Plume/Flowfield Jet Interaction Effects on the Space Shuttle Orbiter during Entry

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During re-entry of the Space Shuttle Orbiter it is necessary to use the reaction control system (RCS) jets for control augmentation in flight regimes where the control surfaces are not fully effective. Since preflight predictions of RCS jet interaction with the Orbiter flowfield were based on wind tunnel tests and theoretical correlations, the first flights of the Space Shuttle have provided the first opportunity to compare high-quality flight data with preflight predictions. Preliminary results indicate that good agreement with preflight predictions was obtained except during initial entry. This discrepancy during early entry is most likely due to a deficiency in the wind tunnel simulation of the leeside flow conditions for Mach numbers greater than 10. Other factors that could affect the early entry data comparison include real gas effects and an unmatched Reynolds number. Neither factor was accounted for in the test data base.

Nomenclature

A	= area
C_l	= body axis rolling moment coefficient
C_m	= body axis pitching moment coefficient
C_n	= body axis yawing moment coefficient
C_y	= body axis side force coefficient
M	= Mach number
$\dot{m}_j/\dot{m}_\infty$	= mass flow rate ratio
P	= pressure
$\bar{q}$	= dynamic pressure
R	= gas constant
Re	= Reynolds number
T	= temperature
α	= angle of attack
Δ	= jet interaction increment
γ	= specific heat ratio
ϕ_j/ϕ_∞	= momentum ratio

Subscripts

imp	= plume impingement
j	= jet conditions
ji	= jet interaction
0	= stagnation conditions
1	= ambient conditions on the plate in the absence of a jet
2	= conditions in the region of the separated boundary layer
$2'$	= conditions at the second peak pressure in the separated boundary layer
3	= conditions in the separated region just before the reattachment shock
4	= conditions in the region corresponding to the peak downstream pressure after the reattachment shock
∞	= freestream conditions

Introduction

THE Space Shuttle Orbiter has two reaction control systems (RCS) that perform a number of operations in the Space Shuttle mission profile. Figure 1 shows the location of the forward reaction control engines mounted in the nose section of the Orbiter and the aft reaction control engines mounted on the orbital maneuvering system (OMS) pods. The forward RCS engines are used in conjunction with the aft RCS engines primarily for orbital flight maneuvering, commencing with external tank separation. The aft RCS system also provides the primary control from deorbit until the control surfaces become effective. Figure 2 illustrates the aft RCS operation in the mission profile from deorbit to conventional flight. The reaction control jets, functioning as rate dampers, are operated in a blended manner with the aerodynamic control surfaces until full aerodynamic control is achieved ($M<1.0$). With the exception of the aft X-translation jets, all aft RCS jets are used during entry. During the very early phase of entry, RCS control is required for all three axes. However, to avoid possible problems with control reversal, the jets used for roll control are inhibited at a dynamic pressure of 478.8 N/m^2 (10 psf) and pitch jets are inhibited at a dynamic pressure of 957.6 N/m^2 (20 psf). Control in yaw is maintained by the side-firing jets in the aft pods until the transition to lower angles of attack, when vertical tail and rudder effectiveness are established (Mach 1). After this transition is completed, all RCS operations are terminated.

Before the first flight of the Space Shuttle, designated Space Transportation System 1 (STS-1), essentially no flight testing had been conducted to investigate the jet interaction phenomena. In any event, no conventional flight testing could have covered the Mach range required by the Orbiter during entry ($0<M<28$). As a result, the jet interaction data base for the Orbiter was derived primarily from wind tunnel testing supplemented by theoretical correlations. Since the flights of STS-1 and STS-2 we have begun to build up a substantial flight data base for RCS jet interaction. The purpose of this paper is to compare STS-1 and STS-2 flight test results with the wind tunnel derived preflight predictions.

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Jet Interaction Phenomena

Before discussing flight test results and the comparison with preflight predictions, it will be instructive to offer a brief description of the jet interaction phenomena and its effects on the Space Shuttle Orbiter.

