Development of Aerodynamic Uncertainties for the Space Shuttle Orbiter

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The Shuttle program development schedule and the management decision to perform an orbital, manned mission on the first launch resulted in a requirement to develop realistic aerodynamic uncertainties for the preflight aerodynamic predictions. This paper addresses the methodology in developing two types of aerodynamic uncertainties. One involves the ability to reproduce aerodynamic results between various wind tunnel tests. The second addresses the differences between preflight aerodynamic predictions and flight results derived from analysis of past aircraft programs. Both types of uncertainties for pitching moment, lateral-directional stability, rudder power, and aileron power are presented. In addition, the application of uncertainties to flight control design and flight test planning is briefly reviewed.

Nomenclature

b	= span, in.
$\bar{c}$	= mean aerodynamic chord, in.
$C_{l_{\delta_a}}$	= aileron roll derivative, deg
C_{l_β}	= dihedral stability, deg
$C_{l_{\delta_r}}$	= rudder roll derivative, deg
C_m	= pitching moment coefficient
$C_{n_{\delta_a}}$	= aileron yaw derivative, deg
C_{n_β}	= directional stability, deg
$C_{n_{\delta_r}}$	= rudder yaw derivative, deg
L_B	= body length, in.
M	= Mach number
MRC	= moment reference center, fuselage station $X_0 = 1077$ in.
$\bar{q}$	= dynamic pressure, psf
S	= reference area, ft^2
α	= angle of attack, deg
β	= angle of sideslip, deg
δ_a	= aileron deflection angle, deg
δ_r	= rudder deflection angle, deg
Δ	= wind tunnel—ADDB difference

Introduction

TWO management policy decisions made during the initial development planning for the Shuttle had a significant impact on the approach to aerodynamic design and verification. In order to meet a compressed development schedule, a decision was made to concurrently design the flight control system (FCS) and conduct aerodynamic verification wind tunnel testing. Realizing the predicted aerodynamics were likely to change during the aerodynamic verification process, the FCS was designed to be insensitive to "reasonable" changes in the aerodynamic characteristics. As a result of this approach, the aerodynamicists were required to provide uncertainties on the preflight aerodynamics. The uncertainties used in the FCS design were defined as tolerances, which are the minimum errors that are expected in the preflight aerodynamics.

Second, the decision to perform an orbital, manned mission on the first launch highlighted the aerodynamicists' problems. This decision raised the general question of how to maximize mission safety without the benefit of either a graduated flight test program (as used by the aircraft industry) or an initial unmanned flight concept (as used by the early space program). The consequence of this decision on the development of an aerodynamic data base resulted in the problem of how to provide an estimate of maximum possible errors in the preflight predicted aerodynamics, especially in previously uncharted flight regimes. However, the estimated errors must not be so great as to completely invalidate the FCS design. Thus, a set of "worst case" aerodynamic uncertainties, defined as variations, was developed. As part of the first flight certification, variations, combined with other system uncertainties, were used to "stress" the flight control system through a multitude of simulations. As a consequence, the initial entry was flown at a center of gravity and with FCS gains which maximized the aerodynamic margins thereby maximizing mission safety for these systems.

This paper briefly addresses the development of the nominal preflight aerodynamics and details the methodology for establishing tolerances and variations.

Preflight Predictions

One of the largest wind tunnel programs in history has been conducted[1] for the development of the Space Shuttle. The Orbiter (Fig. 1) alone has been tested over 27,000 occupancy hours to determine the performance and stability and control characteristics. This extensive wind tunnel program provided the foundation for the formulation and development of the Aerodynamic Design Data Book (ADDB).[2] The ADDB is the result of the combined efforts of the prime contractor and several NASA centers and consists of a digitized set of tables developed from the engineering analysis and fairing of all valid experimental data, complemented by empirical and theoretical data, and extrapolated to flight conditions where appropriate. Thus, the ADDB represents the "best estimate" of the preflight aerodynamics.

