}, F_{F_Z} = \text{Drag and vertical components of forward vertical strut force (carrier body axis coordinate system)} \]

\[ F_{L_X} = \text{Left aft drag force} \]

\[ F_{L_Z} = \text{Left aft vertical force} \]

\[ F_{R_X} = \text{Right aft drag force} \]

\[ F_{R_Y} = \text{Right aft side force} \]

\[ F_{R_Z} = \text{Right aft vertical force} \]

where,

\[ F_{F_X} = F_{F_Z} \sin \lambda, F_{F_Z} = F_{F_Z} \cos \lambda \]

\[ \lambda = 88.27^\circ - \sin^{-1} \left( \frac{929.098 \sin(i_o + 2.734^\circ)}{1723336.5 - 1723333.7 \cos(i_o + 2.734^\circ)} \right) \]
Figure 3. - Orbiter attach point geometry
Also shown in figure 3 are the moment arms from the orbiter c.g. to each load cell attach point based on the carrier body axis coordinate system. Using figure 3 in conjunction with figure 4, the moment arms are determined from the following relations, making note of the fact that the attach point locations are in the orbiter body coordinate system:

\[ \phi_F = \tan^{-1}\left(\frac{Z_{cg_0} - Z_F}{X_{cg_0} - X_F}\right) \]

\[ \phi_A = \tan^{-1}\left(\frac{Z_{cg_0} - Z_R}{X_R - X_{cg_0}}\right) \]

\[ L_F = \frac{Z_{cg_0} - Z_R}{\sin \phi_F} \]
\[ L_A = \frac{Z_{cg_o} - Z_R}{\sin \phi_A} \]

\[ l_1 = L_A \sin(\phi_A + i_o)/12 \]

\[ l_2 = L_A \cos(\phi_A + i_o)/12 \]

\[ l_3 = L_F \sin(\phi_F - i_o)/12 \]

\[ l_4 = L_F \cos(\phi_F - i_o)/12 \]

\[ l_5 = -(Y_L + Y_{cg_o})/12 \]

\[ l_6 = (Y_R - Y_{cg_o})/12 \]

From figure 5, and using the Orbiter moment arms previously calculated, the

---

**Figure 5. - Relative c.g. locations**
position vector is:

\[ \mathbf{d} = \begin{bmatrix} (x_R - x_{cg747})/12 \\ (y_{cg0} - y_{cg747})/12 \\ (z_{cg747} - z_R)/12 - 1 \end{bmatrix} \]

Note that in figure 5, the attach point locations are in the carrier body axis coordinate system.

The following free body diagrams and corresponding equations of motion are used in calculating the aerodynamic force and moment coefficients of the mated vehicle, the SCA in proximity of the orbiter, and the orbiter in proximity of the SCA.

**Mated vehicle aerodynamic coefficients.** - Force coefficients (drag, side force, lift)
\[ F_{\text{AERO}} - m \ddot{R}_m - F_{\text{THRUST}} \]

\[ C_{\text{BODY AXIS}} = \frac{F_{\text{AERO}}}{q \cdot S_c} \]

\[ C_{\text{STABILITY AXIS}} = \begin{bmatrix} g \end{bmatrix} C_{\text{BODY AXIS}} \]

\[ [g]_c = \text{Transformation from Carrier BODY AXIS TO Carrier STABILITY AXIS.} \]

Mated vehicle aerodynamic coefficients. - Moment coefficients

\( M_{\text{TOTAL APPLIED}} = M_{\text{AERO}} + M_{\text{THRUST}} \)

\[ M_{\text{TOTAL APPLIED}} = \begin{bmatrix} I \end{bmatrix}_m \ddot{\omega}_c + \omega_c \begin{bmatrix} I \end{bmatrix}_m \omega_c \]

\[ M_{\text{AERO}} = M_{\text{TOTAL APPLIED}} - M_{\text{THRUST}} \]

\[ C_{\text{MOMENT}} = \frac{M_{\text{AERO}}}{q \cdot S_c \cdot \omega_c} \]
Carrier aerodynamic coefficients (proximity). - Force coefficients (drag, side force, lift)

