N84 10164 -20

THE DEVELOPMENT OF AERODYNAMIC UNCERTAINTIES FOR THE SPACE SHUTTLE ORBITER

James C. Young and Jimmy M. Underwood
NASA Johnson Space Center
Houston, Texas

ABSTRACT

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, inches
$\bar{c}$	Mean aerodynamic chord, inches
$C_{\ell_{\delta_a}}$	Aileron roll derivative, per degree
C_{ℓ_β}	Dihedral stability, per degree
$C_{\ell_{\delta_r}}$	Rudder roll derivative, per degree
C_m	Pitching moment coefficient
$C_{n_{\delta_a}}$	Aileron yaw derivative, per degree
C_{n_β}	Directional stability, per degree
$C_{n_{\delta_r}}$	Rudder yaw derivative, per degree
L_B	Body length, inches

Mach	Mach number
MRC	Moment reference center, fuselage station X_0 = 1077 inches
$\bar{q}$	Dynamic pressure, psf
S	Reference area, sq. ft.
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

ADDB	Aerodynamic Design Data Book
AEDC	Arnold Engineering and Development Center
AFFTC	Air Force Flight Test Center
ARC	Ames Research Center
Calspan	Calspan Corporation
DFRF	Dryden Flight Research Facility
FCS	Flight Control System
HST	Hypersonic Shock Tunnel
HSWT	High Speed Wind Tunnel
JSC	Johnson Space Center
LaRC	Langley Research Center
LTV	Ling-Temco-Vought
NASA	National Aeronautics and Space Administration
NSWC	Naval Surface Weapons Center
RI	Rockwell International
TWT	Transonic Plan Wind Tunnel
UPWT	Unitary Plan Wind Tunnel
16T	16-Foot Transonic

INTRODUCTION

Two management policy decisions made during the initial development planning for 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 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 error that is expected in the preflight aerodynamics.

Secondly, 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 the 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 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 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 figures 2, 3, and 4. From figure 2, it can be seen that a 0.05-scale model, model 39-0, was tested in both ARC 11 x 11-Foot Facility and in the LaRC 16-Foot Transonic Facility. Similarly, a 0.015-scale model, model 44-0, was tested in three facilities: 1) the LTV 4 x 4; 2) the LaRC 8-Foot Tunnel; and 3) the ARC 11 x 11-Foot Facility. In addition, the 0.02-scale model, model 105-0, was tested in the LaRC 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 difference between the wind tunnel results and the ADDB at various angles of attack were plotted versus Mach number, as illustrated in figure 5. Tolerances (wind tunnel uncertainties) were obtained by fairing a curve through these data points using engineering judgement. The nominal angle of attack (fig. 6) was given a high weighting in the fairing process.

Aerodynamic tolerances for lateral-directional stability (ΔC_{n_β}, ΔC_{ℓ_β}) are presented in figures 7 and 8, while tolerances for rudder power ($\Delta C_{n_{\delta_r}}$, $\Delta C_{\ell_{\delta_r}}$) are shown in figures 9 and 10. Aileron power $\Delta C_{n_{\delta_a}}$, $\Delta C_{\ell_{\delta_a}}$) tolerances are presented in figures 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 which were geometrically similar to the Orbiter. Those vehicles chosen as applicable to 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 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 AFFTC, NASA-DFRF, NASA-JSC, and RI was formed to conduct the analysis and reach 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, figure 13; C_{n_β}, figure 14; C_{ℓ_β}, figure 15; $C_{n_{\delta_r}}$, figure 16; $C_{\ell_{\delta_r}}$, figure 17; $C_{n_{\delta_a}}$, figure 18; and $C_{\ell_{\delta_a}}$, figure 19. These figures were taken in part from reference 3.

As can be seen from the flight correlation figures, the flight data is limited to the lower supersonic speeds. In Mach regimes where flight data was 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 reference 3. These recommended variations were modified primarily to facilitate computerization and included in the aerodynamic design data base, reference 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.

ACKNOWLEDGEMENTS

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.