Tolerance Development

Since the wind tunnel data base is the foundation for the preflight predictions, it is reasonable to assume that the minimum error that could be expected (i.e., tolerances) would be the ability to reproduce experimental results between various tests. Therefore, repeat tests were performed using various facilities, different models, and, on occasion, different test organizations. Although the individual causes for

GEOMETRY	COMPONENT	
	WING	VERTICAL TAIL
AREA	2690 FT² (249.9092 m²)	413.25 FT² (38.3922 m²)
SPAN	936.68 (23.8425)	315.72 (8.0193)
ASPECT RATIO	2.265	1.675
TAPER RATIO	0.2	0.404
SWEEP (LE)	81/45 DEG	45 DEG
DIHEDRAL	3.5	--
INCIDENCE	0.5 DEG	--
MAC	474.81 (12.0602)	199.81 (5.0752)

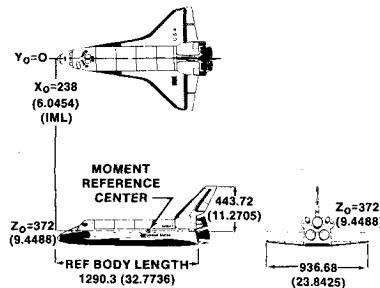NOTE: UNLESS OTHERWISE NOTED, ALL DIMENSIONS ARE IN INCHES (METERS)
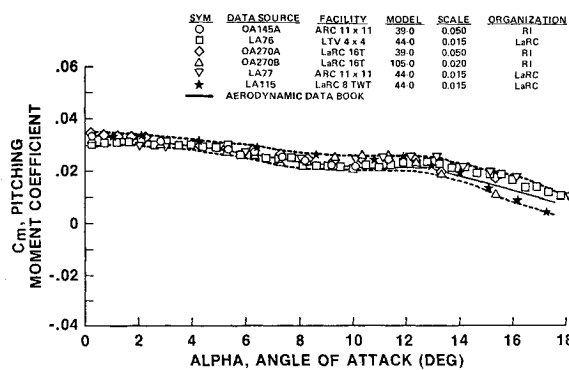

Fig. 1   Space Shuttle Orbiter geometry.
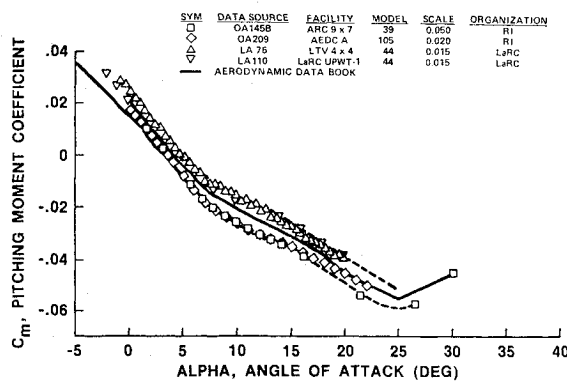

Fig. 2   Pitching moment, Mach 0.6.

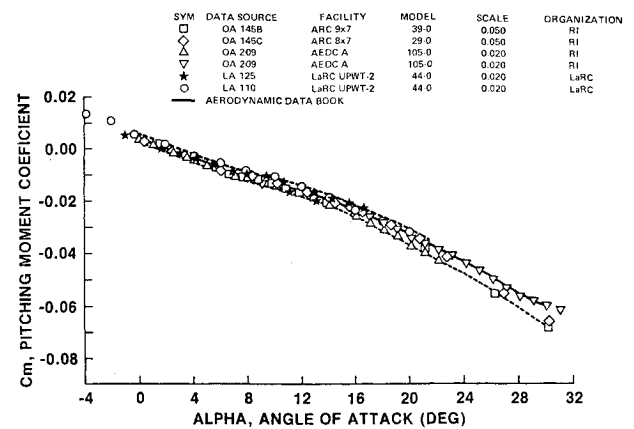
Fig. 3   Pitching moment, Mach 2.0.
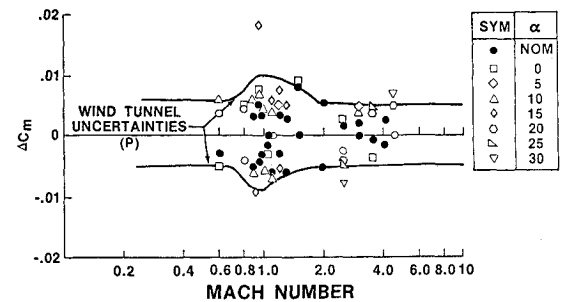

Fig. 4   Pitching moment, Mach 2.5.

Fig. 5   Orbiter pitching moment uncertainty.

(16T) tunnel. With all these potential sources of differences, a peak-to-peak repeatability in C_m of approximately 0.006 was realized. This repeatability represents the combined error sources of the following: 1) the same model in several tunnels (tunnel-to-tunnel repeatability); 2) different models in the same tunnel (model-to-model repeatability); and 3) different test organizations (testing technique differences). This also includes any Reynolds number and blockage effects.