\[ F_{\text{TOTAL APPLIED}} = F_{\text{AERO}} + F_{\text{LOAD CELL}} + F_{\text{THRUST}} \]

\[ F_{\text{TOTAL APPLIED}} = m_c \ddot{R}_c \]

\[ F_{\text{LOAD CELL}} = L_c = L_{\text{fwd}} + L_{\text{left}} + L_{\text{right}} \]

\[ F_{\text{AERO}} = m_c \ddot{R}_c - F_{\text{LOAD CELL}} - F_{\text{THRUST}} \]

\[ C_{\text{BODY AXIS}} = \frac{F_{\text{AERO}}}{q S_c} \]

\[ C_{\text{STABILITY AXIS}} = [G]_c C_{\text{BODY AXIS}} \]
Carrier aerodynamic coefficients (proximity). - Moment coefficients (rolling moment, pitching moment, yawing moment)

\[ M_{\text{TOTAL APPLIED}} = M_{\text{AERO}} + M_{\text{LOAD CELL}} + M_{\text{THRUST APPLIED}} \]

\[ M_{\text{TOTAL APPLIED}} = \left[ I_c \right] \dot{\omega}_c + \omega_c x \left[ I_c \right] \omega_c \]

\[ M_{\text{LOAD CELL}} = \sum_{s=1}^{3} (\rho_s x L_s) \]

\[ M_{\text{AERO}} = M_{\text{TOTAL APPLIED}} - M_{\text{LOAD CELL}} - M_{\text{THRUST APPLIED}} \]

\[ C_{\text{MOMENT}} = \frac{M_{\text{AERO}}}{q S_c g_c} \]

Orbiter aerodynamic coefficients (proximity). - Force coefficients (drag, side force, lift)
\[ F_{\text{TOTAL APPLIED}} = F_{\text{AERO}} + F_{\text{LOAD CELL}} \]

\[ F_{\text{TOTAL APPLIED}} = m_0 \ddot{R}_0 = m_0 \left[ \ddot{R}_c + \omega_c \times \dot{\omega}_c + \omega_c \times (\omega_c \times R) \right] \]

\[ F_{\text{LOAD CELL}} = L_0 = L_{\text{fwd}} + L_{\text{left}} + L_{\text{right}} \]

\[ F_{\text{AERO}} = \left[ A \right] \left[ m_0 \ddot{R}_0 - L_0 \right] \]

\[ C_{\text{BODY AXIS}} = \frac{F_{\text{AERO}}}{q S_0} \]

\[ C_{\text{STABILITY AXIS}} = \left[ \theta_0 \right] \cdot C_{\text{BODY AXIS}} \]

\[ [A] = \text{Transformation from CARRIER to ORBITER coordinate system at INCIDENCE angle } \theta_0. \]

**Orbiter aerodynamic coefficients (proximity). - Moment coefficients (rolling moment, pitching moment, yawing moment)**

\[ M_{\text{TOTAL APPLIED}} = M_{\text{AERO}} - M_{\text{LOAD CELL}} \]

\[ M_{\text{TOTAL APPLIED}} = \left[ I \right] \ddot{\omega}_0 + \omega_0 \times \left[ I \right] \omega_0 + \sum_{s=1}^{3} \left( L_{\omega_0} \times L_{s_0} \right) \]
\[
\begin{align*}
M_{\text{AERO}} & = M_{\text{TOTAL APPLIED}} - M_{\text{LOAD CELL}} \\
C_{\text{MOMENT}} & = \frac{M_{\text{AERO}}}{\frac{q}{3} S_o c_o} \\
\ddot{\theta}_{\text{ORB}} & = \frac{M_{\text{AEROY}}}{I_{yy_o}} \\
\Delta N_Z & = L_0 \left( \frac{W_o + W_c}{W_o W_c} \right)
\end{align*}
\]

Aerodynamic Uncertainties

An integral part of the separation analysis is knowing the uncertainty associated with each coefficient and how that uncertainty affects the size of the separation window, as well as the vehicle trajectory. Each aerodynamic coefficient is a function of \( n_i \) independent measurements, \( n_i \), and the uncertainty of each measurement is \( \Delta n_i \).

\[ C = f(n_1, n_2, n_3, \ldots, n_i) \quad (1) \]

