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MCDONNELL DOUGLAS TECHNICAL SERVICES CO.
HOUSTON ASTRONAUTICS DIVISION

SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

DESIGN NOTE NO. 1.4-7-33

DETERMINATION OF ORBITER AND CARRIER AERODYNAMIC COEFFICIENTS FROM LOAD CELL MEASUREMENTS

MISSION PLANNING, MISSION ANALYSIS AND SOFTWARE FORMULATION

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GLOSSARY OF SYMBOLS

A_{CAR}	AERODYNAMIC REFERENCE AREA OF THE CARRIER ($=5500ft^2$)
A_{ORB}	AERODYNAMIC REFERENCE AREA OF THE ORBITER ($=2690ft^2$)
ALT	APPROACH AND LANDING TEST
$\vec{a}_{s_{CAR}}$	ACCELERATION VECTOR SENSED ON THE CARRIER EXPRESSED IN THE CARRIER VRCS
α_{CAR}	ANGLE ATTACK OF THE CARRIER
α_{ORB}	ANGLE ATTACK OF THE ORBITER
$[B_{21}]$	ORBITER TO CARRIER VRCS TRANSFORMATION MATRIX
$\bar{b}_{CAR}$	LATERAL AERODYNAMIC REFERENCE LENGTH OF THE CARRIER (= 195.7 ft)
$\bar{b}_{ORB}$	LATERAL AERODYNAMIC REFERENCE LENGTH OF THE ORBITER (= 78.0567 ft)
$\bar{c}_{CAR}$	LONGITUDINAL AERODYNAMIC REFERENCE LENGTH OF THE CARRIER (= 27.32 ft)
$\bar{c}_{ORB}$	LONGITUDINAL AERODYNAMIC REFERENCE LENGTH OF THE ORBITER (= 39.5667 ft)
$C_{A_{CAR}}$	AERODYNAMIC AXIAL FORCE COEFFICIENT OF THE CARRIER
$C_{A_{ORB}}$	AERODYNAMIC AXIAL FORCE COEFFICIENT OF THE ORBITER
$C_{D_{CAR}}$	AERODYNAMIC DRAG COEFFICIENT OF THE CARRIER

GLOSSARY OF SYMBOLS (CONT.)

$C_{D_{ORB}}$	AERODYNAMIC DRAG COEFFICIENT OF THE ORBITER
$\vec{CG}_{CAR}$	POSITION OF THE CARRIER cg WITH RESPECT TO THE CARRIER VRCS
$\vec{CG}_{ORB}$	POSITION OF THE ORBITER cg WITH RESPECT TO THE ORBITER VRCS
$\vec{CG}_{REF_{CAR}}$	POSITION OF THE CARRIER MRC WITH RESPECT TO THE CARRIER VRCS (XYZ COMPONENTS = -1339.9, 0, 9.25 in)
$\vec{CG}_{REF_{CAR}}$	POSITION OF THE ORBITER MRC WITH RESPECT TO THE ORBITER VRCS (XYZ COMPONENTS = -1108.75, 0, 25 in)
cg	CENTER OF GRAVITY
$C_{L_{CAR}}$	AERODYNAMIC LIFT COEFFICIENT OF THE CARRIER
$C_{L_{ORB}}$	AERODYNAMIC LIFT COEFFICIENT OF THE ORBITER
$C_{\ell_{CAR}}$	AERODYNAMIC ROLLING MOMENT COEFFICIENT OF THE CARRIER ABOUT ITS MRC
$C_{\ell_{ORB}}$	AERODYNAMIC ROLLING MOMENT COEFFICIENT OF THE ORBITER ABOUT ITS MRC
$C_{\ell_{cg_{CAR}}}$	AERODYNAMIC ROLLING MOMENT COEFFICIENT OF THE CARRIER ABOUT ITS cg
$C_{\ell_{cg_{ORB}}}$	AERODYNAMIC ROLLING MOMENT COEFFICIENT OF THE ORBITER ABOUT ITS cg
$C_{m_{CAR}}$	AERODYNAMIC PITCHING MOMENT COEFFICIENT OF THE CARRIER ABOUT ITS MRC
$C_{m_{ORB}}$	AERODYNAMIC PITCHING MOMENT COEFFICIENT OF THE ORBITER ABOUT ITS MRC

GLOSSARY OF SYMBOLS (CONT.)

$C_{m_{cg_{CAR}}}$	AERODYNAMIC PITCHING MOMENT COEFFICIENT OF THE CARRIER ABOUT ITS cg
$C_{m_{cg_{ORB}}}$	AERODYNAMIC PITCHING MOMENT COEFFICIENT OF THE ORBITER ABOUT ITS cg
$C_{N_{CAR}}$	AERODYNAMIC NORMAL FORCE COEFFICIENT OF THE CARRIER
$C_{N_{ORB}}$	AERODYNAMIC NORMAL FORCE COEFFICIENT OF THE ORBITER
$C_{n_{CAR}}$	AERODYNAMIC YAWING MOMENT COEFFICIENT OF THE CARRIER ABOUT ITS MRC
$C_{n_{ORB}}$	AERODYNAMIC YAWING MOMENT COEFFICIENT OF THE ORBITER ABOUT ITS MRC
$C_{n_{cg_{CAR}}}$	AERODYNAMIC YAWING MOMENT COEFFICIENT OF THE CARRIER ABOUT ITS cg
$C_{n_{cg_{ORB}}}$	AERODYNAMIC YAWING MOMENT COEFFICIENT OF THE ORBITER ABOUT ITS cg
$C_{Y_{CAR}}$	AERODYNAMIC SIDE FORCE COEFFICIENT OF THE CARRIER
$C_{Y_{ORB}}$	AERODYNAMIC SIDE FORCE COEFFICIENT OF THE ORBITER
$\Delta\theta$	ANGLE OF INCIDENCE
$\vec{F}_{A_{CAR}}$	AERODYNAMIC FORCE VECTOR ACTING ON THE CARRIER cg EXPRESSED IN THE CARRIER VRCS
$\vec{F}_{A_{ORB}}$	AERODYNAMIC FORCE VECTOR ACTING ON THE ORBITER cg EXPRESSED IN THE ORBITER VRCS

GLOSSARY OF SYMBOLS (CONT.)

