Space Shuttle Entry Aerodynamic Comparisons of Flight 1 with Preflight Predictions

Paul O. Romere,* David B. Kanipe,* and James C. Young†
NASA Lyndon B. Johnson Space Center, Houston, Texas

The Space Shuttle Orbiter flight test program has required the aerodynamicist to take a new approach in verifying flight characteristics. A conventional flight test program of slowly and cautiously approaching more severe flight conditions was not possible with the Orbiter. On the first flight, the Orbiter entered the atmosphere at Mach 28 and decelerated through the Mach range (the subsonic portion of flight has also been flown by another Orbiter vehicle during the approach and landing test program). Certification for the first flight was achieved by an extensive wind tunnel test and analysis program and by restricting the flight maneuvers severely. The initial flights of the Orbiter are heavily instrumented for the purpose of obtaining accurate aerodynamic data. Even without maneuvers to excite the system, the first flight provided comparisons between flight and wind tunnel-derived predicted data in the areas of aerodynamic performance, longitudinal trim, and reaction control jet interaction.

Nomenclature

b = wingspan, ft
C'_∞ = proportionality factor for the linear viscosity-temperature relationship
C_A = axial force coefficient
C_m = pitching moment coefficient
C_N = normal force coefficient
h = altitude, ft
h/b = ratio of altitude from fuselage lower trailing edge to wingspan
L_B = reference body length
L/D = lift-to-drag ratio
M = Mach number
$\dot{m}_j/\dot{m}_\infty$ = mass flow rate ratio
P = pressure
$\bar{q}$ = dynamic pressure
R = universal gas constant
Re = Reynolds number based on L_B
$S_{\rm ref}$ = reference area
T = temperature
$\bar{V}'_\infty$ = viscous interaction parameter $= M\sqrt{C'_\infty/Re}$
$X_{\rm cp}/L_B$ = center of pressure in body length
X_0, Y_0, Z_0 = orbiter reference axis system
γ = ratio of specific heats
δ_{SB} = speedbrake deflection angle, deg
ϕ = roll angle, deg
ϕ_j/ϕ_∞ = momentum ratio

Subscripts

j = jet exit conditions
0 = total conditions
∞ = freestream

Introduction

An extensive wind tunnel test and analysis program was undertaken to provide a high level of confidence in the aerodynamic predictions of the Space Shuttle Orbiter. Flights of both the approach and landing test (ALT) and the current orbital flight test program have been severely restricted to account for uncertainties in the predicted data base. The vehicles were heavily instrumented to obtain flight data. This approach resulted in both high-quality flight test data and an extensive wind tunnel data base. Thus the aerodynamicist has been given the unique opportunity to compare state-of-the-art prediction techniques with flight data over an extensive range of entry flight conditions.

The Space Shuttle program's first flight did not contain any specifically designed data extraction maneuvers. This deficiency restricted the present flight data analysis effort to only the steady-state aerodynamic performance and trim characteristics. In addition, analysis of the side-firing reaction control system (RCS) jets, which are used to supplement yaw control from on-orbit to Mach 1, was limited to roll reversals and various other unplanned maneuvers. The side-firing reaction control jets, located at the rear of the vehicle, are used to supplement yaw control during the flight from entry down to Mach 1.

Space Shuttle Orbiter Design Characteristics

The physical characteristics of the Space Shuttle Orbiter are illustrated in Fig. 1. The body flap is the predominant longitudinal trim device, whereas the wing-mounted elevons are used for both longitudinal stability and as ailerons for lateral trim and control. The vertical tail consists of a fin and a combination rudder/speedbrake, with the speedbrake providing L/D modulation during the approach and landing phase of the flight. Aft-mounted, side-firing reaction control jets are used to supplement yaw stability from entry down to Mach 1.0.

The Space Shuttle Orbiter is designed to perform an unpowered, gliding entry from orbit at an angle of attack of 30 to 40 deg, depending upon crossrange requirements. A gradual pitchdown is initiated at Mach 14 and is completed at Mach 2. From Mach 2 to touchdown, more conventional angles of attack, 3 to 10 deg, are flown. At the beginning of entry, downrange modulation is achieved by periodically performing roll reversals across the prescribed ground track. The STS-1 entry flight conditions are illustrated in Figs. 2a-d.

Aerodynamically, during the major portions of the flight from entry to touchdown, the vehicle is longitudinally and laterally stable. In certain flight regimes, where the vehicle is statically unstable, the stability is artificially provided by the flight control system.

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*Aerospace Engineer.

†Aerospace Engineer. Member AIAA.

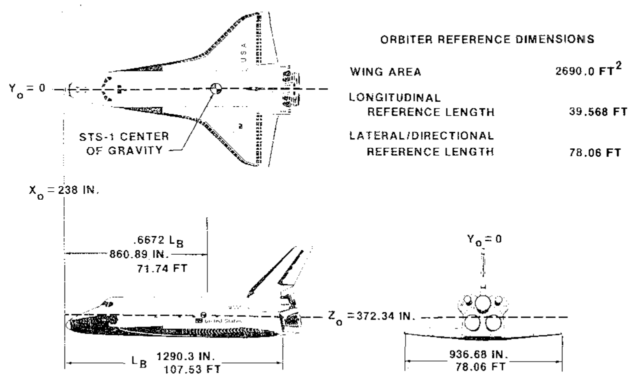

Fig. 1 Space Shuttle Orbiter configuration.