The uncertainty in each calculated coefficient is obtained using the following equation:

\[ \Delta C = \left[ \left( \frac{\delta C}{\delta n_1} \right)^2 (\Delta n_1)^2 + \left( \frac{\delta C}{\delta n_2} \right)^2 (\Delta n_2)^2 + \ldots + \left( \frac{\delta C}{\delta n_i} \right)^2 (\Delta n_i)^2 \right]^{1/2} \quad (2) \]

The uncertainties in the aerodynamic coefficients are based on the quoted accuracies of the load measurement system and the flight test instrumentation.
The uncertainty in the Orbiter force and moment coefficients are calculated as follows. The Orbiter aerodynamic forces are first calculated with respect to the SCA body coordinate system from the following equations:

\[ C_X = \frac{M_0[N_x + q\Delta Z \dot{r} + q\Delta y + q^2 \Delta x + r p \Delta z - r^2 \Delta x]}{q \cdot S_0} - \sum F_X \]

\[ C_Y = \frac{M_0[N_y - \dot{p} \Delta Z + \dot{r} \Delta x - p^2 \Delta y + p q \Delta x + r q \Delta z - r^2 \Delta y]}{q \cdot S_0} - \sum F_Y \]

\[ C_Z = \frac{M_0[N_z + \dot{p} \Delta y - \dot{q} \Delta x - p^2 \Delta z + p r \Delta x - q^2 \Delta z + q r \Delta y]}{q \cdot S_0} - \sum F_Z \]

From equation (2), the uncertainty in \( C_X \) is:

\[ N'_X = \left[ \frac{M_0}{q S_0} \right]^2 [\Delta N_X]^2 \]

\[ p' = \left[ \frac{M_0 (q \Delta y + r \Delta z)}{q S_0} \right]^2 [\Delta p]^2 \]

\[ q' = \left[ \frac{M_0 (p \Delta y - 2q \Delta x)}{q S_0} \right]^2 [\Delta q]^2 \]

\[ r' = \left[ \frac{M_0 (p \Delta z - 2q \Delta x)}{q S_0} \right]^2 [\Delta r]^2 \]

\[ \dot{p}' = \ldots \]
\[
\dot{q}' = \left[ \frac{M_o \Delta z}{qS_o} \right]^2 [\Delta q]^2
\]

\[
\dot{r}' = \left[ \frac{M_o \Delta y}{qS_o} \right]^2 [\Delta r]^2
\]

\[
\overline{q}' = \left[ -M_o (N_x + \dot{q} \Delta z - \dot{r} \Delta y - q \Delta y - q^2 \Delta x + r \Delta z - r^2 \Delta x) + L_{XT} \right] \frac{1}{q^2 S_o} [\Delta q]^2
\]

\[
\overline{F}_X' = \left[ \frac{1}{qS_o} \right]^2 [\Delta F_X]^2
\]

\[
\overline{F}_X' = \left[ \frac{1}{qS_o} \right]^2 [\Delta F_L]^2
\]

\[
\overline{F}_R' = \left[ \frac{1}{qS_o} \right]^2 [\Delta F_R]^2
\]

\[
\Delta C_{\chi} = \left[ N_x' + p' + q' + r' + p' + q' + r' + \overline{q}' + \overline{F}_X' + F_L' + F_R' \right]^{1/2}
\]

Similarly, the uncertainty in \( C_Z \) is calculated. The coefficients are then transformed into the Orbiter body axis coordinate system.

\[
C_{A_o} = C_{\chi} \cos(i_o) - C_Z \sin(i_o),
\]

\[
C_{N_o} = C_{\chi} \sin(i_o) + C_Z \cos(i_o).
\]
The uncertainties in these two coefficients are:

\[ \Delta C_{A_o} = \left[ (\cos i_o)^2 (\Delta C_x)^2 + (\sin i_o)^2 (\Delta C_z)^2 \right]^{1/2}, \]

\[ \Delta C_{N_o} = \left[ (\sin i_o)^2 (\Delta C_x)^2 + (\cos i_o)^2 (\Delta C_z)^2 \right]^{1/2}. \]