First consider a simple flat plate with a transverse jet firing upward, as sketched in Fig. 3. This type of configuration is generally classified as "classical" jet interaction. The plume acts like a step, or barrier, to the flow and induces the boundary layer upstream of the plume to separate. A separation shock originates at the separation point. Because of the boundary-layer separation the static pressure upstream of the jet rises to P_2 and then, because of the counter-rotating vortices, jumps again to $P_{2'}$ in the immediate vicinity of the jet. Immediately downstream of the jet is a second separated region designated by the pressure P_3. For supersonic flow, P_3

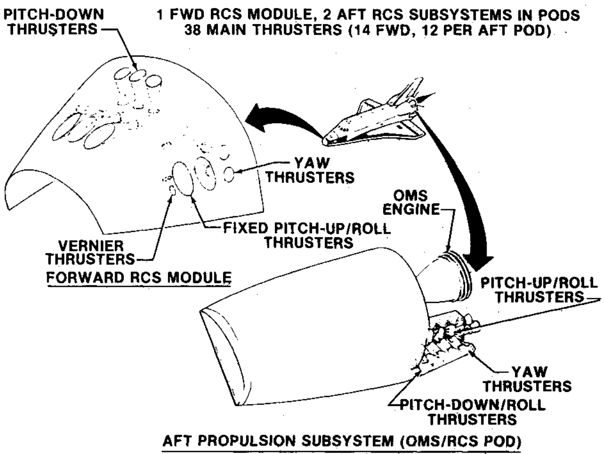

Fig. 1 Space Shuttle Orbiter RCS configuration.

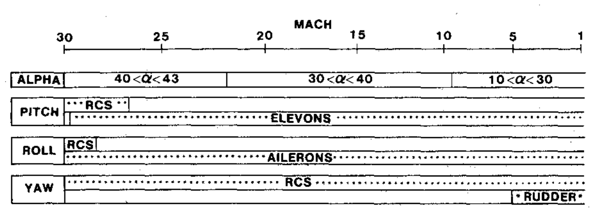

Fig. 2 Aft RCS operation in the Space Shuttle mission profile.

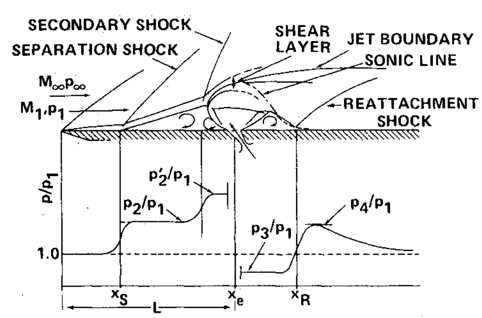

Fig. 3 Two-dimensional jet interaction flow geometry and analytical model.

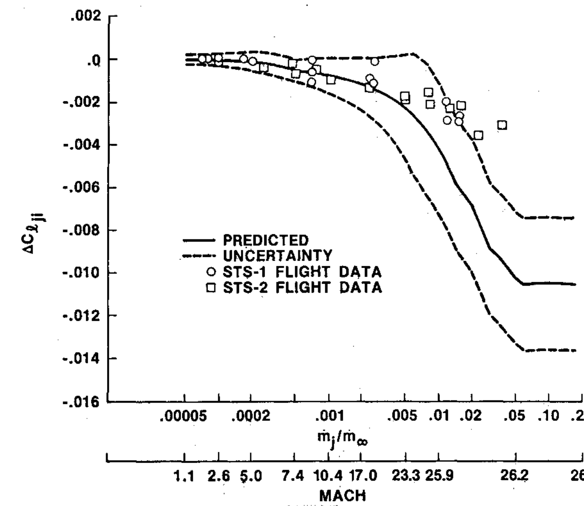

Fig. 4 Rolling moment jet interaction increment due to aft left-hand yaw jets.