$\vec{F}_c$	FORCE VECTOR ACTING ON THE CARRIER cg BY THE ORBITER COUPLED THRU THE ATTACH STRUCTURES EXPRESSED IN THE CARRIER VRCS
$\vec{F}_{CAR}$	TOTAL EXTERNAL FORCE VECTOR ACTING ON THE CARRIER cg EXPRESSED IN THE CARRIER VRCS
$\vec{F}_F$	FORCE VECTOR IN THE FRONT ATTACH STRUT EXPRESSED IN THE CARRIER VRCS
$\vec{F}_{LA}$	FORCE VECTOR IN THE LEFT AFT ATTACH STRUT EXPRESSED IN THE CARRIER VRCS
$\vec{F}_{MAT}$	TOTAL EXTERNAL FORCE VECTOR ACTING ON THE MATED cg EXPRESSED IN THE CARRIER VRCS
$\vec{F}_{ORB}$	TOTAL EXTERNAL FORCE VECTOR ACTING ON THE ORBITER cg EXPRESSED IN THE ORBITER VRCS
$\vec{F}_{RA}$	FORCE VECTOR IN THE RIGHT AFT ATTACH STRUT EXPRESSED IN THE CARRIER VRCS
$\vec{F}_T$	CARRIER ENGINE THRUST EXPRESSED IN THE CARRIER VRCS
$\vec{G}_{A_{CAR}}$	AERODYNAMIC MOMENT VECTOR ACTING ABOUT THE CARRIER cg EXPRESSED IN THE CARRIER VRCS
$\vec{G}_{A_{ORB}}$	AERODYNAMIC MOMENT VECTOR ACTING ABOUT THE ORBITER cg EXPRESSED IN THE ORBITER VRCS
$\vec{G}_c$	MOMENT VECTOR ACTING ABOUT THE CARRIER cg BY THE ORBITER COUPLED THRU THE ATTACH STRUCTURES EXPRESSED IN THE CARRIER VRCS
$\vec{G}_{CAR}$	TOTAL EXTERNAL MOMENT VECTOR ACTING ABOUT THE CARRIER EXPRESSED IN THE CARRIER VRCS

GLOSSARY OF SYMBOLS (CONT.)

$\vec{G}_{MAT}$	TOTAL EXTERNAL MOMENT VECTOR ACTING ABOUT THE MATED cg EXPRESSED IN THE CARRIER VRCS
$\vec{G}_{ORB}$	TOTAL EXTERNAL MOMENT VECTOR ACTING ABOUT THE ORBITER cg EXPRESSED IN THE ORBITER VRCS
$[I_{CAR}]$	INERTIA TENSOR MATRIX OF THE CARRIER
$[I_{MAT}]$	INERTIA TENSOR MATRIX OF THE MATED VEHICLE
$[I_{ORB}]$	INERTIA TENSOR MATRIX OF THE ORBITER
MDTSCO	MCDONNELL DOUGLAS TECHNICAL SERVICES COMPANY
MRC	MOMENT REFERENCE CENTER
M_{CAR}	MASS OF THE CARRIER
M_{MAT}	MASS OF THE MATED VEHICLE
M_{ORB}	MASS OF THE ORBITER
$\vec{P}_{F}$	POSITION OF THE FRONT ATTACH STRUT (PINNED TO THE CARRIER) WITH RESPECT TO THE CARRIER VRCS (XYZ COMPONENTS = -680, 0, -172 in)
$\vec{P}_{LA}$	POSITION OF THE LEFT AFT ATTACH POINT WITH RESPECT TO THE CARRIER VRCS (XYZ COMPONENTS = -1607, -96.5, -200 in)
$\vec{P}_{RA}$	POSITION OF THE RIGHT AFT ATTACH POINT WITH RESPECT TO THE CARRIER VRCS (XYZ COMPONENTS = -1607, 96.5, -200 in)
$\vec{P}_{RA_{ORB}}$	POSITION OF THE RIGHT AFT ATTACH POINT WITH RESPECT TO THE ORBITER VRCS (XYZ COMPONENTS = -1317, 96.5, 132.4 in)

$\vec{P}_T$	POSITION OF THE THRUST APPLICATION POINT WITH RESPECT TO THE CARRIER VRCS (XYZ COMPONENTS = -1331.946, 0, 77.652 in)
$\bar{q}$	DYNAMIC PRESSURE
RI	ROCKWELL INTERNATIONAL
$\vec{R}$	RELATIVE POSITION OF THE ORBITER cg WITH RESPECT TO THE CARRIER cg EXPRESSED IN THE CARRIER VRCS
$\vec{R}_F$	RELATIVE POSITION OF THE FRONT ATTACH STRUT WITH RESPECT TO THE CARRIER cg EXPRESSED IN THE CARRIER VRCS
$\vec{R}_{LA}$	RELATIVE POSITION OF THE LEFT AFT ATTACH POINT WITH RESPECT TO THE CARRIER cg EXPRESSED IN THE CARRIER VRCS
$\vec{R}_{RA}$	RELATIVE POSITION OF THE RIGHT AFT ATTACH POINT WITH RESPECT TO THE CARRIER cg EXPRESSED IN THE CARRIER VRCS
$\vec{R}_{RA_{ORB}}$	RELATIVE POSITION OF THE RIGHT AFT ATTACH POINT WITH RESPECT TO THE ORBITER cg EXPRESSED IN THE ORBITER VRCS
$\vec{R}_T$	RELATIVE POSITION OF THE THRUST APPLICATION POINT WITH RESPECT TO THE CARRIER cg EXPRESSED IN THE CARRIER VRCS
$\vec{R}_1$	RELATIVE POSITION OF THE CARRIER cg WITH RESPECT TO THE MATED cg EXPRESSED IN THE CARRIER VRCS
$\vec{R}_2$	RELATIVE POSITION OF THE ORBITER cg WITH RESPECT TO THE MATED cg EXPRESSED IN THE CARRIER VRCS
SVDS	SPACE VEHICLE DYNAMICS SIMULATION
VRCS	VEHICLE REFERENCED COORDINATE SYSTEM
$\vec{\omega}$	ANGULAR RATE VECTOR OF THE CARRIER EXPRESSED IN THE CARRIER VRCS
$\dot{\vec{\omega}}$	ANGULAR ACCELERATION VECTOR OF THE CARRIER EXPRESSED IN THE CARRIER VRCS