Finally, these coefficients are transformed into the Orbiter stability axis coordinate system,

\[ C_D = C_{A_o} \cos(\alpha_c + i_o) + C_{N_o} \sin(\alpha_c + i_o), \]

\[ C_L = -C_{A_o} \sin(\alpha_c + i_o) + C_{N_o} \cos(\alpha_c + i_o), \]

and the uncertainties in the Orbiter coefficients of lift and drag are:

\[ \Delta C_L = \left[ (\cos(\alpha_c + i_o))^2 (\Delta C_{A_o})^2 + (\sin(\alpha_c + i_o))^2 (\Delta C_{N_o})^2 \right]^{1/2} \]

\[ + (C_{A_o} \sin(\alpha_c + i_o) - C_{N_o} \cos(\alpha_c + i_o))^2 (\Delta \alpha_c)^2 \]^{1/2}

\[ \Delta C_D = \left[ (\sin(\alpha_c + i_o))^2 (\Delta C_{A_o})^2 + (\cos(\alpha_c + i_o))^2 (\Delta C_{N_o})^2 \right]^{1/2} \]

\[ + (C_{A_o} \cos(\alpha_c + i_o) + C_{N_o} \sin(\alpha_c + i_o))^2 (\Delta \alpha_c)^2 \]^{1/2}.

The uncertainty in the Orbiter side force coefficient, \( \Delta C_y \), is found in the same way.

The Orbiter moment coefficients are based on the following equations:
\[
\begin{align*}
C_{m_x} &= \frac{\dot{p}_o I_{xx} + \alpha \alpha \rho_0 (I_{zz} - I_{yy}) + I_{xz} (\dot{\rho}_o + \rho_o \dot{\rho}_o)}{\dot{q} S_o b_o} \\
&\quad + \frac{F_{FZ} \rho_{FY} + F_{FY} \rho_{FZ} - F_{ILZ} \rho_{LY} - F_{FRZ} \rho_{FY} + F_{RY} \rho_{RZ}}{\dot{q} S_o b_o} \\
C_{m_y} &= \frac{\dot{q}_o I_{yy} + \rho_0 \rho_0 (I_{xx} - I_{zz}) + I_{xz} (\rho_o^2 - \rho_o)}{\dot{q} S_o c_o} \\
&\quad + \frac{F_{FZ} \rho_{FX} - F_{FX} \rho_{FZ} + F_{ILZ} \rho_{LX} - F_{LX} \rho_{LZ} + F_{FRZ} \rho_{RX} - F_{RX} \rho_{RZ}}{\dot{q} S_o c_o} \\
C_{m_z} &= \frac{\dot{\rho}_o I_{zz} + \rho_0 \rho_0 (I_{yy} - I_{xx}) - I_{xz} (\rho_o \rho_o - \dot{\rho}_o)}{\dot{q} S_o b_o} \\
&\quad + \frac{F_{FX} \rho_{FY} + F_{FY} \rho_{FX} + F_{LX} \rho_{LY} - F_{RY} \rho_{RX} + F_{RX} \rho_{RY}}{\dot{q} S_o b_o}
\end{align*}
\]

Again using equation (2), the uncertainty in the Orbiter pitching moment is:

\[
\begin{align*}
\dot{q}' &= \left(\frac{I_{yy}}{\dot{q} S_o c_o}\right)^2 [\Delta \dot{q}]^2 \\
p' &= \left[\frac{\rho_o (I_{xx} - I_{zz}) + 2 \rho_o I_{xz}}{\dot{q} S_o c_o}\right]^2 [\Delta p]^2 \\
r' &= \left[\frac{\rho_o (I_{xx} - I_{zz}) - 2 \rho_o I_{xz}}{\dot{q} S_o c_o}\right]^2 [\Delta r]^2
\end{align*}
\]
Similarly, the uncertainties in the rolling moment and yawing moment are calculated.
Analysis of the uncertainties in the SCA proximity and mated vehicle coefficients is performed in a like manner.

Predictions

One of the subroutines in the program uses the Algorithms presented in reference 1 and reference 2 to build-up force and moment coefficients for each vehicle using contributing elements, such as control surface deflections and proximity effects, etc. The data is a digitized version of the data presented in references 1 and 2 and stored in look-up tables in the program. Input to this subroutine comes from configuration and attitude parameters recorded on the flight data tape and orbiter elevon position time histories.