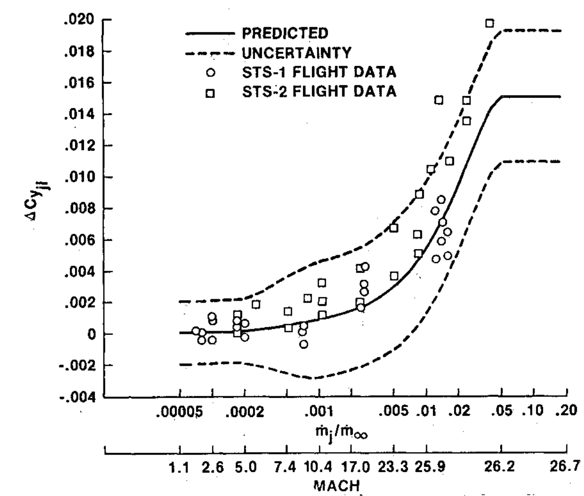

Fig. 5 Side force jet interaction increment due to aft left-hand yaw jets.

is less than the initial pressure P_1. However, if the external flow is hypersonic, the downstream pressure P_3 is often greater than P_1. A recompression shock downstream of the separated region turns the flow parallel to the wall and raises the static pressure to P_4.

The Orbiter flowfield, of course, is much more complex, and "classical" jet interaction effects are significant only for the aft yaw jets firing transversely from the side of the OMS pods. In addition, there is some interaction of the plume with the flowfield over the top of the wing which creates a significant interaction in roll. A left-hand yaw jet, by virtue of its location above the center of gravity, will induce a positive rolling moment. The jet interaction effects are strong enough in some instances to not only reduce this positive rolling moment but reverse it.

Although "classical" jet interaction plays a part in the effectiveness of the up- and down-firing RCS jets, these jets also have a significant effect on nearby vehicle surfaces through plume interaction with the boundary layer and plume impingement to the surface itself.

The down-firing jets, although canted outboard and aft of the vehicle, impinge heavily on the wing trailing edge and on the body/flap. There is also a significant amount of jet interaction independent of plume impingement. These interactions (both impingement and jet interaction) induce a strong pitch-up moment and, for a left-hand jet, a left-wing-down rolling moment and a nose-right yawing moment.

The up-firing jets provide considerable interaction with the vertical tail. Since this jet is operated in a flight regime where the angle of attack is quite high ($\alpha \approx 40$ deg) and the tail is in separated flow, most of the plume interaction with the vertical tail is due to plume impingement which produces sizable—and opposing—interaction moments in roll and yaw. A minimal amount of pitching moment is induced because there is very little jet interaction between the jet and the flow over the top of the OMS pods.

Jet Interaction Scaling Parameter

When establishing the simulation requirements for the classic jet interaction flowfield, Spaid and Cassel[1] state the conditions for simulation as 1) geometric similarity of both body and nozzles; 2) duplication of Mach number (M) and Reynolds number (Re); and 3) duplication of gas specific heat ratio (γ_j), total temperature ratio $[(RT_0)_j/(RT_0)_\infty]$, and total pressure ratio (P_{0_j}/P_{0_∞}).

Matching all these parameters may be possible for a limited number of missile configurations; however, this is impossible for the Space Shuttle Orbiter during entry because the flight conditions are highly variable and the flow is so complex that it defies theoretical analysis. Therefore a decision was made to rely heavily on empiricism to obtain full-scale flight estimates. The basic assumption made in taking the empirical approach was that enough geometric and gasdynamic variables would be considered in the test program to bracket the "true" simulation parameters.