From this type of basic plot, the differences between the wind tunnel results and the ADDB at various angles of attack were plotted vs Mach number, as illustrated in Fig. 5. Tolerances (wind tunnel uncertainties) were obtained by fairing a curve through these data points using engineering judgment. The nominal angle of attack (Fig. 6) was given a high weighting in the fairing process.

Aerodynamic tolerances for lateral-directional stability $(C_{n_\beta}, C_{l_\beta})$ are presented in Figs. 7 and 8, while tolerances for rudder power $(\Delta C_{n_{\delta_r}}, \Delta C_{l_{\delta_r}})$ are shown in Figs. 9 and 10. Aileron power $(\Delta C_{n_{\delta_a}}, \Delta C_{l_{\delta_a}})$ tolerances are presented in Figs. 11 and 12. Table 1 presents the facilities and models used in this evaluation.

Variations Development

It was felt the most reasonable approach to the development of variations would be to analyze the wind tunnel to flight test differences of past aircraft programs. Unfortunately, the verification of preflight-predicted aerodynamics was not a major objective of most of the earlier flight test programs. This severely limited the amount of data available for conducting flight test to wind tunnel comparisons. The flight data base was further limited by restricting the comparison to those vehicles that were geometrically similar to the Orbiter. Those vehicles chosen as applicable to the Orbiter are presented in Table 2. Also presented are geometric factors and other considerations pertinent to the vehicle configuration choices.

Variations were established by fairing the differences between the flight and predicted aerodynamics as a function

any differences were not specifically identified, it is felt the total difference is representative of what may be expected for wind tunnel test repeatability.

As an illustration of the mechanics of this procedure, consider pitching moment coefficient, where repeat tests were plotted along with ADDB estimates, as typically shown in Figs. 2-4. It can be seen from Fig. 2 that an 0.05 scale model (model 39-0) was tested in both the Ames Research Center (ARC) 11×11-ft facility and the Langley Research Center (LaRC) 16-ft transonic facility. Similarly, an 0.015 scale model (model 44-0) was tested in three facilities: 1) the Ling-Temco-Vought (LTV) 4×4; 2) the LaRC 8-ft tunnel; and 3) the ARC 11×11-ft facility. In addition, the 0.02 scale model (model 105-0) was tested in the LaRC 16-ft transonic

of Mach number. The selections of the configurations and the fairing process are very subjective in nature. For this reason, a team of aerodynamicists from the Air Force Flight Test Center (AFFTC), NASA Dryden Flight Research Facility (NASA-DFRF), NASA Johnson Space Center (NASA-JSC), and Rockwell International (RI) was formed to conduct the analysis and, a concensus on variations.

The team's flight-to-predicted correlation and their recommended variation fairings are presented as a function of Mach number for C_m, C_{n_β}, C_{l_β}, $C_{n_{\delta_r}}$, $C_{l_{\delta_r}}$, $C_{n_{\delta_a}}$, and $C_{l_{\delta_a}}$, Figs. 13-19, respectively. These figures were taken in part from Ref. 3.

As can be seen from the flight correlation figures, the flight data are limited to the lower supersonic speeds. In Mach
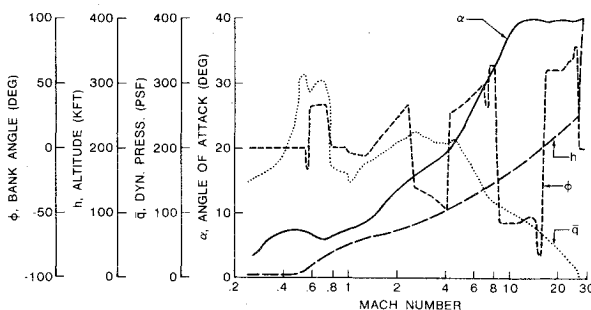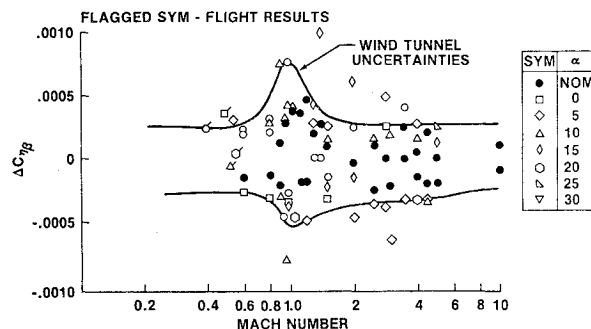
Fig. 8   Orbiter dihedral stability uncertainty.