Special thanks to James P. Arrington, Bernard Spencer, Jr. and George M. Ware of LaRC; Joseph Cleary and Lee Jorgensen of ARC; and Paul O. Romere of JSC for their effort in the development of wind tunnel uncertainties.

The difficult task of establishing variations was accomplished by a team composed of Joe Weil of DFRF; Paul W. Kirsten of AFFTC;and Dave Tymms of JSC.

Don C. Schlosser ably represented Rockwell International in both endeavors.

REFERENCES

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

2. Aerodynamic Design Data Book. Vol. I Orbiter Vehicle. NASA CR-160903, Nov. 1980. (Rockwell Rept. No. SD72-SH-0060-1M.)

3. Weil, Joseph; Powers, Bruce G.: Correlation of Predicted and Flight Derived Stability Derivatives with Particular Application to Tailless Delta Wing Configurations, NASA TM-81361.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 1.- WIND TUNNEL TESTS USED FOR UNCERTAINTY EVALUATION

TEST ID	FACILITY	MODEL NO.	MODEL SCALE	Re_c $(\times 10^6)$	BLOCKAGE (%)
Transonic					
1. OA145A	ARC 11x11 FT	39-0	0.05	5.9, 9.9, 17.8	1.09
2. OA270A	LaRC 16T	39-0	0.05	7.9	.65
3. OA270B	LaRC 16T	105-0	0.02	3.1	.10
4. LA70	CALSPAN 8 FT	44-0	0.015	2.1, 2.7, 4.7	.18
5. LA76	LTV 4x4 HSWT	44-0	0.015	4.5, 5.3, 5.9	.74
6. LA77	ARC 11x11 FT	44-0	0.015	4.7	.10
7. LA111	LaRC 8 FT TWT	44-0	0.015	4.1	.24
8. LA115	LaRC 8 FT TWT	44-0	0.015	2.5	.24
Supersonic					
9. OA145B	ARC 9x7 FT	39-0	0.05	3.0, 6.9, 8.9	
10. OA145C	ARC 8x7 FT	39-0	0.05	2.0, 5.0, 6.4, 7.9	
11. OA209	AEDC A	105-0	0.02	3.4, 7.7, 10.4	
12. LA63A	LaRC UPWT-1	44-0	0.015	1.2	
13. LA63B	LaRC UPWT-2	44-0	0.015	1.2	
14. LA75	LaRC UPWT-2	44-0	0.015	1.2	
(5.) LA76	LTV 4x4 HSWT	44-0	0.015	4.5	
15. LA101	LaRC UPWT-1	44-0	0.015	1.2	
16. LA110	LaRC UPWT-1	44-0	0.015	1.2	
17. LA114	LaRC UPWT-2	44-0	0.015	1.2	
18. LA125	LaRC UPWT-2	105-0	0.02	1.6	

TABLE 2.- ORBITER CORRELATION APPLICABILITY (ref.3)

AIRCRAFT	GEOMETRIC FACTORS					REMARKS
	WING PLANFORM	WING FLAP LONG. CONTROL	WING ELEVON LATERAL CONTROL	SINGLE VERTICAL TAIL	LARGE FCS	
XB-70	✓	✓	✓			GOOD PRED. BASE, M RANGE CANARD, LIMITED α RANGE
YF-12	✓	✓	✓			GOOD M RANGE, LIMITED α RANGE
X-15				✓	✓	WIDE α M RANGE
TACT$_{\Lambda=58^\circ}$	✓			✓	✓	ONLY LIMITED DATA CURRENTLY AVAILABLE
HP115	✓	✓	✓	✓		LOW SPEED DATA ONLY
B-58	✓	✓	✓	✓		GOOD PREDICTIVE BASE, M RANGE
YF-16 F-8SCW				✓		SOURCE OF RUDDER CONTROL DATA

*SEE REFERENCE 3 FOR AIRCRAFT IDENTIFICATION

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)