Most analyses of plume problems assume that, since the momentum within the plume is conserved, a jet can be characterized by its momentum flux at the nozzle exit. Consequently, early Shuttle RCS tests concentrated on momentum ratio ϕ_j/ϕ_∞, jet exit pressure ratio P_j/P_∞, and scaled nozzle area matching A_j/A_∞ (which also matches thrust ratio) as the principal matching parameters. The primary indication from these early tests was that momentum ratio was the key scaling parameter; therefore subsequent tests concentrated on momentum ratio, thrust ratio, and plume boundary at the wing (to approximate impingement). Cold nitrogen or air was the primary simulation gas except in a few tests where a mixture of argon and helium was used to vary $(RT_0)_j/(RT_0)_\infty$ in an attempt to assess the effect of gas temperature ratio. Thus the empirical approach taken was to design a variable set of RCS nozzles, combine different nozzles with different simulation gases and different wind tunnel conditions, and vary the simulated RCS chamber pressure. This approach would effectively generate a substantial set of incremental forces and moments produced by the RCS jets as a function of various simulation parameters. The remaining problem then was to select the appropriate set of simulation parameters in order to adjust the test results to produce full-scale flight predictions. The data from all applicable tests are plotted as a function of the selected candidate simulation parameters. The parameters that correlated (i.e., minimized the scatter of) the force and moment data were selected as the governing simulation parameters. This approach was continued for all jet groups until substantial confidence was established for candidate simulation parameters. Since different jets or combinations of jets mixed with substantially different flows, it turned out that a single correlation parameter was not applicable for all cases. The results of testing and analysis yielded mass flow rate ratio ($\dot{m}_j/\dot{m}_\infty$) as the scaling parameter for sideward-firing jets and momentum ratio (ϕ_j/ϕ_∞) as the scaling parameter for upward- and downward-firing jets.

Wind Tunnel Uncertainties

As mentioned previously, the RCS jet interaction data base was derived primarily from wind tunnel test data. In subsequent sections, flight test results are compared with preflight predictions (wind tunnel data). One criterion by which the quality of agreement is judged is whether or not the flight data fall within the uncertainty limits placed on the preflight predictions. These limits essentially are a measure of our confidence in the predicted data base and a brief discussion of their evolution will be useful.

Whenever a measurement is made during an experiment, there is always a certain amount of uncertainty associated with the absolute value of that measurement. For example, in a wind tunnel the possible sources of uncertainty include tunnel flow stability, model geometry accuracy, and balance accuracy. However, by making enough repeat runs at given conditions it is possible to determine the effective data uncertainty, or repeatability, for a given wind tunnel and model at a given set of tunnel conditions.

In its early stages, the RCS jet interaction test program was as much a search for a valid scaling parameter as it was to establish a data base. Consequently, many different nozzle configurations were tested as well as different Orbiter models in different wind tunnels around the country. In addition, various jet simulation gases were tested to examine real gas effects and both metric and nonmetric test configurations were used. After the accumulation of a sizable data base, a contract was given to General Dynamics, Convair Division, to collate the data and determine the most valid scaling parameter.[2] After selecting a scaling parameter it was possible to generate an RCS jet interaction model by performing a least-squares curve fit of the data base as a function of the appropriate scaling parameter. In addition, the rms error, or uncertainty, of all the points in the curve fit was also generated. As a result, the "error" associated with the jet interaction model includes the following effects:

1) tunnel-to-tunnel differences,
2) model-to-model differences,
3) balance accuracy,
4) real gas effects,
5) different nozzle configurations,
6) metric and nonmetric test configurations, and
7) angle of sideslip, ± 3 deg.

The uncertainty bounds shown around the predicted value in the following comparisons are all twice the rms error value, or 2σ. For most Space Shuttle prediction models a 3σ uncertainty band is required. However, in the case of the jet interaction model, it was felt that, because of the large number of variables inherent in the data base, and thus, a wider data scatter, the 2σ uncertainty bounds were sufficiently conservative.