PROGRAM DECK SET-UP

Data needed to run GRACIE, other than that on the flight data tape, are input using subroutines and data cards. Two subroutines require changes for reducing data from each flight.

The first subroutine is called ORBDEF and is used to provide orbiter control surface deflection time histories.

```
SUBROUTINE ORBDEF

SUBROUTINE ORBDEF(TIME,LELV,RELV,ORUD,I),DELZ,TC,DELBF)

SUBROUTINE TO PROVIDE ORBITER CONTROL SURFACE DEFORMATIONS

REAL LELV,IO
TI = TIME - 30766.
IF(TI.LT.11.6) LELV = 0.
IF(TI.GE.11.6.AND.TI.LT.16.6) LELV = 1.7
IF(TI.GE.16.6.AND.TI.LT.17.6) LELV = 0.
IF(TI.GE.17.6.AND.TI.LT.27.5) LELV = -1.3
IF(TI.GE.27.5.AND.TI.LT.30.5) LELV = 6.
IF(TI.GE.30.5.AND.TI.LT.44.4) LELV = 1.
IF(TI.GE.44.4) LELV = 0.
IF(TI.LT.11.6) RELV = 0.
IF(TI.GE.11.9.AND.TI.LT.16.8) RELV = 1.7
IF(TI.GE.16.8.AND.TI.LT.17.8) RELV = 0.
IF(TI.GE.17.8.AND.TI.LT.27.7) RELV = -1.3
IF(TI.GE.27.7.AND.TI.LT.30.7) RELV = 6.
IF(TI.GE.30.7.AND.TI.LT.44.6) RELV = -1.
ORUD = 0.0
IO = 6.0
DELZ = 0.
TC = 1.0
DELBF = -9.7
RETURN
END
```
The subroutine returns control surface positions for use in the main program for each time step on the flight data tape.

The second subroutine is called TRUST and provides a time history of the carrier thrust for portions of the flight of interest.

```
SUBROUTINE TRUST    73/74 OPT=1

      SUBROUTINE TRUST(TIME,THRUST,TZ)
      C
      C       ***** SUBROUTINE TO PROVIDE CARRIER THRUST *****
      C       ***** THRUST FOR CA-1 SEP DATA RUN
      5
      TZ = 0.
      THRUST = -1100.
      RETURN
      END
```

Where:

TZ = The normal component of thrust which is always 0.

THRUST = Axial component of thrust for all four carrier engines in pounds. (REAL)
Three data cards are also required to run GRACIE. They are used to input mated vehicle gross weight, data locations on the data tape, print-plot options, and plot titles.

The first data card contains the mated vehicle gross weight in thousand pounds. The example card represents 523,000 lb.

The second data card contains the first point location on the data tape, the final point location on the data tape, and the print plot option. For the print plot option:

1 = print tabulated listing and plot results

2 = print tabulated data only

3 = plot results only
The example card asks for data from file 1 on the data tape to file 220, and for both tabulated listings and plotted results. Examples of the tabulated listings and plotted data are found in appendix A and appendix B, respectively.

The third and final data card is used for titling the plotted results. The titles are plotted in blocks of 30 figures. The example card below prints the title as shown on the example plots in appendix B.

```
CAPTIVE ACTIVE FLIGHT NO. 1  ELEVON BIAS = -1.0