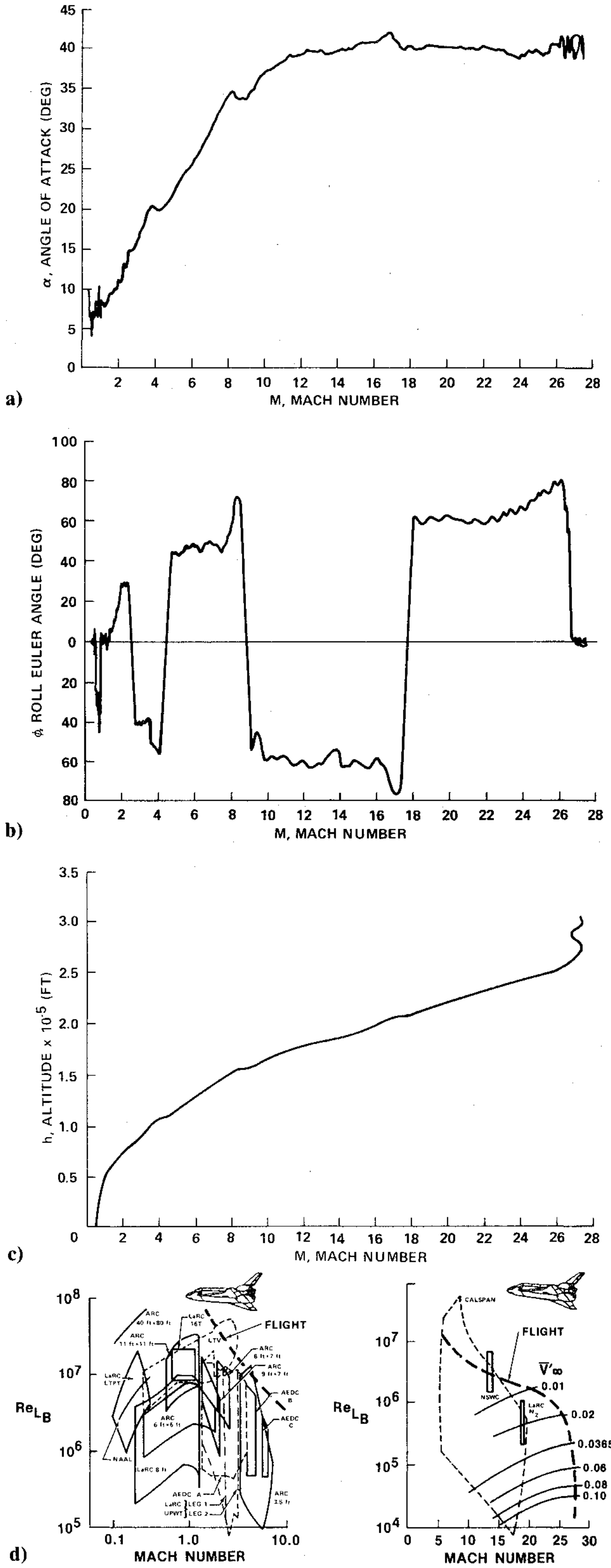

Fig. 2a) STS-1 entry flight condition, angle of attack. b) roll angle. c) altitude. d) Reynolds number simulation.

Preflight Predictions

The preflight aerodynamic predictions[1] are built on a foundation of 27,000 occupancy hours of wind tunnel testing. This testing program utilized state-of-the-art facilities and covered a Mach number range from subsonic to 19.

Wind tunnel data cannot be used directly for prediction. Even the most valid set of wind tunnel results must be adjusted for unsimulated conditions. An extensive analysis of the wind tunnel data base was performed to establish the most valid set of wind tunnel results, and the data base was scrutinized for blockage and sting effects. Greatest consideration was given to those tests of higher Reynolds and/or high model fidelity, and engineering judgment was used to fair the data. This procedure resulted in a wind tunnel data base to which corrections for unsimulated conditions were applied as discussed subsequently.

The traditional freestream Reynolds number was selected for the flowfield scaling parameter below Mach 15, while $\bar{V}'_\infty$ was utilized at higher Mach numbers. Since the test facilities were able to provide near-flight Reynolds number simulations over a large Mach number range (as illustrated in Fig. 2d), no corrections to the wind tunnel results were required. The hypersonic wind tunnel data were not adjusted for real gas effects, since $\bar{V}'_\infty$ was a prime simulation parameter for those tests. At lower Mach numbers, the traditional adjustments were applied for Reynolds number effect on friction drag. Additional adjustments were applied to the profile drag to account for the added roughness of the thermal protection system tiles and for minor protuberances, which could not be simulated on the wind tunnel test models.

In general, no attempt was made to obtain a wind tunnel simulation of the effects of structural deformation on aerodynamics. Since at higher dynamic pressures these effects are significant, some adjustment to the wind tunnel data to account for structural deformation was made to provide adequate estimates of the flight aerodynamics.