Fig. 6   Typical Orbiter entry trajectory.

Fig. 9   Orbiter rudder yaw derivatives uncertainty.

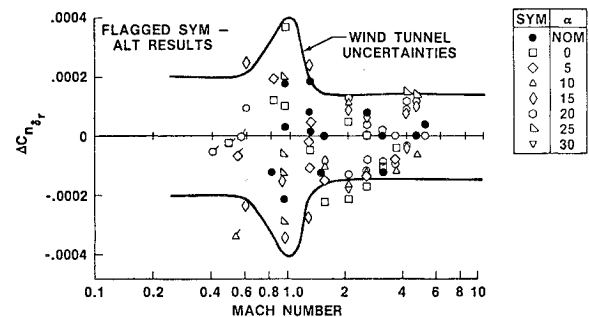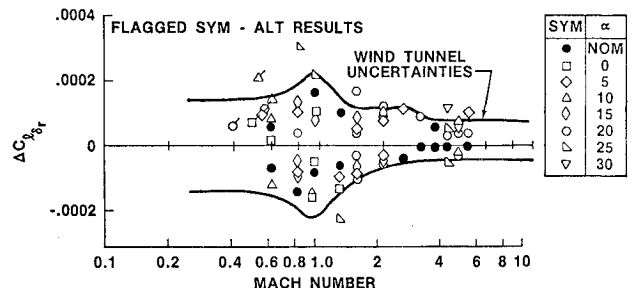Fig. 7   Orbiter directional stability uncertainty.

Fig. 10   Orbiter rudder roll derivatives uncertainty.

Table 1   Wind tunnel tests used for uncertainty evaluation

Test ID	Facility	Model No.	Scale	Re_c, $\times 10^6$	Blockage, %
		Transonic			
OA145A	ARC 11×11 ft	39-0	0.05	5.9, 9.9, 17.8	1.09
OA270A	LaRC 16T	39-0	0.05	7.9	0.65
OA270B	LaRC 16T	105-0	0.02	3.1	0.10
LA70	Calspan 8 ft	44-0	0.015	2.1, 2.7, 4.7	0.18
LA76	LTV 4×4 HSWT	44-0	0.015	4.5, 5.3, 5.9	0.74
LA77	ARC 11×11 ft	44-0	0.015	4.7	0.10
LA111	LaRC 8 ft TWT	44-0	0.015	4.1	0.24
LA115	LaRC 8 ft TWT	44-0	0.015	2.5	0.24
		Supersonic			
OA145B	ARC 9×7 ft	39-0	0.05	3.0, 6.9, 8.9	
OA145C	ARC 8×7 ft	39-0	0.05	2.0, 5.0, 6.4, 7.9	
OA209	AEDC A	105-0	0.02	3.4, 7.7, 10.4	
LA63A	LaRC UPWT-1	44-0	0.015	1.2	
LA63B	LaRC UPWT-2	44-0	0.015	1.2	
LA75	LaRC UPWT-2	44-0	0.015	1.2	
LA76	LTV 4×4 HSWT	44-0	0.015	4.5	
LA101	LaRC UPWT-1	44-0	0.015	1.2	
LA110	LaRC UPWT-1	44-0	0.015	1.2	
LA114	LaRC UPWT-2	44-0	0.015	1.2	
LA125	LaRC UPWT-2	105-0	0.02	1.6	

Note: HSWT = high-speed wind tunnel, TWT = transonic plan wind tunnel, UPWT = unitary plan wind tunnel.

Table 2   Orbiter correlation applicability (Ref. 3)

Aircraft[a]	Geometric factors					Remarks
	Wing planform	Wing flap longitudinal control	Wing elevon lateral control	Single vertical tail	Large FCS	
XB-%	×	×	×			Good predictive base, M range canard, limited α range
YF-12	×	×	×			Good M range, limited α range
X-15				×	×	Wide α, M range
TACT$_{\Lambda=58°}$	×			×	×	Only limited data currently available Low-speed data only
HP115	×	×	×	×		Good predictive base,
B-58	×	×	×	×		M range
YF-16				×		Source of rudder
F-8SCW						control data

[a]See Ref. 3 for aircraft identification.
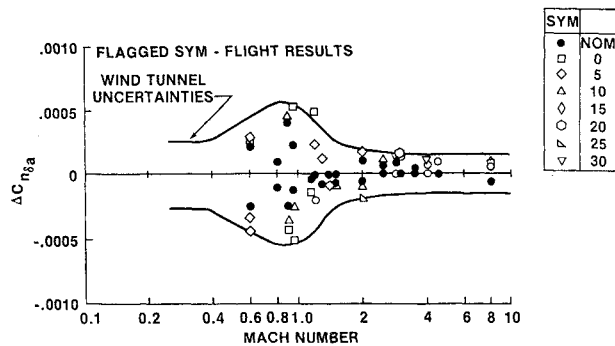
Fig. 11   Orbiter aileron yaw derivatives uncertainty.