```

![Example card](image)
<table>
<thead>
<tr>
<th>CAPTIVE/ACTIVE FLIGHT NO.</th>
<th>1</th>
<th>DATE</th>
<th>6/28/77</th>
<th>1 TO 220</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIME</td>
<td>COEF.</td>
<td>MCM.</td>
<td>I+L</td>
<td>I-L</td>
</tr>
<tr>
<td>8.332690</td>
<td>0.339</td>
<td>0.273</td>
<td>0.112</td>
<td>0.247</td>
</tr>
<tr>
<td></td>
<td>0.359</td>
<td>0.024</td>
<td>0.055</td>
<td>0.179</td>
</tr>
<tr>
<td></td>
<td>0.356</td>
<td>0.070</td>
<td>0.061</td>
<td>0.425</td>
</tr>
<tr>
<td></td>
<td>0.007</td>
<td>0.005</td>
<td>0.014</td>
<td>0.032</td>
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<tr>
<td></td>
<td>0.445</td>
<td>0.153</td>
<td>0.263</td>
<td>0.038</td>
</tr>
<tr>
<td></td>
<td>0.000</td>
<td>0.002</td>
<td>0.027</td>
<td>0.079</td>
</tr>
<tr>
<td></td>
<td>0.025</td>
<td>0.010</td>
<td>0.002</td>
<td>0.202</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>0.010</td>
<td>0.007</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>0.000</td>
<td>0.002</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>8.332695</td>
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<td>0.024</td>
<td>0.016</td>
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<tr>
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<td>0.025</td>
<td>0.005</td>
<td>0.371</td>
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<tr>
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<td>0.193</td>
<td>0.070</td>
<td>0.055</td>
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<td></td>
<td>0.008</td>
<td>0.004</td>
<td>0.022</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td>0.444</td>
<td>0.153</td>
<td>0.263</td>
<td>0.039</td>
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<tr>
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<td>0.000</td>
<td>0.002</td>
<td>0.027</td>
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<td></td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

| AGGD | 0.035 | 0.041 | AGCD = 0.022 | 0.004 | AGCD = 0.045 | 0.035 | AGCD = 0.029 | 0.002 |
| ACDL | 0.356 | 0.370 | ACDLC = 0.063 | 0.031 | ACDLC = 0.976 | 1.894 | ACDLC = 0.000 | 0.004 |
| ACHC | 0.023 | 0.042 | ACHNC = 0.006 | 0.030 | ACHNC = 0.003 | 0.030 | ACHNC = 0.000 | 0.000 |
TIME  Time of day (pacific time) - hours minutes seconds hundredths

COEF.  Vehicle aerodynamic coefficients

   O  - Orbiter
   C  - Carrier (SCA)
   M  - Mated

CMR - Vehicle pitching moment about the vehicle moment reference center

NOM.  Coefficients as calculated from GRACIE

I+L  Absolute value of the uncertainty due to instrumentation inaccuracies plus the uncertainty due to LMS inaccuracies

I-L  Absolute value of the uncertainty due to instrumentation inaccuracies minus the uncertainty due to LMS inaccuracies

DATA BOOK  Predicted coefficients based on the "Orbiter/747 Carrier Separation Aerodynamic Data Book"

RT. ELV  Right hand inboard Orbiter elevon position (deg)

LT. ELV  Left hand inboard Orbiter elevon position (deg)

DELNZ  Relative normal acceleration ± uncertainty, predicted (g)

QDOTO  Instantaneous Orbiter pitch acceleration ± uncertainty, predicted (deg/sec²)

INCIDENCE  Orbiter incidence angle (deg)

ALPHAC  SCA angle of attack (deg)

ALPHAO  Orbiter angle of attack (deg)

BETA  SCA angle of sideslip (deg)

GAMMA  SCA flight path angle (deg)

THETA  SCA pitch angle (deg)

ROLL  SCA roll angle (deg)

YAW  SCA yaw angle (deg)