As a result of the Space Shuttle program management's desire to desensitize the flight control system with respect to the aerodynamics, uncertainties (defined as variations) were provided for use with the preflight predictions. These variations (see Ref. 1) are based on historical predicted-to-flight differences of similar configurations and on engineering judgment.

Comparisons of STS-1 Flight to Predicted Data

The aerodynamic analyst is faced with a dilemma in the comparison of preflight predictions and flight data. In wind tunnel testing, which is the basis of the preflight predictions, the independent parameters are known precisely, whereas the aerodynamics are questionable. In flight testing, the aerodynamics are known exactly, by definition, but the accuracy of the independent parameters may be in question. To minimize the impact of this dilemma, the aerodynamic comparisons were selected such that the errors in the flight-independent parameters are minimized.

The L/D was selected for comparison of predicted and flight aerodynamic performance, since it is independent of flight dynamic pressure. As may be seen in Fig. 3, the preflight predictions agreed well with flight L/D above Mach 1. Below Mach 1, the flight exhibited higher L/D than predicted.

The X_{cp}/L_B, which is also independent of dynamic pressure, was selected for trim comparisons. For a trimmed vehicle, the longitudinal center of pressure (the imaginary

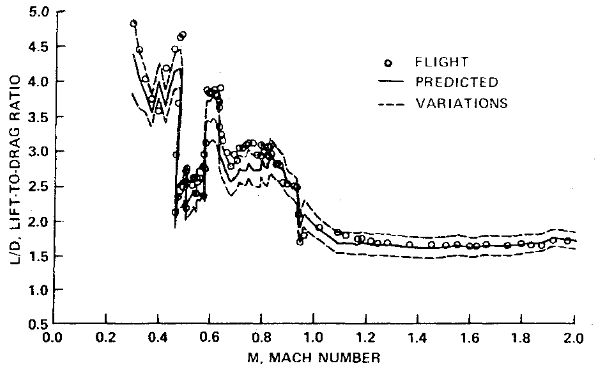

Fig. 3a Aerodynamic performance comparison, Mach 0.0 to 2.0.

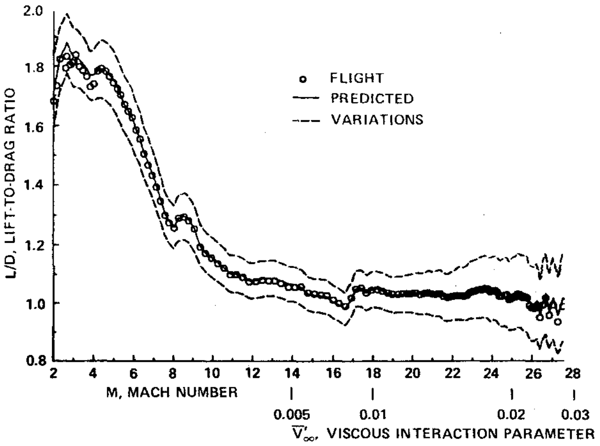

Fig. 3b Aerodynamic performance comparison, Mach 2.0 to 28.0.

point on the vehicle where the pitching moment is zero) coincides with the center of gravity. Figure 4 presents a comparison of the flight and predicted centers of pressure. As can be seen in Fig. 4b, at Mach numbers above 10, the predicted center of pressure is more aft by as much as 0.7% of the reference body length (1.9% of the mean aerodynamic chord) than the flight data would indicate. For the Mach range of 14 to 20, differences are outside of predicted variations. In the Mach range, where the Reynolds number was simulated ($2.0<M<10$; Fig. 2d), trim was predicted precisely, even though unusually high angles of attack between 15 and 30 deg were flown. The predictions for the transonic and subsonic range were less than satisfactory, although they were within the predicted variations.

In addition, C_A and C_N comparisons have been made. Figure 5 shows the excellent C_N agreement with flight. Two observations can be made from the C_A comparison in Fig. 6. Since C_N was well predicted in the subsonic speed range, one can conclude the underprediction of L/D previously reported was a result of the overprediction of C_A in the same range. It can be concluded from Fig. 6b that $\bar{V}'_\infty$ was a wise choice of scaling parameters for C_A, since its trends and magnitudes were well predicted.

Longitudinal Trim Difference Analysis

As in past programs, there were problems in predicting pitching moment at subsonic and transonic speeds. It appears that state-of-the-art facilities, testing techniques, and analysis approaches do not adequately predict flight trim in these speed regimes.

Hypersonically, flight data indicate a more forward center of pressure than predicted by 0.7% of reference body length. This difference in flight trim resulted in a trimmed body flap deflection of 16 deg, whereas the predicted deflection was only 8 deg. A possible cause for the difference could be the overprediction of body flap effectiveness by a factor of 2; however, a reexamination of the wind tunnel data available

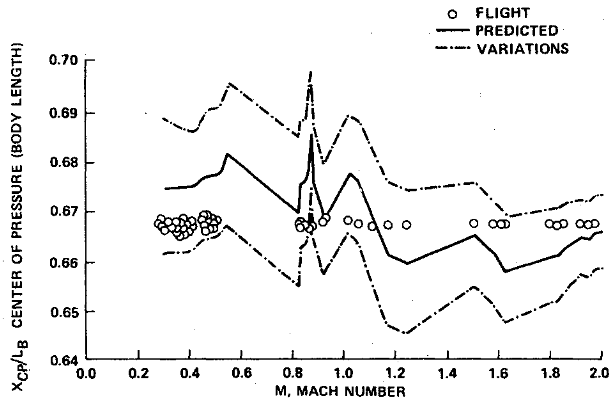

Fig. 4a Longitudinal aerodynamic center of pressure comparison, Mach 0.0 to 2.0.