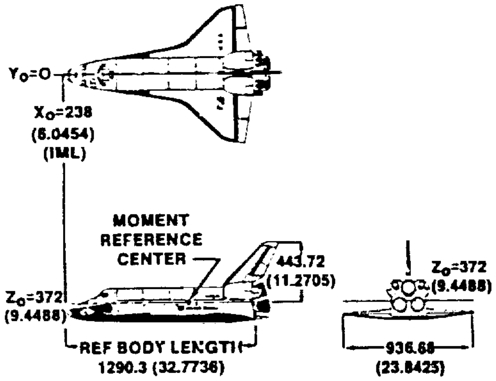


Figure 1.- Space Shuttle Orbiter geometry.

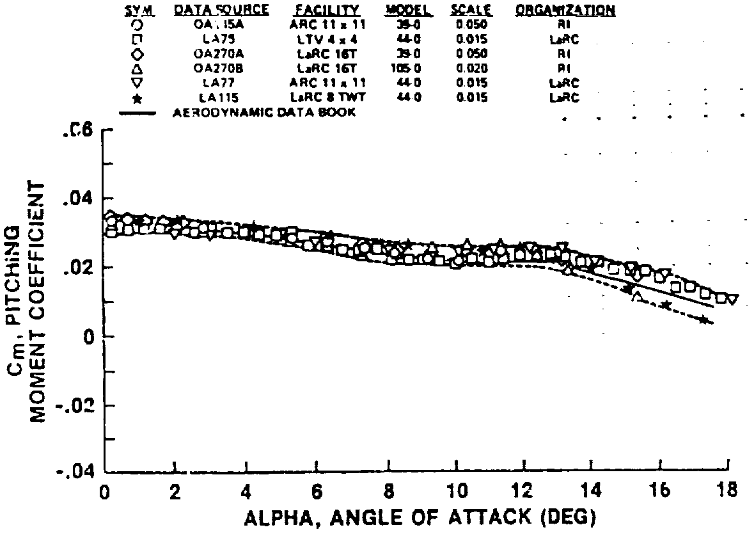
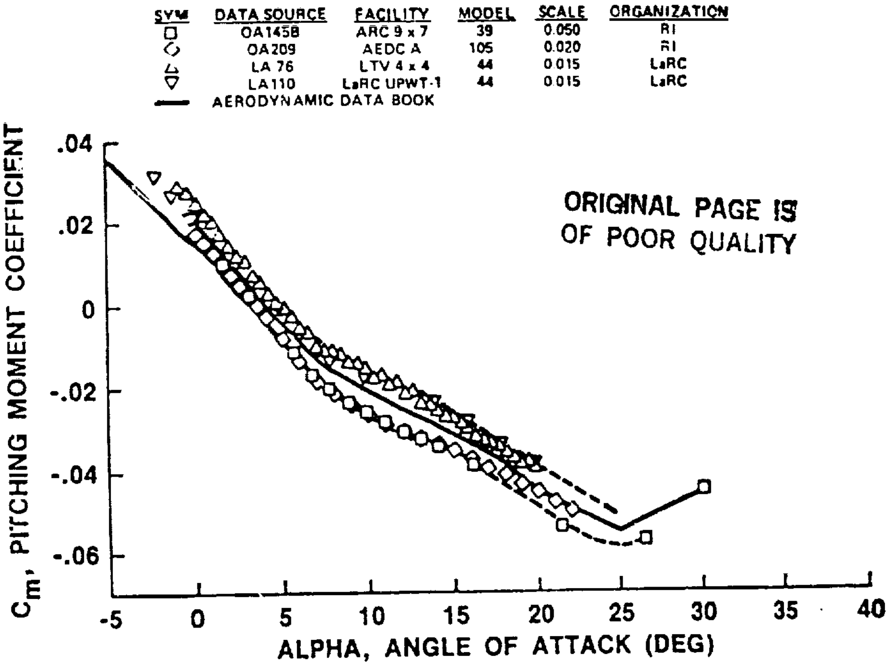


Figure 2.- Pitching moment, Mach 0.6.