1.0 SUMMARY

A method of determining orbiter and carrier total aerodynamic coefficients from load cell measurements is required to support the inert and the captive active flights of the ALT program. This report documents the derivation of a set of equations expressing the orbiter and carrier total aerodynamic coefficients in terms of the load cell measurements, the sensed dynamics of the Boeing 747 (carrier) aircraft, and the relative geometry of the orbiter/carrier.

The requirement for a method of determining orbiter and carrier total aerodynamic coefficients is stated in Section 2.0. The assumptions, the geometry, and the derivation of the equations are presented in Section 3.0. Numerical results of the derived equations are evaluated in Section 4.0. The conclusions and recommendations are summarized in Section 5.0. Supporting reference sources are listed in Section 6.0.

2.0 INTRODUCTION

A method of determining orbiter and carrier total aerodynamic coefficients from load cell measurements is required to support the inert and the captive active flights of the ALT program. During the inert and captive active flights, the mated vehicle will perform the pre-separation maneuver and attain equilibrium glide at the target separation conditions. In addition, during the captive active flights, the orbiter pilot will move the elevons to several positions about the trim position. During these procedures, load cell readings in the front and aft attach struts will be recorded. This load cell data in combination with other data recorded on the flight recorders (i.e. sensed acceleration of the carrier, body angular rates and accelerations of the carrier, thrust of the carrier engines, angle of attack of the carrier,and dynamic pressure) will be used to compute the total aerodynamic coefficients of the orbiter and the carrier. These computed values will then be compared to the wind tunnel predicted values. If there are significant differences between the two sets of values the target separation conditions will be adjusted accordingly.

The objective of this MDTSCO "Determination of Orbiter and Carrier Aerodynamic Coefficients from Load Cell Measurements" is to present a straight forward derivation of the equations necessary to determine the orbiter and carrier total aerodynamic coefficients from data recorded during the ALT flights.

3.0 DISCUSSION

This section presents the assumptions, the geometry, and the derivation of the equations necessary to determine the orbiter and carrier total aerodynamic coefficients. Maximum utilization of previous analyses is made and source data is referenced accordingly in the subsequent text.

The derivation of the equations of the orbiter and carrier total aerodynamic coefficients is performed in five steps. The first step is to write the total external forces and moments acting on the mated vehicle at its cg in terms of the total external forces and moments acting on the orbiter and carrier at their respective cg's and also in terms of parameters recorded during the ALT flight. In the second step, the total external forces and moments acting on the carrier at its cg are written in terms of parameters recorded during the ALT flight. The third step is to solve the equations from steps 1 and 2 simultaneously to obtain equations expressing the total external forces and moments acting on the orbiter at its cg. In the fourth step, the forces and moments due to engine thrust are subtracted from the forces and moments from steps 2 and 3 to obtain the total aerodynamic forces and moments acting on the orbiter and carrier at their respective cg's. In step 5, the forces and moments from step 4 are used to determine the aerodynamic axial, side, and normal force coefficients and the rolling, pitching, and yawing moment coefficients of both the orbiter and carrier at their respective cg's. Also, the aerodynamic forces of the orbiter and carrier from step 4 are transformed to their respective stability axes and transferred to their respective MRC's to determine the aerodynamic drag and lift coefficients and the rolling, pitching, and yawing moment coefficients of both the orbiter and carrier at their respective MRC's.

3.1 Assumptions

There are two categories of assumptions used in this report. The first category is assumptions pertaining to the form of the recorded data while the assumptions of the second category serve to simplify the problem.

It is assumed that the following parameters will be expressed (where applicable) in the vehicle referenced coordinate system (VRCS) of the carrier and will be given in the units indicated.

1) The force vectors in the front, left aft, and right aft attach struts, $\vec{F}_F$, $\vec{F}_{LA}$, and $\vec{F}_{RA}$ respectively in lb.
2) The force vector due to carrier engine thrust, $\vec{F}_T$ in lb.
3) The sensed acceleration vector of the carrier, $\vec{a}_{s_{CAR}}$ in ft/sec^2
4) The angular rate vector of the carrier, $\vec{\omega}$ in rad/sec.
5) The angular acceleration vector of the carrier, $\dot{\vec{\omega}}$ in rad/sec^2.
6) The dynamic pressure sensed on the carrier, $\bar{q}$ in lb/ft^2.
7) The angle of attack of the carrier α_{CAR} in rad.

To simplify the problem, the following assumptions are made.

1) The mated vehicle is considered to be two rigid bodies (the orbiter and the carrier) constrained to move as one rigid body.

2) The dynamic pressure of the orbiter is equal to that of the carrier. This assumption is necessary since during the time that the orbiter's air data probe is in proximity to the carrier, it will make incorrect measurements.

3.2 Geometry of the Orbiter/Carrier

The orbiter is oriented in the vehicle's plane of symmetry with respect to the carrier at an angle of incidence. The incidence angle and location and orientation of the VRCS of both vehicles are illustrated in Figure 1. The transformation of the orbiter VRCS to the carrier VRCS may be expressed as

$$[B_{21}] = \begin{bmatrix} \cos\Delta\theta & 0.0 & \sin\Delta\theta \\ 0.0 & 1.0 & 0.0 \\ -\sin\Delta\theta & 0.0 & \cos\Delta\theta \end{bmatrix} \qquad [3.2.1]$$

Figure 2 illustrates the relative positions of the attach points, the orbiter cg, the carrier cg, and the mated cg.