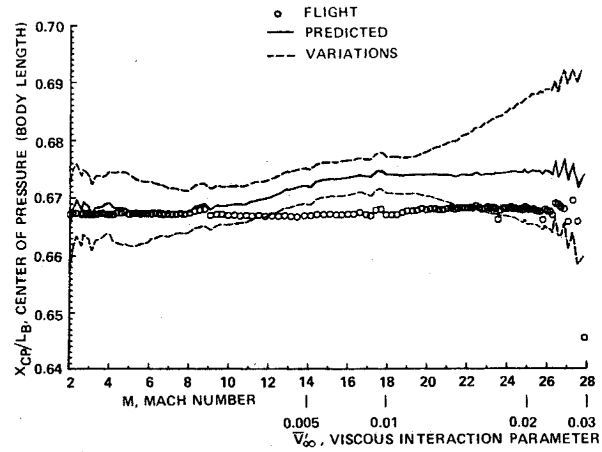

Fig. 4b Longitudinal aerodynamic center of pressure comparison, Mach 2.0 to 28.0.

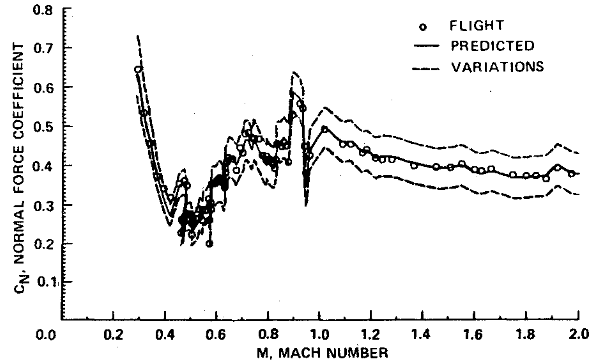

Fig. 5a Normal force coefficient comparison, Mach 0.0 to 2.0.

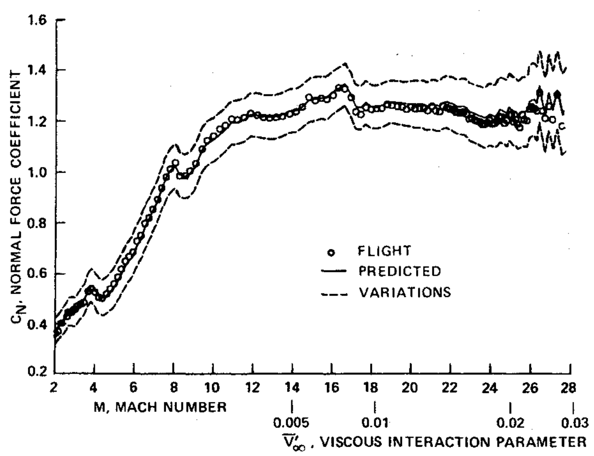

Fig. 5b Normal force coefficient comparison, Mach 2.0 to 28.0.

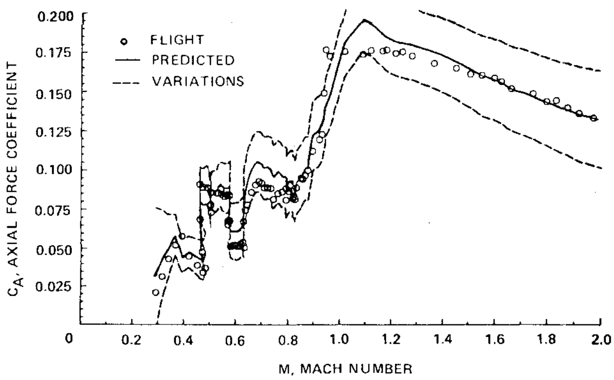

Fig. 6a Axial force coefficient comparison, Mach 0.0 to 2.0.

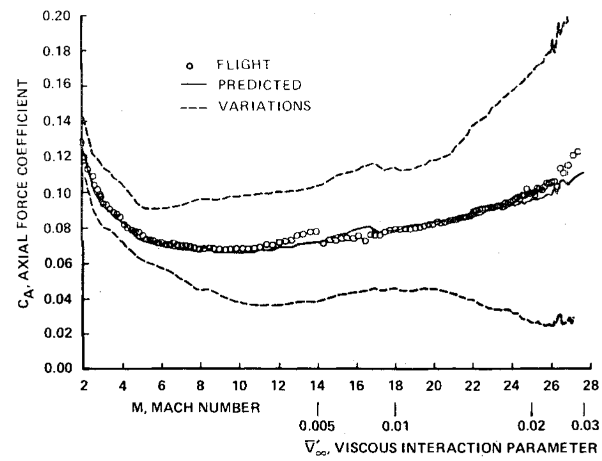

Fig. 6b Axial force coefficient comparison, Mach 2.0 to 28.0.

from the Naval Surface Weapons Center, Calspan Corporation, and Arnold Engineering Development Center does not support such a possibility. In addition, examination of body flap effectiveness, as determined from flight data,[2] although of limited quality, does not support a degradation in body flap effectiveness of this magnitude.