Flight Test Results

As was mentioned earlier, the jets were used in concert with the control surfaces to provide stability during entry. As a result, the jets and control surfaces are almost always operating concurrently. This concurrent operation makes it very difficult to extract the effects due to the RCS jets and exclude those due to the control surfaces. However, a program called Modified Maximum Likelihood Estimator (MMLE) has been used quite successfully for extracting stability derivatives from aircraft flight test results.[3] This was the technique used to extract flight data for the Space Shuttle Orbiter during entry. Basically, the MMLE is a modified Newton-Raphson optimization program. It begins with the measured control inputs and iterates using the Newton-Raphson method until a match is obtained between the measured vehicle response and the response as calculated from the control inputs.

The majority of the data extraction effort has been expended on the lateral/directional jet interaction effects of the aft yaw jets. The reason for this is that the yaw jets are in almost continuous use from entry interface down to Mach 1 and the flight control system is very sensitive to the magnitude of the jet interaction effects from these jets, especially the lateral/directional effects. However, some work has been done on the jet interaction effects of the pitch and roll jets during very early entry and these results will also be presented in this paper.

The primary area of interest with regard to the yaw jets is the rolling moment induced when the jet is fired. Generally, the roll-due-to-yaw effect is very difficult to measure in the wind tunnel and, consequently, there is a large uncertainty associated with the wind tunnel prediction. 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. As a result, the flight control system is very sensitive to the rolling moment jet interaction induced by an aft side-firing (yaw) jet. The induced yawing moment due to the yaw jets is also important, but the flight control system is somewhat less sensitive to this parameter.

Analysis of Results

To evaluate the lateral/directional effects of yaw jet interaction, the preflight predictions and flight test data have been plotted on a semilog graph to compress the entire trajectory into one convenient plot. The jet interaction increment coefficient for rolling moment, side force, and yawing moment as a function of mass flow ratio and freestream Mach number can be seen in Figs. 4, 5, and 6, respectively.

In general, the results shown in these figures indicate better agreement between flight data and preflight predictions at the lower mass flow rate ratios (late entry) than at the higher mass

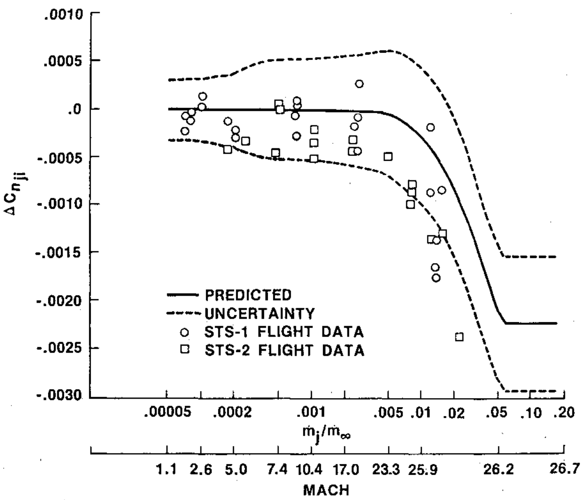

Fig. 6 Yawing moment jet interaction increment due to aft left-hand yaw jets.

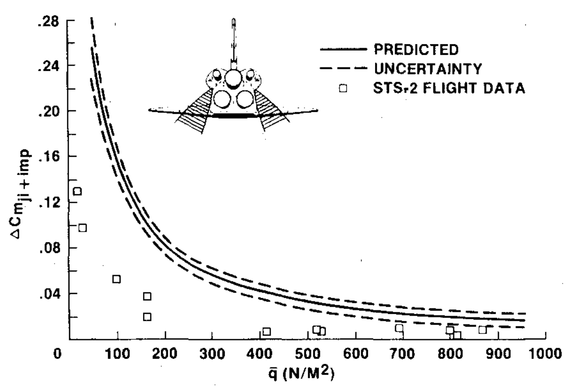

Fig. 7 Pitching moment jet interaction and impingement increment due to two aft down-firing jets (one each side).

flow rate ratios (early entry). This is especially true of the induced rolling moment due to yaw jets, as shown in Fig. 4. In this case the flight test data and preflight predictions show a significant and consistent divergence beginning at about $\dot{m}_j/\dot{m}_\infty = 0.008$. The data for side force and yawing moment (Figs. 5 and 6, respectively) show a similar trend but it is much less pronounced. It is felt that the discrepancy seen in rolling moment and that seen in yawing moment and side force are due to different jet interaction mechanisms. Consequently, it is convenient to break the discussion of results into two parts: 1) the rolling moment jet interaction due to yaw jets, and 2) the yawing moment and side force jet interaction due to the aft yaw jets.