Fig. 14   Correlation of flight and predicted directional stability.
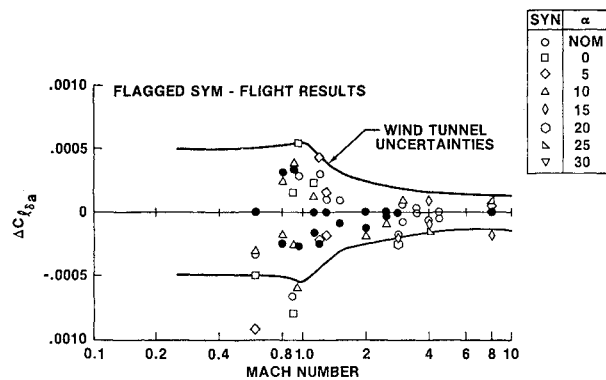

Fig. 12   Orbiter aileron roll derivatives uncertainty.

Fig. 15   Correlation of flight and predicted dihedral stability.
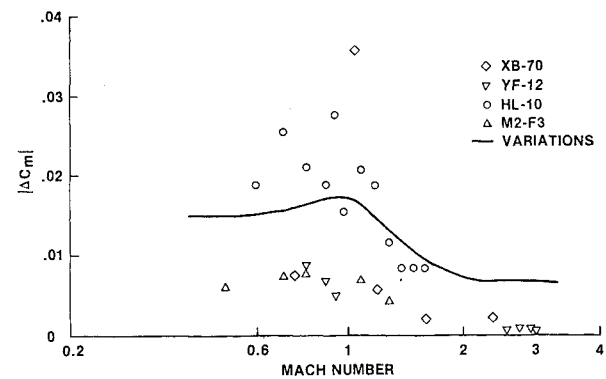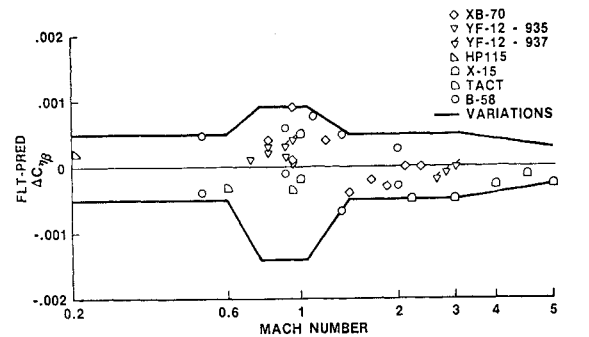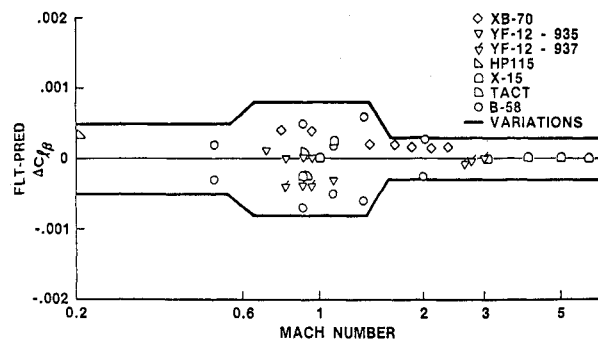

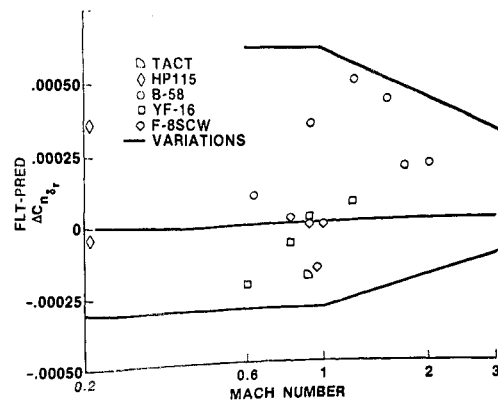Fig. 13   Correlation of flight and predicted pitching moment.