ORIGINAL PAGE IS OF POOR QUALITY

Figure 3.- Pitching moment, Mach 2.0.

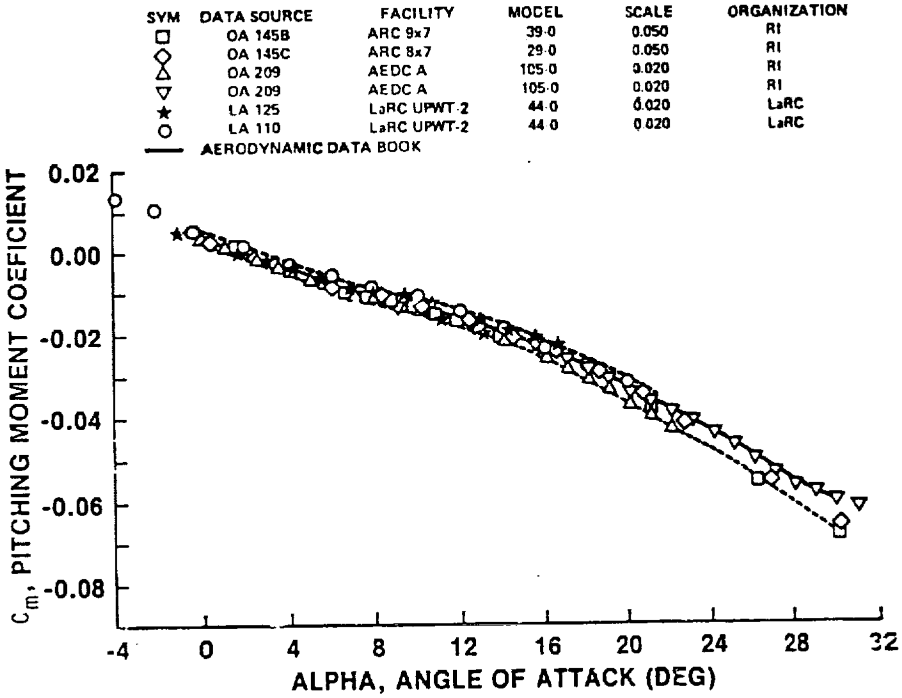


Figure 4.- Pitching moment, Mach 2.5.

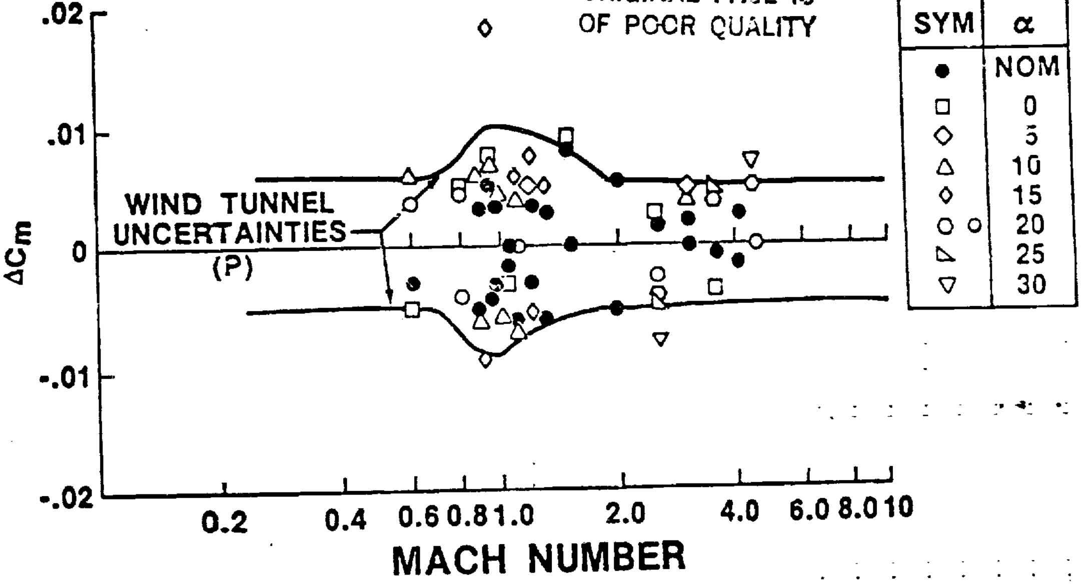


Figure 5.- Orbiter pitching moment uncertainty.