A more probable cause for the hypersonic trim discrepancy would be an error in the predicted basic pitching moment of the vehicle. Here again, the wind tunnel results were examined and no indication of such a discrepancy between the wind tunnel test data and the preflight aerodynamic data base was noted.

One must conclude that the proper scaling was not realized for the hypersonic trim characteristics, either because the scaling parameter was improperly selected or because the test facilities were not capable of reproducing the proper environment. It is hoped that detailed analysis of the extensive Shuttle flight data base will provide insight into these problems.

Subsonic Performance Difference Analysis

As a result of the discrepancy between flight performance and predicted performance in the subsonic range, the Orbiter was analyzed with respect to drag, C_N, and speedbrake effectiveness. Data from Space Transportation System Flight 1 (STS-1) and ALT flights 4 and 5 are used. The drag analysis was centered on C_A and included only the flight data taken with a speedbrake deflection of less than 30 deg, with the landing gear retracted, and above the region of ground effects (i.e., $h/b > 1.5$). Correlation plots of flight with predicted data are presented in Fig. 7 and indicate an overprediction of C_A by a constant 40 counts ($\Delta C_A = 0.004$) for all three flight data sets. A significant improvement in the correlation resulted from correcting the predicted profile drag by -40 counts (see Fig. 8). The data presented in Figs. 7 and 8 are for Mach ≈ 0.47-0.5.

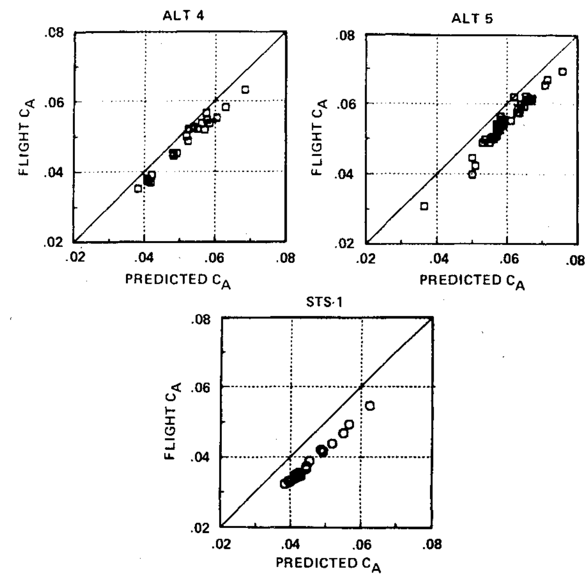

Fig. 7 Axial force coefficient correlations of flight data with predicted data.

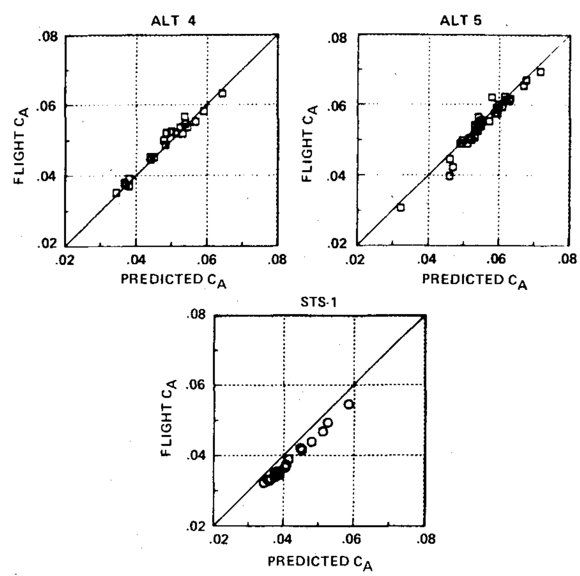

Fig. 8 Axial force coefficient correlations of flight data with predicted data corrected by -40 counts.

The C_N analysis was conducted using the same Mach ≈ 0.47-0.5 data as in the C_A analysis. As can be seen in the plots of Fig. 9, the ALT 4 correlation of flight with predicted data is almost perfect and includes an angle-of-attack variation from 3.1 to 8 deg. The ALT 5 data show good correlation at angles-of-attack less than 6 deg, with an apparent shift at the higher angles-of-attack. The data from STS-1, representing only angles-of-attack greater than 6 deg, tend to generally agree with the shifted data seen in the ALT 5 correlation. Since the shift for high angles-of-attack was not apparent in all three available flight data sets, resolution of this phenomenon is deferred until the flight data results from subsequent orbital flights are analyzed and reviewed further.