The mass properties of the mated vehicle, in terms of the mass properties of the orbiter and carrier and the geometry, may be written as

$$M_{MAT} = M_{CAR} + M_{ORB} \quad \text{and} \qquad [3.2.2]$$

$$[I_{MAT}] = [I_{CAR}] + [B_{21}]\,[I_{ORB}]\,[B_{21}]^T + \frac{M_{CAR} M_{ORB}}{M_{MAT}} [\vec{R}^T\vec{R} - \vec{R}\vec{R}^T] \qquad [3.2.3]$$

From the VRCS positions of the attach points and the thrust application point (Reference 1) the relative position vectors shown in Figure 2 may be written as

$$\vec{R}_F = \vec{P}_F - \vec{CG}_{CAR} , \qquad [3.2.4]$$

$$\vec{R}_{LA} = \vec{P}_{LA} - \vec{CG}_{CAR} , \qquad [3.2.5]$$

$$\vec{R}_{RA} = \vec{P}_{RA} - \vec{CG}_{CAR} , \qquad [3.2.6]$$

$$\vec{R}_{RA_{ORB}} = \vec{P}_{RA_{ORB}} - \vec{CG}_{ORB} , \qquad [3.2.7]$$

$$\vec{R}_T = \vec{P}_T - \vec{CG}_{CAR} , \qquad [3.2.8]$$

$$\vec{R} = \vec{R}_{RA} - [B_{21}] \vec{R}_{RA_{ORB}} , \qquad [3.2.9]$$

$$\vec{R}_1 = -\frac{M_{ORB}}{M_{MAT}} \vec{R}, \text{ and} \qquad [3.2.10]$$

$$\vec{R}_2 = -\frac{M_{CAR}}{M_{MAT}} \vec{R}. \qquad [3.2.11]$$

3.3 Derivation of Equations

The total external forces acting on the mated vehicle may be expressed, in terms of the total external forces acting on the orbiter and the carrier, as

$$\vec{F}_{MAT} = \vec{F}_{CAR} + [B_{21}] \vec{F}_{ORB} . \qquad [3.3.1]$$

Similarily, the total external moments acting on the mated vehicle may be expressed as

$$\vec{G}_{MAT} = \vec{G}_{CAR} + [B_{21}]\vec{G}_{ORB} + \vec{R}_1 x \vec{F}_{CAR} + \vec{R}_2 x [B_{21}] \vec{F}_{ORB} . \qquad [3.3.2]$$

By substituting equations [3.2.10] and [3.2.11] for $\vec{R}_1$ and $\vec{R}_2$, equation [3.3.2] may also be written as

$$\vec{G}_{MAT} = \vec{G}_{CAR} + [B_{21}]\vec{G}_{ORB} - \frac{M_{ORB}}{M_{MAT}} \vec{R} \times \vec{F}_{CAR} + \frac{M_{CAR}}{M_{MAT}} \vec{R} \times [B_{21}]\vec{F}_{ORB}. \qquad [3.3.3]$$

Also, the total external forces and moments on the mated vehicle may be expressed, in terms of data recorded during the flight, as

$$\vec{F}_{MAT} = M_{MAT} \left\{ \vec{a}_{s_{CAR}} - \dot{\vec{\omega}} \times \vec{R}_1 - \vec{\omega} \times (\vec{\omega} \times \vec{R}_1) \right\} \qquad [3.3.4]$$

$$G_{MAT} = [I_{MAT}] \dot{\vec{\omega}} + \vec{\omega} \times [I_{MAT}] \vec{\omega}. \qquad [3.3.5]$$

By substituting equations [3.2.3] and [3.2.10] for $[I_{MAT}]$ and $\vec{R}_1$, equations [3.3.4] and [3.3.5] may be written as

$$\vec{F}_{MAT} = M_{MAT} \vec{a}_{s_{CAR}} + M_{ORB} \dot{\vec{\omega}} \times \vec{R} + M_{ORB} \left\{ \vec{\omega} \times (\vec{\omega} \times \vec{R}) \right\} \qquad [3.3.6]$$

$$G_{MAT} = [I_{CAR}] \dot{\vec{\omega}} + \vec{\omega} \times [I_{CAR}] \vec{\omega} + \qquad [3.3.7]$$

$$[B_{21}] [I_{ORB}] [B_{21}]^T \dot{\vec{\omega}} + \vec{\omega} \times [B_{21}] [I_{ORB}] [B_{21}]^T \vec{\omega} +$$

$$\frac{M_{CAR} M_{ORB}}{M_{MAT}} [\vec{R}^T \vec{R} - \vec{R}\vec{R}^T] \dot{\vec{\omega}} + \frac{M_{CAR} M_{ORB}}{M_{MAT}} \left\{ \vec{\omega} \times [\vec{R}^T \vec{R} - \vec{R}\vec{R}^T] \vec{\omega} \right\}.$$

Reference 2 shows that the forces and moments imparted to the carrier by the orbiter thru the attach structures may be expressed in the following two ways.

$$\vec{F}_c = M_{CAR}\,\vec{a}_{s_{CAR}} - \vec{F}_{CAR} \qquad [3.3.8]$$

$$\vec{F}_c = -(\vec{F}_F + \vec{F}_{LA} + \vec{F}_{RA}) \qquad [3.3.9]$$

$$\vec{G}_c = [I_{CAR}]\,\dot{\vec{\omega}} + \vec{\omega} \times [I_{CAR}]\,\vec{\omega} - \vec{G}_{CAR} \qquad [3.3.10]$$

$$\vec{G}_c = -(\vec{R}_F \times \vec{F}_F + \vec{R}_{LA} \times \vec{F}_{LA} + \vec{R}_{RA} \times \vec{F}_{RA}) \qquad [3.3.11]$$