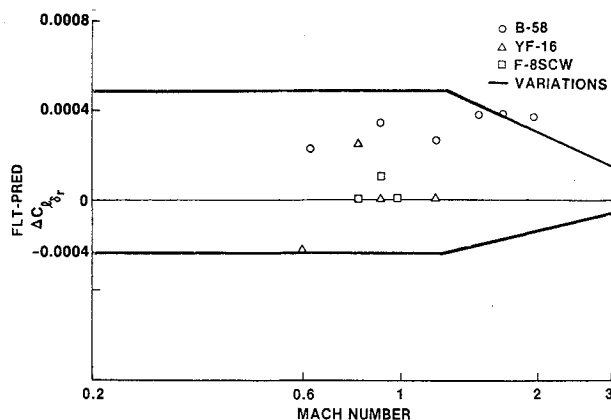Fig. 16   Correlation of flight and predicted rudder yaw derivative.

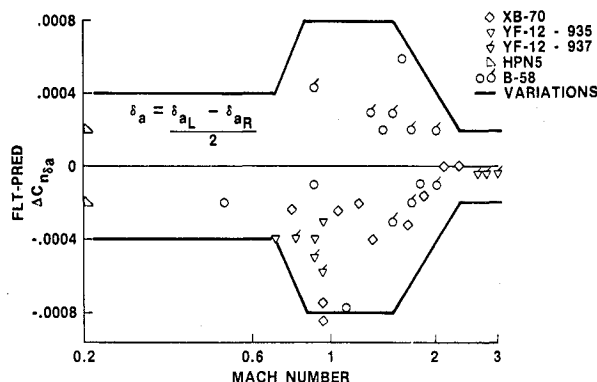Fig. 17　Correlation of flight and predicted rudder roll derivatives.

Fig. 18　Correlation of flight and predicted aileron yaw derivatives.
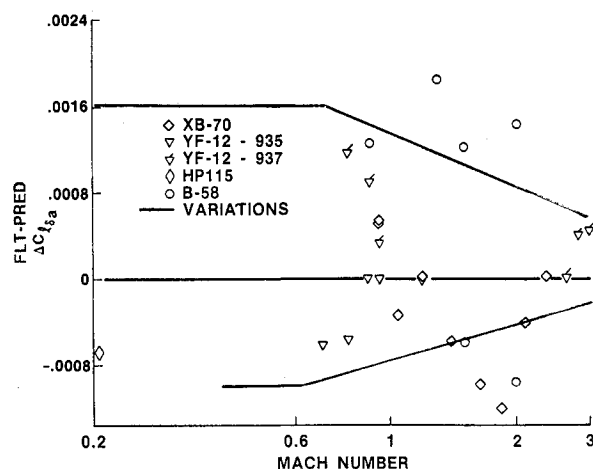

Fig. 19　Correlation of flight and predicted aileron roll derivatives.

regimes where flight data were unavailable, variations were obtained by multiplying the tolerances by a safety factor (usually 1.5).

Comparison of tolerances and variations at the lower Mach numbers indicate, as one might expect, that tolerances are less than variations.

A more detailed development of variations is found in Ref. 3. These recommended variations were modified primarily to facilitate computerization and were included in the aerodynamic design data base.[2]

Concluding Remarks

Requirements of the Shuttle program resulted in the development of the first comprehensive set of uncertainties in predicting preflight aerodynamics. In the process of the uncertainties development, a systematic wind tunnel study has been performed which demonstrates the need for testing multiple models/facilities when precise preflight aerodynamic predictions are needed.

The application of these uncertainties resulted in a desensitization of the flight control system to aerodynamics, thus providing increased confidence in the safety aspects of conducting a manned orbital mission on the first launch of the Orbiter.

Acknowledgments

The development of variations and wind tunnel uncertainties was a team effort in every sense of the word. Space does not permit recognizing everyone who participated in this effort but the authors, as representatives of the Shuttle program, would like to recognize key government and contractor personnel.

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References

[1]Whitnah, A.M. and Hillje, E.R., "Space Shuttle Wind Tunnel Program Summary," AIAA Paper 82-0562, March 1982.

[2]"Aerodynamic Design Data Book, Vol. 1: Orbiter Vehicle, STS-1, Final Report," NASA CR-160903, Nov. 1980.

[3]Weil, J. and Powers, B.G., "Correlation of Predicted and Flight Derived Stability Derivatives with Particular Application to Tailless Delta Wing Configurations," NASA TM-81361, 1980.