For the analysis of speedbrake effectiveness, flight test data were selected where body flap deflection was approximately 0 deg and the speedbrake was swept through a large deflection range. The flight data were then corrected to an angle of attack of 5 deg and an elevon deflection of 5 deg through the use of the coefficient slopes, as determined from the predicted data base. The resultant effectiveness with respect to axial force coefficient is presented in Fig. 10. For STS-1, the effectiveness was underpredicted by approximately 60 counts at a 55-deg speedbrake deflection angle. Results from ALT 4

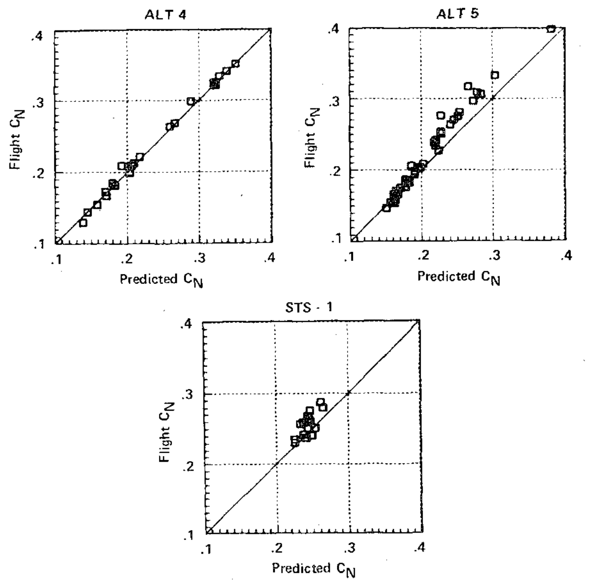

Fig. 9 Normal force coefficient correlations of flight data with predicted data.

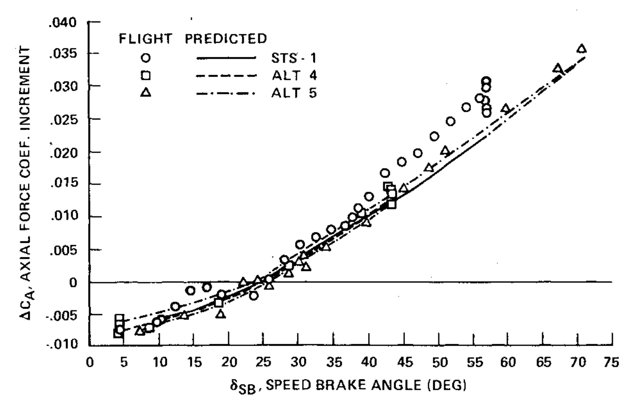

Fig. 10 Subsonic axial force coefficient increment due to speedbrake deflection.

and ALT 5 do not indicate this underprediction. Resolution of this flight data inconsistency will require further analysis. The flight normal-force coefficient effectiveness, as illustrated in Fig. 11, exhibited random scatter about the predicted effectiveness.

Reaction Control System

The Space Shuttle Orbiter has both forward and aft RCS jets. The forward system (14 jets) is located in the nose forward of the cabin, and the aft system is located on the rear extensions of the orbital maneuvering system (OMS) pods (12 on each pod). Each RCS thruster develops approximately 870 lb of thrust and uses monomethylhydrazine as fuel and nitrogen tetroxide as the oxidizer.

The forward jets are used primarily for orbital maneuvers and during the separation of the external tank. They are also used for certain abort maneuvers such as a return-to-launch-site abort.

The aft jets work in concert with the control surfaces to effect a smooth transition from orbital conditions to a flight regime where the control surfaces are effective enough to provide stability without jet augmentation. In addition, the aft yaw jets, which are of primary interest during entry, are used to supplement yaw stability above sonic speeds.

Wind Tunnel Data Base

The evolution of the RCS jet interaction data base has involved a significant amount of wind tunnel testing over

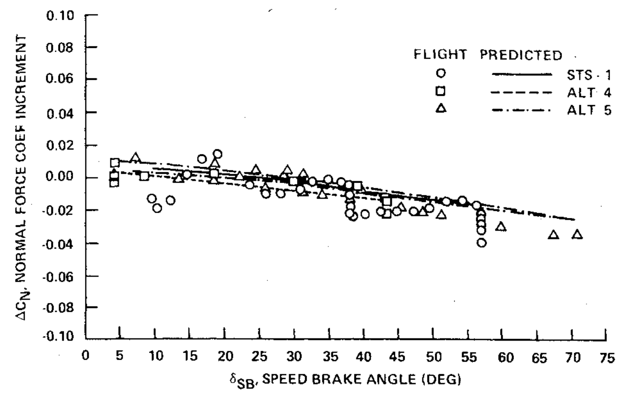

Fig. 11 Subsonic normal force coefficient increment due to speedbrake deflection.

flight conditions ranging from near Mach 1 to very high-altitude simulations. Testing was begun in May 1973 in the Langley Research Center Unitary Plan Wind Tunnel (UPWT) and continued up until 2 months before STS-1. In all, 12 tests were conducted to investigate jet interaction effects on the Orbiter during entry. These tests used several Orbiter models ranging in size from 1-1.5% of full scale and were conducted in several different facilities at Mach numbers ranging from 1.6 to 10.33. In addition, the data base includes the effects of elevon, body flap, and speedbrake deflection as well as jet configuration and jet scaling parameters.