From equations [3.3.8] thru [3.3.11], the total external forces and moments acting on the carrier at its cg may be solved for in terms of the recorded data, mass properties, and geometry.

$$\vec{F}_{CAR} = M_{CAR}\,\vec{a}_{s_{CAR}} + \vec{F}_F + \vec{F}_{LA} + \vec{F}_{RA}\,. \qquad [3.3.12]$$

$$\vec{G}_{CAR} = [I_{CAR}]\,\dot{\vec{\omega}} + \vec{\omega} \times [I_{CAR}]\,\vec{\omega} + \vec{R}_F \times \vec{F}_F + \vec{R}_{LA} \times \vec{F}_{LA} + \vec{R}_{RA} \times \vec{F}_{RA} \qquad [3.3.13]$$

By solving equations [3.3.1], [3.3.3], [3.3.6], [3.3.7], [3.3.12], and [3.3.13] simultaneously, the total external forces and moments acting on the orbiter at its cg may be written in terms of the recorded data, the mass properties, and the relative geometry of the orbiter/carrier.

$$\vec{F}_{ORB} = [B_{21}]^T \left\{M_{ORB}[\vec{a}_{s_{CAR}} + \vec{\omega}\times\vec{R} + \vec{\omega}\times(\vec{\omega}\times\vec{R})] - (\vec{F}_F + \vec{F}_{LA} + \vec{F}_{RA})\right\} \qquad [3.3.14]$$

$$\vec{G}_{ORB} = [I_{ORB}][B_{21}]^T \dot{\vec{\omega}} + [B_{21}]^T \vec{\omega} \times [I_{ORB}][B_{21}]^T \vec{\omega} + \qquad [3.3.15]$$

$$[B_{21}]^T \left\{(\vec{R}-\vec{R}_F) \times \vec{F}_F + (\vec{R}-\vec{R}_{LA}) \times \vec{F}_{LA} + (\vec{R}-\vec{R}_{RA}) \times \vec{F}_{RA}\right\}$$

To obtain the total aerodynamic forces and moments, the forces and moments due to the engine thrust must be subtracted from the total external forces and moments. Therefore the aerodynamic forces and moments acting on the orbiter and carrier at their respective cgs may be written as

$$\vec{F}_{A_{ORB}} = \vec{F}_{ORB} , \qquad [3.3.16]$$

$$\vec{G}_{A_{ORB}} = \vec{G}_{ORB} , \qquad [3.3.17]$$

$$\vec{F}_{A_{CAR}} = \vec{F}_{CAR} - \vec{F}_T \text{ , and} \qquad [3.3.18]$$

$$\vec{G}_{A_{CAR}} = \vec{G}_{CAR} - \vec{R}_T \times \vec{F}_T . \qquad [3.3.19]$$

From the forces and moments given by equations [3.3.16] and [3.3.17], the orbiter aerodynamic coefficients $C_{A_{ORB}}$, $C_{Y_{ORB}}$, $C_{N_{ORB}}$, $C_{\ell_{cg_{ORB}}}$, $C_{m_{cg_{ORB}}}$, and $C_{n_{cg_{ORB}}}$ may be written as

$$C_{A_{ORB}} = - F_{X_{A_{ORB}}} \Big/ \bar{q} \cdot A_{ORB}, \qquad [3.3.20]$$

$$C_{Y_{ORB}} = F_{Y_{A_{ORB}}} / \bar{q} \cdot A_{ORB} \, , \qquad [3.3.21]$$

$$C_{N_{ORB}} = - F_{Z_{A_{ORB}}} / \bar{q} \cdot A_{ORB} \, , \qquad [3.3.22]$$

$$C_{\ell_{cg_{ORB}}} = G_{X_{A_{ORB}}} / \bar{q} \cdot A_{ORB} \cdot \bar{b}_{ORB} \, , \qquad [3.3.23]$$

$$C_{m_{cg_{ORB}}} = G_{Y_{A_{ORB}}} / \bar{q} \cdot A_{ORB} \cdot \bar{c}_{ORB} \, , \text{ and} \qquad [3.3.24]$$

$$C_{n_{cg_{ORB}}} = G_{Z_{A_{ORB}}} / \bar{q} \cdot A_{ORB} \cdot \bar{b}_{ORB} . \qquad [3.3.25]$$

By transforming the forces given by equation [3.3.16] to the stability axis system of the orbiter and transferring them to the orbiter's MRC, the aerodynamic coefficients $C_{D_{ORB}}$, $C_{L_{ORB}}$, $C_{\ell_{ORB}}$, $C_{m_{ORB}}$, and $C_{n_{ORB}}$ may be written as

$$C_{D_{ORB}} = -[F_{X_{A_{ORB}}} \cdot COS(\alpha_{CAR} + \Delta\theta) + F_{Z_{A_{ORB}}} \cdot SIN(\alpha_{CAR} + \Delta\theta)] / \bar{q} \cdot A_{ORB} , \qquad [3.3.26]$$

$$C_{L_{ORB}} = -[-F_{X_{A_{ORB}}} \cdot SIN(\alpha_{CAR} + \Delta\theta) + F_{Z_{A_{ORB}}} \cdot SIN(\alpha_{CAR} + \Delta\theta)] / \bar{q} \cdot A_{ORB} , \qquad [3.3.27]$$

$$C_{\ell_{ORB}} = [G_{X_{A_{ORB}}} \Big/ \bar{b}_{ORB} + (CG_{Y_{REF_{ORB}}} - CG_{Y_{ORB}}) \cdot F_{Z_{A_{ORB}}} - (CG_{Z_{REF_{ORB}}} - CG_{Z_{ORB}}) \cdot F_{Y_{A_{ORB}}}] \Big/ \bar{q} \cdot A_{ORB},$$