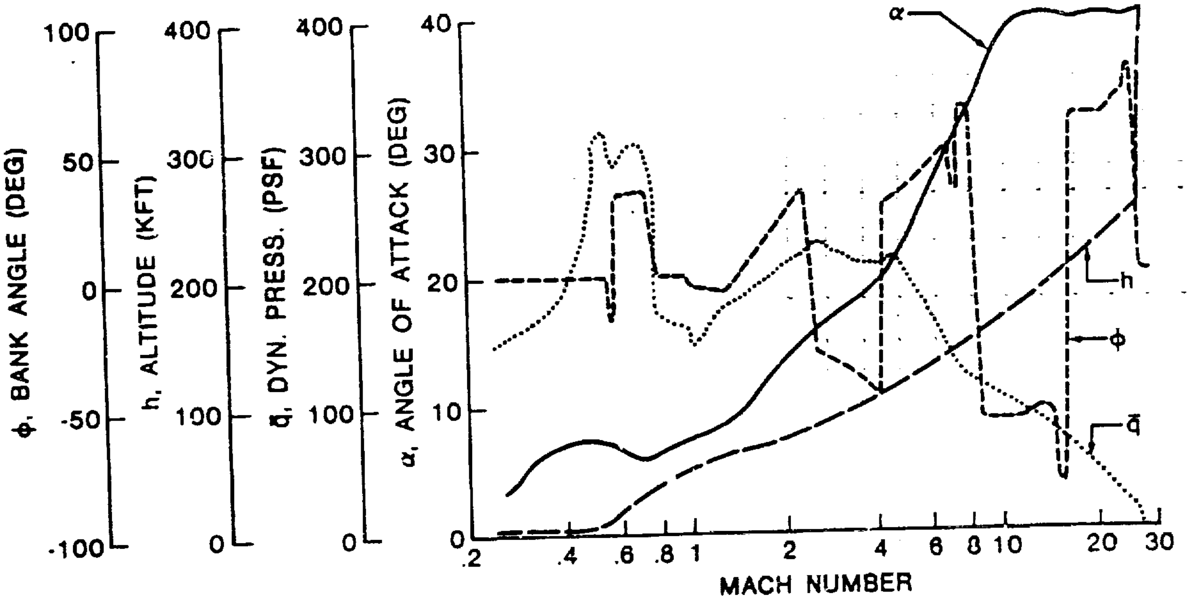


Figure 6.- Typical Orbiter entry trajectory.