ORBAIL  Orbiter aileron angle (deg)
<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORBRUD</td>
<td>Orbiter rudder position (deg)</td>
</tr>
<tr>
<td>QBAR</td>
<td>Dynamic pressure (lb/ft²)</td>
</tr>
<tr>
<td>ALT</td>
<td>Altitude (MSL ft)</td>
</tr>
<tr>
<td>VKEAS</td>
<td>Velocity (knots equivalent airspeed)</td>
</tr>
<tr>
<td>VFPS</td>
<td>True airspeed (ft per sec)</td>
</tr>
<tr>
<td>NLF</td>
<td>Mated vehicle load factor (g)</td>
</tr>
<tr>
<td>XCGC</td>
<td>SCA cg location in body coordinate system (in.)</td>
</tr>
<tr>
<td>YCGC</td>
<td></td>
</tr>
<tr>
<td>ZCGC</td>
<td></td>
</tr>
<tr>
<td>NX</td>
<td>SCA cg linear acceleration (ft/sec²)</td>
</tr>
<tr>
<td>NY</td>
<td></td>
</tr>
<tr>
<td>NZ</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>SCA body angular rates (deg/sec)</td>
</tr>
<tr>
<td>Q</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td></td>
</tr>
<tr>
<td>PD</td>
<td>SCA body angular accelerations (deg/sec²)</td>
</tr>
<tr>
<td>QD</td>
<td></td>
</tr>
<tr>
<td>RD</td>
<td></td>
</tr>
<tr>
<td>FFY</td>
<td></td>
</tr>
<tr>
<td>FFZ</td>
<td></td>
</tr>
<tr>
<td>FLX</td>
<td>LMS attach forces (lb)</td>
</tr>
<tr>
<td>FLZ</td>
<td></td>
</tr>
<tr>
<td>FRX</td>
<td></td>
</tr>
<tr>
<td>FRY</td>
<td></td>
</tr>
<tr>
<td>FRZ</td>
<td></td>
</tr>
<tr>
<td>HSTAB</td>
<td>SCA horizontal stabilizer position (deg)</td>
</tr>
<tr>
<td>ELVI/O</td>
<td>SCA elevator (inboard/outboard) position (deg)</td>
</tr>
<tr>
<td>RUDU/L</td>
<td>SCA rudder (upper/lower) position (deg)</td>
</tr>
<tr>
<td>SPO/M/I</td>
<td>SCA spoiler panel (outboard/middle/inboard) position (deg)</td>
</tr>
<tr>
<td>AILI/O</td>
<td>SCA aileron (inboard/outboard) position (deg)</td>
</tr>
<tr>
<td>CW</td>
<td>SCA control wheel position (deg)</td>
</tr>
</tbody>
</table>
WTC
IXXC
IYYC
IZZC
IXZC

SCA weight (lb) and inertias (slug-ft²)

WTO
IXXO
IYYO
IZZO
IXZO

Orbiter weight (lb) and inertias (slug-ft²)

THRUST

SCA total engine thrust (lb)

Average coefficient values for previous twenty samples are tabulated after twentieth time step in the following format:

\[
\text{COEFFICIENT} = \frac{\text{AVERAGE \ CALCULATED}}{\text{DATA \ BOOK}}
\]
APPENDIX B

PLOTS
PROGRAM PLOTTING CAPABILITY

GRACIE generates time history plots of the aerodynamic coefficients for each vehicle, the angle of attack of each vehicle, the relative normal load factor ($\Delta N_z$), and the instantaneous pitch acceleration of the Orbiter ($\beta$). With minor modifications, the program has the capability to plot any input or calculated parameter. As an example, GRACIE generated the following set of plots.
GRACIE (D.J. HOMAN)

Captive Active Flight No. 1:
- Elevon Bias = +1.0
- Body Flap = -9.7
- Tail Cone On
- C.G. = 63.6
- Incidence = 6

<table>
<thead>
<tr>
<th>Angle of Attack</th>
<th>Time (Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.00</td>
<td>30770.00</td>
</tr>
<tr>
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<tr>
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<td>30774.50</td>
</tr>
<tr>
<td>-8.00</td>
<td>30775.00</td>
</tr>
</tbody>
</table>
GRACIE (J. J. HOMAN)

CAPTIVE:ACTIVE:FLIGHT_NO.:1
ELEVON_BIAS = +1.0
BODY_FLAP = -9.7
TAIL_CONE_ON
C.G. = 63.8
INCIDENCE = 6.

TIME...SEC.
GRACE (D.J. HOMAN)

CACTIVE ACTIVE FLIGHT NO.
ELEVON BIAS = -1.0
BODY FLAP = -9.7
TAIL CONE ON
C.G. = 63.6
INCIDENCE = 6°
<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Orbiter CL</th>
<th>0.90</th>
<th>0.80</th>
<th>0.70</th>
<th>0.60</th>
<th>0.50</th>
<th>0.40</th>
<th>0.30</th>
<th>0.20</th>
<th>0.10</th>
<th>0.00</th>
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<tbody>
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<td></td>
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<tr>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**GRACIE (O.J. HUMAN)**

- CAPTIVE ACTIVE FLIGHT NO. 1
- ELEVON BIAS = 1.0
- BODY FLAP = -9.7
- TAIL CONE ON
- C.G. = 63.8
- INCIDENCE = 6.