[3.3.28]

$$C_{m_{ORB}} = [G_{Y_{A_{ORB}}} \Big/ \bar{c}_{ORB} + (CG_{Z_{REF_{ORB}}} - CG_{Z_{ORB}}) \cdot F_{X_{A_{ORB}}} - (CG_{X_{REF_{ORB}}} - CG_{X_{REF_{ORB}}}) \cdot F_{Z_{A_{ORB}}}] \Big/ \bar{q} \cdot A_{ORB},$$

[3.3.29]

$$C_{n_{ORB}} = [G_{Z_{A_{ORB}}} \Big/ \bar{b}_{ORB} + (CG_{X_{REF_{ORB}}} - CG_{X_{ORB}}) \cdot F_{Y_{A_{ORB}}} - (CG_{Y_{REF_{ORB}}} - CG_{Y_{ORB}}) \cdot F_{X_{A_{ORB}}} \Big/ \bar{q} \cdot A_{ORB}.$$

[3.3.29]

Similarily from equations [3.3.18]and [3.3.19], the carrier aerodynamic coefficients $C_{A_{CAR}}$, $C_{Y_{CAR}}$, $C_{N_{CAR}}$, $C_{D_{CAR}}$, $C_{L_{CAR}}$, $C_{\ell_{cg_{CAR}}}$, $C_{m_{cg_{CAR}}}$, $C_{n_{cg_{CAR}}}$, $C_{\ell_{CAR}}$, $C_{m_{CAR}}$, and $C_{n_{CAR}}$ may be written as

$$C_{A_{CAR}} = - F_{X_{A_{CAR}}} \Big/ \bar{q} \cdot A_{CAR},$$ [3.3.31]

$$C_{Y_{CAR}} = F_{Y_{A_{CAR}}} \Big/ \bar{q} \cdot A_{CAR},$$ [3.3.32]

$$C_{N_{CAR}} = -F_{Z_{A_{CAR}}} \Big/ \bar{q} \cdot A_{CAR} ,$$ [3.3.33]

$$C_{D_{CAR}} = -[F_{X_{A_{CAR}}} \cdot COS\alpha_{CAR} + F_{Z_{A_{CAR}}} \cdot SIN\alpha_{CAR}] \Big/ \bar{q} \cdot A_{CAR},$$ [3.3.34]

$$C_{L_{CAR}} = -[-F_{X_{A_{CAR}}} \cdot SIN\alpha_{CAR} + F_{Z_{A_{CAR}}} \cdot COS\alpha_{CAR}] \Big/ \bar{q} \cdot A_{CAR},$$ [3.3.35]

$$C_{\ell_{cg_{CAR}}} = G_{X_{A_{CAR}}} \Big/ \bar{q} \cdot A_{CAR} \cdot \bar{b}_{CAR},$$ [3.3.36]

$$C_{m_{cg_{CAR}}} = G_{Y_{A_{CAR}}} \Big/ \bar{q} \cdot A_{CAR} \cdot \bar{c}_{CAR},$$ [3.3.37]

$$C_{n_{cg_{CAR}}} = G_{Z_{A_{CAR}}} \Big/ \bar{q} \cdot A_{CAR} \cdot \bar{b}_{CAR},$$ [3.3.38]

$$C_{\ell_{CAR}} = [G_{X_{A_{CAR}}} / \bar{b}_{CAR} + (CG_{Y_{REF_{CAR}}} - CG_{Y_{CAR}}) \cdot F_{Z_{A_{CAR}}} - (CG_{Z_{REF_{CAR}}} - CG_{Z_{CAR}}) \cdot F_{Y_{A_{CAR}}}] / \bar{q} \cdot A_{CAR},$$

[3.3.40]

$$C_{m_{CAR}} = [G_{Y_{A_{CAR}}} / \bar{c}_{CAR} + (CG_{Z_{REF_{CAR}}} - CG_{Z_{CAR}}) \cdot F_{X_{A_{CAR}}} - (CG_{X_{REF_{CAR}}} - CG_{X_{CAR}}) \cdot F_{Z_{A_{CAR}}}] / \bar{q} \cdot A_{CAR},$$ and

[3.3.41]

$$C_{n_{CAR}} = [G_{Z_{A_{CAR}}} / \bar{b}_{CAR} + (CG_{X_{REF_{CAR}}} - CG_{X_{CAR}}) \cdot F_{Y_{A_{CAR}}} - (CG_{Y_{REF_{CAR}}} - CG_{Y_{CAR}}) \cdot F_{X_{A_{CAR}}}] / \bar{q} \cdot A_{CAR}.$$

[3.3.41]

4.0 RESULTS

To evaluate numerical results of the derived equations [3.3.20] thru [3.3.41], the Space Vehicle Dynamics Simulation (SVDS) Program is used to generate the parameters required that will be recorded during an ALT flight. The mass properties used in this example are for flight number 1 with the tailcone on as defined in Reference 3, the incidence angle is set at 6.5 deg, and the time point is at the instant separation would occur. Tabulated in Table 1 are the parameters required, their SVDS mnemonic names, their values, and their units as output by the SVDS. The results of the derived equations ([3.3.20] thru [3.3.41]) for the orbiter and carrier aerodynamic coefficients are tabulated in Tables 2 and 3 respectively. For the ease of comparison, the actual values of the coefficients computed by the SVDS and the percent error in the hand computed coefficients are also tabulated in Tables 2 and 3. In this analysis, all computations were carried out to 8 significant digits.

Table 2 shows that the range of error in the hand computed values of the orbiter coefficients compared to the values output by the SVDS is 0.087% to 0.0936%. This is much smaller than the 5% accuracy of the dynamic pressure (see Reference 1).

Table 3 shows no difference in the carrier coefficients out to 5 significant digits. The largest error encountered is less than 0.00032% and the smallest is 0%. These errors are accounted for by the truncation inherent in digit computers.