Scaling Parameter Evolution

The primary difficulty in performing jet interaction wind tunnel testing is scaling the model plume to correctly simulate the full-scale plume. According to Spaid and Cassel,[3] six conditions must be matched in order to establish a true similarity for interaction: 1) geometric similarity of vehicle body and nozzle, 2) M_∞, 3) Re, 4) γ_j, 5) $R_jT_{0j}/R_\infty T_{0_\infty}$, and 6) P_{0j}/P_{0_∞}. Unfortunately, it is not possible, except in fortuitous situations, to simulate all of these parameters at once when testing for jet interaction effects. A thorough investigation of scaling parameters and their effects on the data were accomplished by Rausch.[4] On the basis of the ability of a particular scaling parameter to correlate the data, Rausch concluded that for the Orbiter, ϕ_j/ϕ_∞ was the best scaling parameter for the pitch/roll jets and $\dot{m}_j/\dot{m}_\infty$ was the best scaling parameter for the yaw jets. Therefore, the Orbiter jet interaction data base was derived as a function of these two simulation parameters.

STS-1 Comparisons

The aft yaw jets are used frequently from early entry down to Mach 1.0. Because of their location, the jets produce not only a yawing moment but a sizable amount of rolling moment. In addition, the interaction of the jet exhaust plume with the local flow induces additional moments that affect the moment due to thrust. Normally these induced moments are relatively small; however, their small size also makes them extremely difficult to measure accurately in the wind tunnel. This inability to measure the induced moment translates into a large uncertainty about a measured small number. The possibility that the actual induced moment may be as large as the uncertainty boundary requires that the flight control system be able to handle such an excursion. Consequently, the flight control system is very sensitive to these induced moments, primarily roll due to yaw jets. There is a great desire to define these moments accurately throughout the trajectory in order to ultimately reduce the magnitude of the uncertainty and increase the efficiency of the flight control system. The flight of STS-1 provided the opportunity to analyze flight data and evaluate the reliability of the prediction model for jet interaction.

Because of the instantaneous nature of an RCS firing, it is very difficult to analyze flight data for any particular jet firing. Therefore, a technique to extract reliable jet interaction data from the general flight data is still being sought. However, there is a modified maximum likelihood estimator (MMLE) program[5,6] which analyzes flight data from a maneuver and determines stability derivatives over the period of the maneuver through a motion-matching technique. Prior to STS-1, the program was set up to extract jet interaction effects during maneuvers by treating the jets as if they were a control surface. The primary difference is that the jets have only four discrete levels of control instead of an infinite number. Fortunately, during STS-1, the pilot performed several maneuvers that required the assistance of the aft yaw jets. The resultant data derived by MMLE forms the jet interaction flight test data base.

The primary area of interest with regard to the yaw jets is the rolling moment induced when the jet is fired. The induced yawing moment is also important but to a lesser extent. Figure 12 presents the rolling moment as a function of various parameters for the entry trajectory down to Mach 1.0. The solid line represents the jet interaction model derived from the wind tunnel data base and STS-1 flight conditions, and the symbols represent MMLE-derived flight data. Figure 13 is a similar plot for induced yawing moment. It would appear that the induced yawing moment was well predicted throughout the trajectory. The induced rolling moment, however, while agreeing very well at the late-entry conditions (Mach < 10), does not agree well with predictions for the maneuvers above Mach 19.

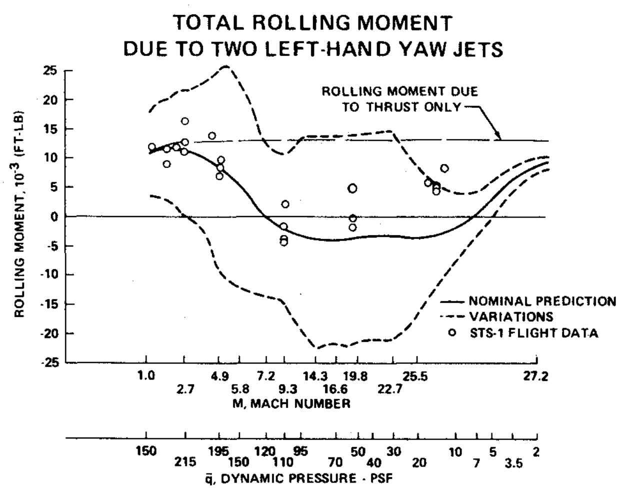

Fig. 12 Total rolling moment due to two left-hand yaw jets as a function of STS-1 entry conditions.

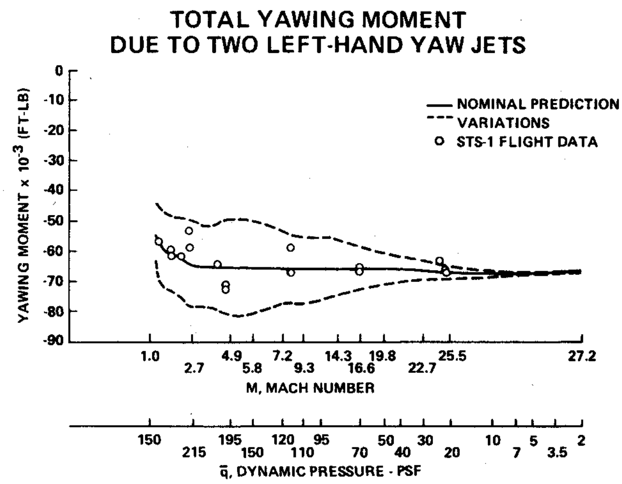

Fig. 13 Total yawing moment due to two left-hand yaw jets as a function of STS-1 entry conditions.