Rolling Moment Due to Yaw Jets

Upon examining Fig. 4 we can see that the prediction model (based on wind tunnel data) adequately predicted the jet interaction effects at the later entry conditions ($M<10$) but significantly overpredicted the effects at Mach numbers greater than 10. The major question, of course, is, why does the prediction model appear to be satisfactory for one part of the trajectory and unsatisfactory for another part?

The majority of the yaw RCS jet interaction data base applicable to very high Mach numbers was derived at Mach 10.3 in the Langley 31-in. Continuous Flow Hypersonic Wind Tunnel. It is generally accepted that for hypersonic flow there is little Mach effect. But it is obvious from a comparison of flight test data and wind tunnel data that there is a definite problem in correlating the Mach 10.3 data base with the flight data at the higher Mach numbers even though the scaling parameter was matched. This problem is probably due, at least in part, to the incompatibility between the leeside flow as

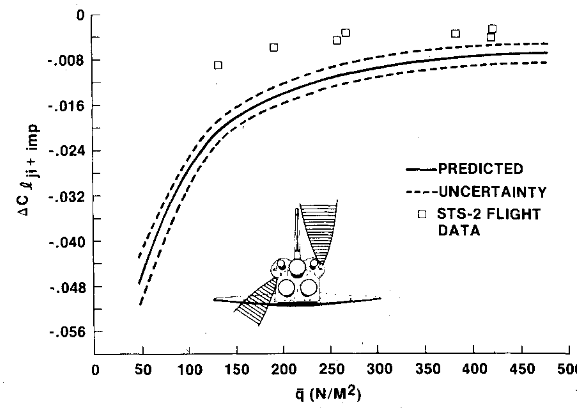

Fig. 8 Rolling moment jet interaction and impingement increment due to a roll couple (one up-firing and one down-firing jet on opposite sides).

modeled in the wind tunnel and that experienced in flight at higher Mach numbers. An inadequate simulation of the leeside flow apparently would have little effect on the overall aerodynamics but could have significant influence on jet interaction effects. Since the data used to simulate jet interaction at the higher Mach numbers (as high as Mach 27) were obtained at Mach 10.3, the characteristics of the leeside flowfield are artificially fixed at the Mach 10.3 conditions. Furthermore, the plume simulation parameter, $\dot{m}_j/\dot{m}_\infty$, is based on freestream conditions while, in reality, the plume sees entirely different conditions in the leeside flow. If the Mach 10.3 simulation of the higher Mach number leeside conditions is not valid, then the relationship between freestream and leeside conditions above Mach 10.3 is not the same as it is at Mach 10.3. This dissimilarity could easily introduce distortions into the plume simulation.

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

Yawing Moment and Side Force Due to Yaw Jets

An aft left-hand yaw jet produces a positive side force and a negative yawing moment. From a traditional jet interaction point of view, we would expect a slight amplification of both yawing moment and side force due to jet interaction. This is exactly what was predicted in the wind tunnel. However, examination of the flight data in Figs. 5 and 6 indicates that the vehicle apparently experienced a larger amplification due to jet interaction than was predicted. Considering the data set as a whole, the increase in side force appears to correlate with the increase in negative yawing moment. Unfortunately, the actual level of the increase in amplification indicated by the flight results is not obvious because of the scatter in the flight test data. It is felt that the scatter in the flight data is due to the difficulty of measuring the yawing moment and side force induced by the yaw jets. These two components are difficult to extract because, of the total yawing moment and side force applied to the vehicle, the portion due to jet interaction is small. By contrast, the rolling moment due to yaw jet interaction is a large part of the total rolling moment applied to the vehicle and, at least at the higher Mach numbers, is much easier to extract. Thus, while it is very probable that the side force and yawing moment are greater than predicted, the erratic correlation of the flight data and the rather significant data scatter may be making the agreement between flight and wind tunnel look worse than it really is. Until more consistent flight data are available, little else can be concluded.