5.0 CONCLUSIONS AND RECOMMENDATIONS

From the above plus the results discussed in Section 4.0, it is concluded that the equations derived in Section 3.0 will yield acceptable results within the operating region of the ALT flights. It is therefore recommended that equations [3.3.20] thru [3.3.41] be used in the determination of the orbiter and carrier aerodynamic coefficients from load cell measurements.

6.0 REFERENCES

1. RI document SD73-SH-0180E, "Space Shuttle Separation System Data Book", dated November 1975.

2. MDTSCO TM No. 1.4-7-D-18, "Orbiter/747 Loads Model in SVDS", dated 16 May 1975.

3. MDTSCO TM No. 1.4-7-159, "Data Base Update for ALT Orbiter/ Carrier Separation Analysis", dated 23 December 1975.

FIGURE 1 GEOMETRY OF THE ORBITER/CARRIER

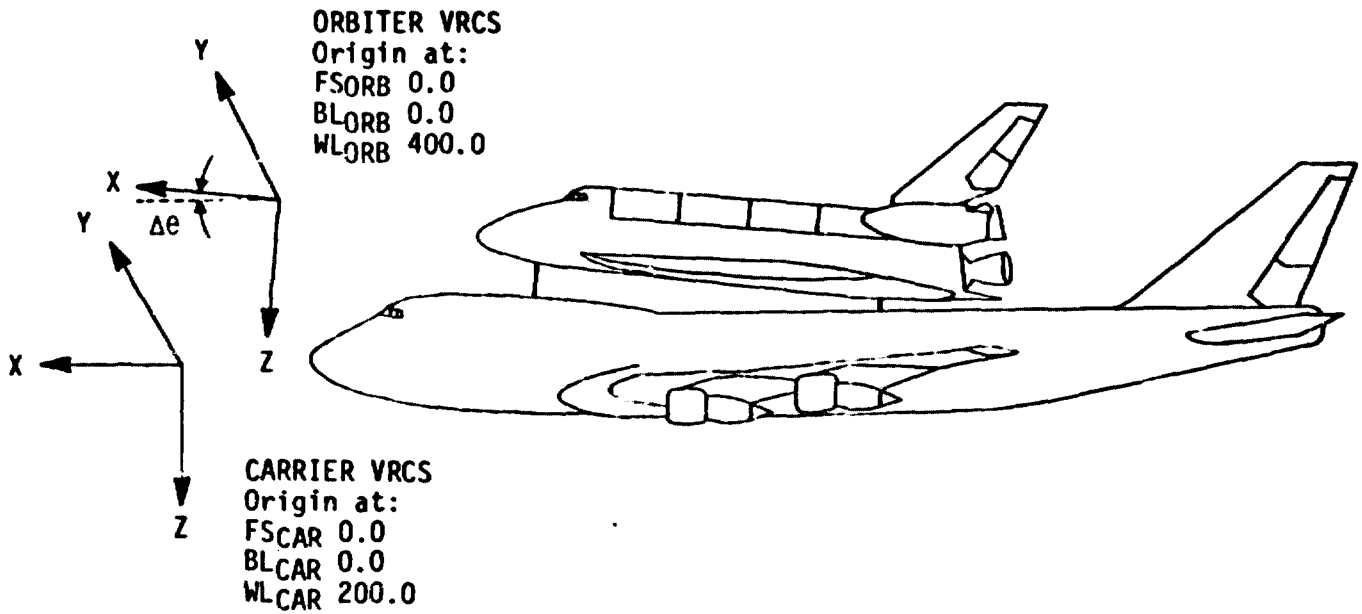

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FIGURE 2 RELATIVE POSITION VECTORS