**Time Scale:**
- 0.00: 0.00, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50
- 1.00: 1.00, 1.05, 1.10, 1.15, 1.20, 1.25, 1.30, 1.35, 1.40, 1.45, 1.50

**CL (Degree):**
- 0.00: 0.00, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 1.00

**Notes:**
- Data plotted for CL (Degree) against time for GRACIE (O.J. HUMAN) during captive active flight No. 1 with specified settings.
GRACIE (D.J. HOMAN)
CAPTIVE ACTIVE FLIGHT NO. 1
ELEVON BIAS = -1.0
BODY FLAP = -9.7
TAIL CONE ON
C.G. = 63.6
INCIDENCE = 6

TIME: SEC
30770.00 30770.50 30771.00 30771.50 30772.00 30772.50 30773.00 30773.50 30774.00 30774.50 30775.00
GRACIE (O.J. HOMAN)

CAPTIVE ACTIVE FLIGHT NO. 1

ELEVON BIAS = -1.0
BODY FLAP = -9.7
TAIL CONE ON
C.G. = 63.6
INCIDENCE = 6.

---

TIME: SEC
30770.00 30770.50 30771.00 30771.50 30772.00 30772.50 30773.00 30773.50 30774.00 30774.50 30775.00
GRACIE (D.J. HOMAN)

<table>
<thead>
<tr>
<th>CAPTIVE.ACTIVE.FLIGHT NO.</th>
<th>1</th>
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</thead>
<tbody>
<tr>
<td>ELEVON.BIAS.</td>
<td>-1.0</td>
</tr>
<tr>
<td>BODY.FLAP.</td>
<td>-9.7</td>
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<tr>
<td>TAIL.CONE ON.</td>
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</tr>
<tr>
<td>C.G.</td>
<td>63.8</td>
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<tr>
<td>INCIDENCE</td>
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</table>

**CL**

<table>
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<td>0.00</td>
</tr>
<tr>
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</tr>
<tr>
<td>0.20</td>
</tr>
<tr>
<td>0.40</td>
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**CARRIER**

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</tr>
<tr>
<td>0.40</td>
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<tr>
<td>0.60</td>
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</table>
GRACIE (D.J. HOMAN)

Captive Active Flight No. 1
ELEVON BIAS = -1.0
BODY FLAP = -9.7
TAIL CONE ON
C.G. = 63.8
INCIDENCE = 6.1

TIME...SEC.
GRADIE (D.J. HOMAN)

CAPTIVE_ACTIVE_FLIGHT_NO.1
ELEVON_BIAS = -1.0
BODY FLAP = -9.7
TAIL_CONE_ON

C.G. = 63.8
INCIDENCE = 6°
GRACIE (D.J. HOMON)

CAPTIVE ACTIVE FLIGHT NO. 1
ELEVON BIAS = 1.0
BODY FLAP = -9.7
TAIL CONE ON
C.G. = 63.8
INCIDENCE = 6.
<table>
<thead>
<tr>
<th>CAPTIVE:ACTIVE_FLIGHT_NO.</th>
<th>BODY_FLAP</th>
<th>ELEVON_BIAS</th>
<th>TAIL_CONE_ON</th>
<th>C.G.</th>
<th>INCIDENCE</th>
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<tbody>
<tr>
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<td>-9.2</td>
<td></td>
<td>63.8</td>
<td>6</td>
</tr>
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</table>
GRACIE (D.J. HUMAN)

CAPTIVE ACTIVE FLIGHT NO. 1

ELEVON BIAS = -1.0
BODY FLAP = -9.7
TAIL CONE ON
C.G. = 63.8
INCLINATION = 6.

TIME...SEC

FRIED. LOADS, x104
GRACIE (D.J. HOMAN)

Captive Active Flight No. 1

Elevator Bias: -1.0
Body Flap: -8.7
Tail Cone on
C.G.: 65.0
Incidence: 6°