Analysis of Results

Upon examining the results of the flight test as compared to preflight predictions (Figs. 12 and 13), one can see that the agreement for the yawing moment data is better than that for the rolling moment data. Consequently, this discussion will concentrate on the discrepancies in the rolling moment data.

Basically, the preflight prediction model showed good agreement with the flight test data at the later-entry conditions (Mach < 10). However, for early entry, the preflight model significantly overpredicted the magnitude of the rolling moment jet interaction. The major question, of course, is why does the prediction model appear to work so well for one part of the trajectory and not as well during another part.

The majority of the jet interaction data base applicable to very high Mach numbers was derived at Mach 10.3 in the Langley Continuous Flow Hypersonic Tunnel. It is generally accepted that for hypersonic flow there is little Mach effect. But it is obvious from the comparisons of flight and wind tunnel test data that there is a definite simulation problem. Consequently, it seems that the discrepancy most likely resides in the simulation of the RCS yaw jet plumes.

The simulation parameter for the yaw jets is $\dot{m}_j/\dot{m}_\infty$. Flight test results indicate that this parameter worked very well at Mach numbers less than 10 but began to break down at Mach numbers greater than 10.

There are several possible reasons for such a breakdown. The simulation parameter, $\dot{m}_j/\dot{m}_\infty$, is referenced to freestream conditions. However, in the case of the Orbiter at high angles-of-attack, the jet is operating in the wake of the wing. The wake flow is highly unpredictable and vastly different from the flowfield conditions in the freestream. Thus, the plume simulation parameter is based on the freestream conditions, whereas, in reality, the plume sees entirely different conditions. This would not be a problem if the wake modeled in the wind tunnel at Mach 10.3 was similar to the wake at Mach 27, but examination of oil flow test results indicate it is not. The data base was derived primarily from wind tunnel data at Mach 10.3, which corresponds to specific wake flow conditions on the leeside of the wing. Since these data are used to simulate jet interaction at higher Mach numbers (as high as Mach 27), the wake structure is artificially fixed at the Mach 10.3 value. However, at the higher flight Mach numbers, where the discrepancies occurred, the wake characteristics may be substantially different. Thus, if the simulation parameter was based on the local conditions behind the shock wave, instead of the freestream conditions, then it is obvious that the value of the simulation parameter could be significantly different.

Other factors that may contribute to the discrepancy during early entry include real gas effects and an unmatched Reynolds number. Neither factor was accounted for in the data base; therefore, either could conceivably have an effect.

Below Mach 10, agreement between predicted and flight data becomes much improved. There are several possible explanations. First, matching Mach number below Mach 10 is well within the capability of many facilities. Second, the angle of attack decreases with decreasing Mach number so that the jets are less likely to be operating directly in the wake of the wing. The conditions the jet encounters are probably closer to freestream conditions and the relationship of the jet and the freestream flow approximates that of the traditional jet interaction configuration. Therefore, the correlation parameter would be better suited to the situation and should perform better.

Concluding Remarks

The completion of the first flight of the Space Shuttle Orbiter has given aerodynamicists the first opportunity to test their prediction skills over diverse flight conditions. The performance predictions were in excellent agreement with flight performance above Mach 1; however, drag was overpredicted at subsonic Mach numbers.

The trim characteristics were predicted adequately in the Mach range of 2 to 10; however, above Mach 10 and below Mach 2, the predictions were less than satisfactory.

The preflight predictions of jet interaction effects for the aft yaw jets were in good agreement with flight data for yawing moment. Likewise, rolling moment jet interaction due to the yaw jets was well predicted at Mach numbers less than 10. However, at Mach numbers greater than 10, rolling moment jet interaction was overpredicted.

References

[1]"Aerodynamic Design Data Book, Volume 1, Orbiter Vehicle 102," Space Division, Rockwell International, Downey, Calif., SD72-SH-0060, Vol. 1L, Rev. 5, Oct. 1978.

[2]Iliff, K.W., Maine, R.E., and Cooke, D.R., "Selected Stability and Control Derivatives from the First Space Shuttle," AIAA Paper 81-2451, Nov. 1981.

[3]Spaid, F.W. and Cassel, L.A., "Aerodynamic Interference Induced by Reaction Controls," AGARD-AG-173, Dec. 1973.

[4]Rausch, J.R., "Space Shuttle Orbiter Rear Mounted Reaction Control System Jet Interaction Study," General Dynamics Convair Division, San Diego, Calif., CASD-NSC-77-003, May 1977.

[5]Main, R.E. and Iliff, K.W., "A Fortran Program for Determining Aircraft Stability and Control Derivatives from Flight Data," NASA TN D-7831, April 1975.

[6]Main, R.E. and Iliff, K.W., "User's Manual for MMLE3, a General FORTRAN Program for Maximum Likelihood Parameter Estimation," NASA TP 1563, Nov. 1980.