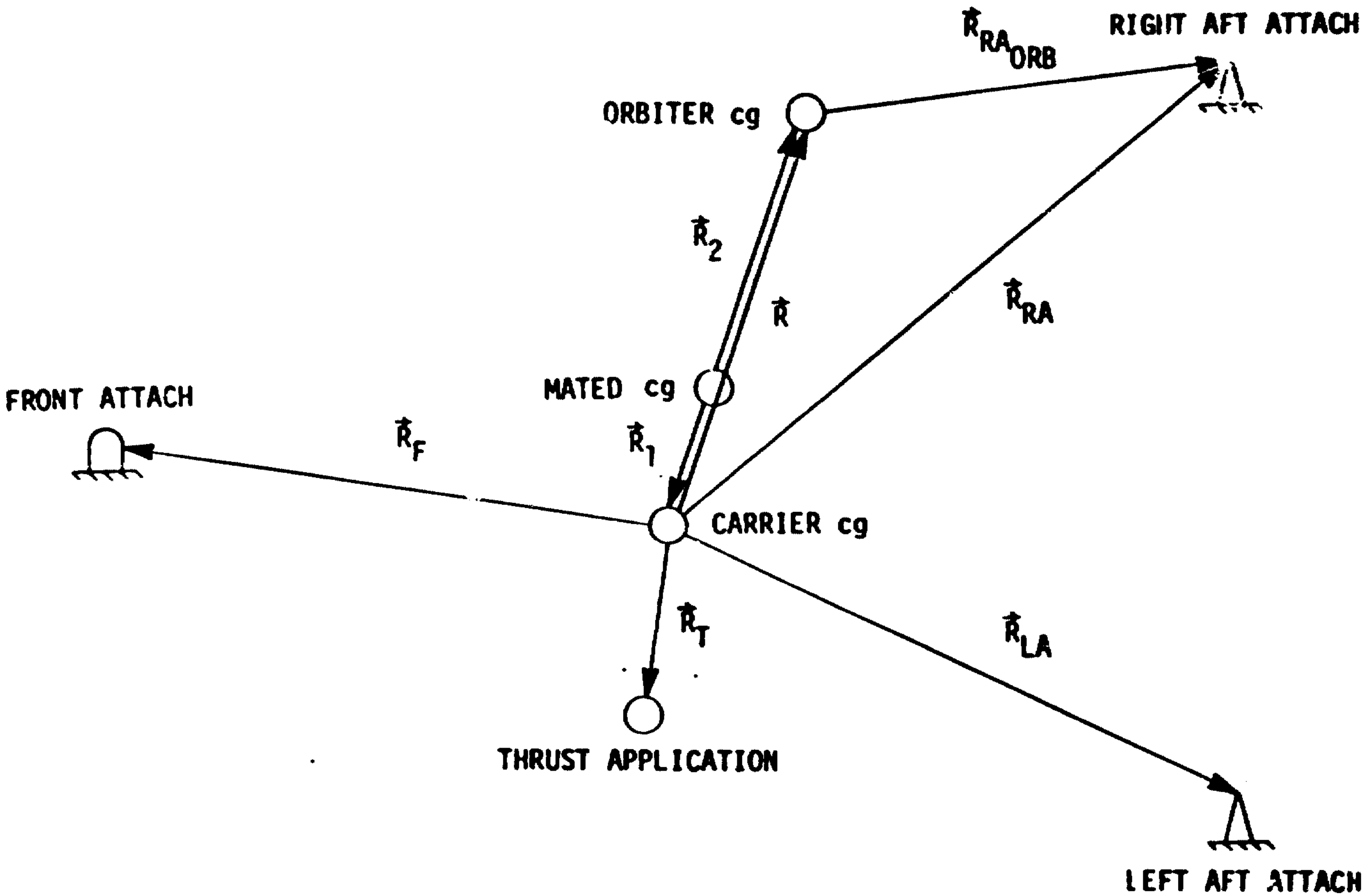

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TABLE 1 DATA REQUIRED FOR ANALYSIS

PARAMETER	SVDS MNEMONIC	VALUE	UNITS
$\vec{F}_F$	FFV(1) FFV(2) FFV(3)	1.5504×10^3 -1.6446×10^{-4} 2.6494×10^4	LB
$\vec{F}_{LA}$	FAL(1) FAL(2) FAL(3)	1.3177×10^3 0.0 2.6758×10^4	LB
$\vec{F}_{RA}$	FAR(1) FAR(2) FAR(3)	1.2637×10^3 -1.8641 2.6363×10^4	LB
$\vec{a}_{s_{CAR}}$	SAC47X SAC47Y SAC47Z	-4.3488 -1.3629×10^{-2} -3.1595×10^1	ft/sec²
$\vec{\omega}$	OMEGX OMEGY OMEGZ	7.3742×10^{-3} -1.5785×10^{-2} 2.3054×10^{-2}	deg/sec
$\dot{\vec{\omega}}$	OMEGXD OMEGYD OMEGZD	-2.0051×10^{-4} 5.6490×10^{-3} 8.9711×10^{-5}	deg/sec²
$\vec{F}_T$	FBTMX FBTMY FBTMZ	9.8046×10^3 0.0 -4.2834×10^2	Lb
$\bar{q}$	QBAR	2.3482×10^2	LB/ft²
α_{CAR}	ALPHA	2.6111	deg

TABLE 2 RESULTS OF DERIVED EQUATIONS
(ORBITER)

COEFFICIENT	SVDS MNEMONIC	HAND COMPUTED	OUTPUT BY SVDS	PERCENT ERROR
$C_{A_{ORB}}$		-2.2565×10^{-3}	-2.2586×10^{-3}	0.0932
$C_{Y_{ORB}}$	CY	-9.8334×10^{-5}	-9.8424×10^{-5}	0.0907
$C_{N_{ORB}}$		3.6130×10^{-1}	3.6164×10^{-1}	0.0935
$C_{D_{ORB}}$	CD	5.4983×10^{-2}	5.5034×10^{-2}	0.0930
$C_{L_{ORB}}$	CL	3.5710×10^{-1}	3.5743×10^{-1}	0.0936
$C_{\ell_{cg_{ORB}}}$	CLL	1.1839×10^{-4}	1.1850×10^{-4}	0.0926
$C_{m_{cg_{ORB}}}$	CM	1.4610×10^{-2}	1.4624×10^{-2}	0.0936
$C_{n_{cg_{ORB}}}$	CLN	1.1642×10^{-6}	1.1652×10^{-6}	0.0870
$C_{\ell_{ORB}}$		1.2156×10^{-2}	1.2167×10^{-2}	0.0935
$C_{m_{ORB}}$		-1.5346	-1.5360	0.0935
$C_{n_{ORB}}$		4.9799×10^{-4}	4.9844×10^{-4}	0.0910

TABLE 3 RESULTS OF DERIVED EQUATIONS (CARRIER)

COEFFICIENT	SVDS MNEMONIC	HAND COMPUTED	OUTPUT BY SVDS	PERCENT ERROR
$C_{A_{CAR}}$		4.0403×10^{-2}	4.0403×10^{-2}	less than .00032
$C_{Y_{CAR}}$	CY	-1.1430×10^{-4}	-1.1430×10^{-4}	
$C_{N_{CAR}}$		1.9965×10^{-1}	1.9965×10^{-1}	
$C_{D_{CAR}}$	CD	-4.9456×10^{-2}	4.9456×10^{-2}	
$C_{L_{CAR}}$	CL	1.9760×10^{-1}	1.9760×10^{-1}	
$C_{\ell_{cg_{CAR}}}$	CLL	-1.2846×10^{-5}	-1.2846×10^{-5}	
$C_{m_{cg_{CAR}}}$	CM	-1.3553×10^{-2}	-1.3553×10^{-2}	
$C_{n_{cg_{CAR}}}$	CLN	2.0738×10^{-6}	2.0738×10^{-6}	
$C_{\ell_{CAR}}$		2.9100×10^{-4}	2.9100×10^{-4}	
$C_{m_{CAR}}$		7.3718×10^{-2}	7.3718×10^{-2}	
$C_{n_{CAR}}$		-1.0270×10^{-4}	-1.0270×10^{-4}	