Aft Pitch and Roll Jets

As was mentioned earlier, the aft RCS roll and pitch jets are inhibited beyond dynamic pressures of 478.8 and 957.6 N/m^2

(10 and 20 psf), respectively. Limits were placed on the use of these jets based on wind tunnel test data that showed the possibility of control reversal if these jets are used beyond those dynamic pressures. However, flight test results from STS-2 for two specific jet configurations suggest that the wind tunnel predictions were too conservative and that the jet interaction effects due to the pitch and roll jets are much smaller than originally predicted.

Flight test results vs preflight predictions for the aft downward-firing pitch jets are shown in Fig. 7. It is obvious from this plot that the preflight prediction substantially overpredicts the jet effects in pitch. The flight data, however, do appear to follow the same trend as the predicted curve. Flight test results for a roll jet configuration (one upward-firing jet on one side and one downward-firing jet on the other side) are shown in Fig. 8 along with preflight predictions. This plot exhibits essentially the same characteristics as Fig. 7; that is, an overprediction of the jet effects, while flight data follow a similar trend to the predicted data. The principal cause of this discrepancy is not known at this time. The most likely candidate, of course, is an incorrect scaling parameter. The fact that both configurations have similar characteristics would suggest that there is a common simulation problem. However, for these particular jets at these flight conditions, there is an additional complicating factor that will make it very difficult to pin down the precise cause of the discrepancy.

In general, jet induced plume effects can be due to two different mechanisms: 1) interaction of the plume with the surrounding flowfield and vehicle boundary layer (jet interaction), and 2) plume impingement to the vehicle surfaces. In the previous sections concerning yaw RCS jet effects, it was assumed that the effects of yaw jet plume impingement on the Orbiter were negligible such that the induced effects were attributed solely to jet interaction. It is not possible to make this assumption for the pitch and roll jets. Their interval of operation is at such low dynamic pressures, $\bar{q}<957.6$ N/m^2 (20 psf), that impingement is a major factor and must be considered when analyzing the results. Unfortunately, the impingement and jet interaction effects cannot be uncoupled easily, if at all, and this makes it very difficult to determine whether a particular discrepancy is due to an error in the simulation of plume impingement or of jet interaction, or both. Consequently, the results from one test flight are not enough to draw any specific conclusions regarding jet interaction or impingement due to the aft pitch and roll jets. Nevertheless, it is probably safe to conclude that the aft pitch and roll jets are much more effective than originally expected.

Conclusions

The initial comparison between Space Shuttle flight test data and wind tunnel predictions for jet interaction due to the aft yaw jets is somewhat disappointing. Although the rolling moment induced by a yaw jet was satisfactorily predicted at the lower Mach numbers ($M<10$) it was significantly overpredicted at Mach numbers greater than 10. It is felt that this is due primarily to an incorrect wind tunnel simulation of the flow conditions on the leeside of the wing which results in a distortion of the interaction effects due to the sideward-firing yaw jets.

The side force and yawing moment induced by the aft yaw jets appears to be underpredicted. However, the scatter in the flight data is significant enough to make any comparison inconclusive.

The pitch and roll jet data from one test flight strongly suggest that the preflight predictions were overly conservative and, in actuality, these jets are much more effective than originally expected. It is not known at this time why these effects were so greatly overpredicted. Further analysis and testing are needed to understand the phenomenon and explain the discrepancies noted during these early test flights.

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