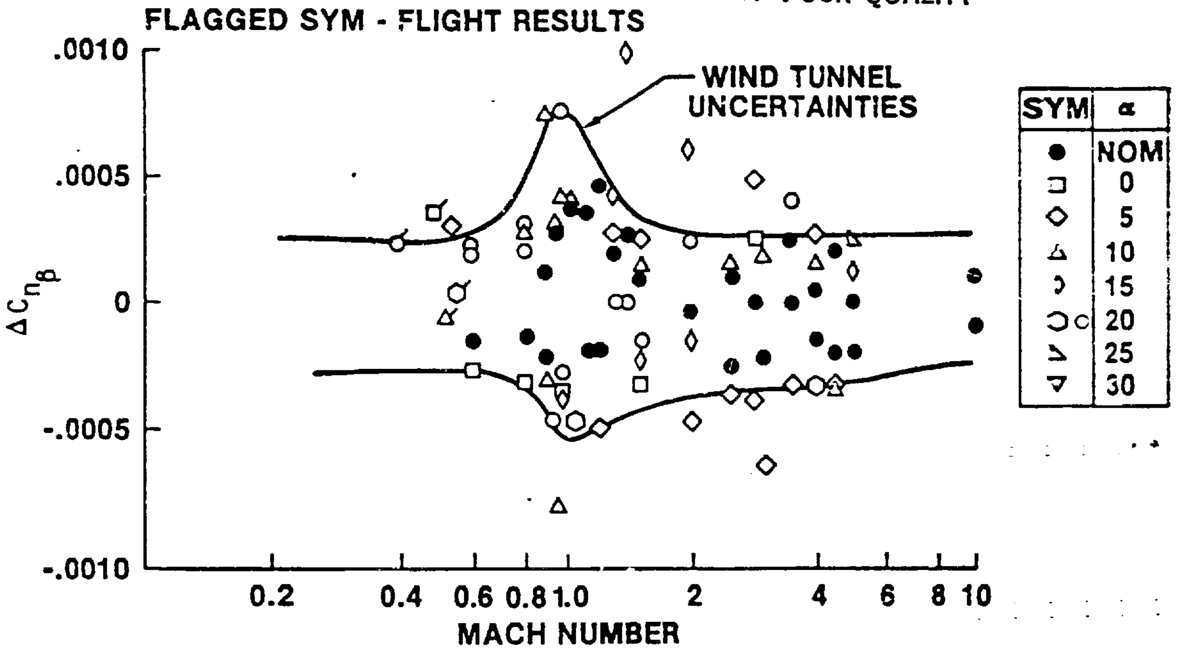


Figure 7.- Orbiter directional stability uncertainty.

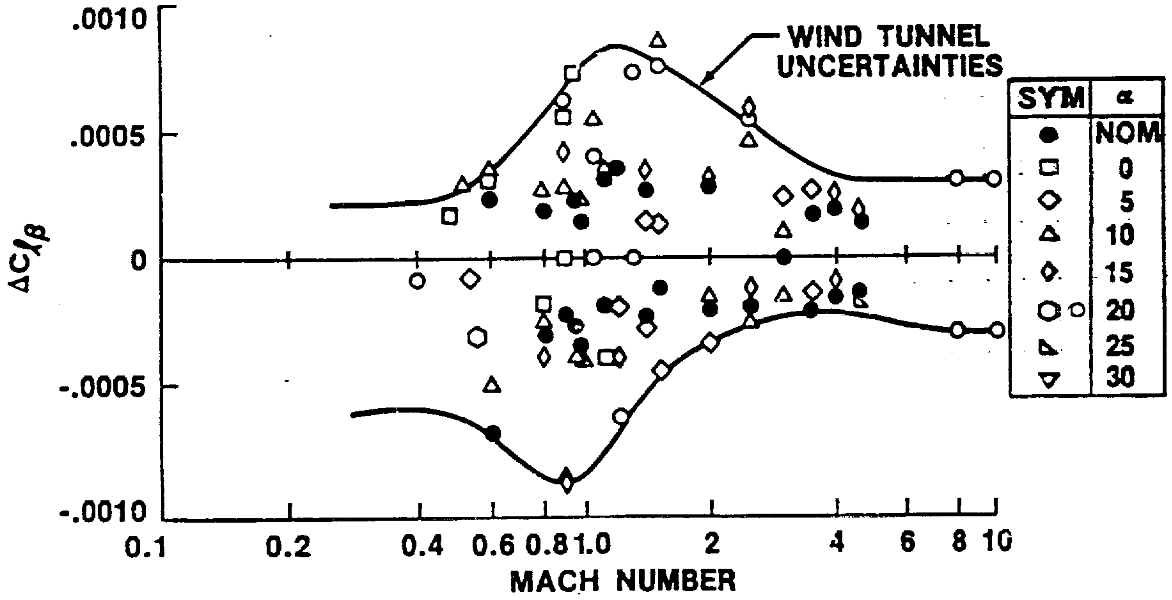


Figure 8.- Orbiter dihedral stability uncertainty.

ORIGINAL PAGE IS
OF POOR QUALITY

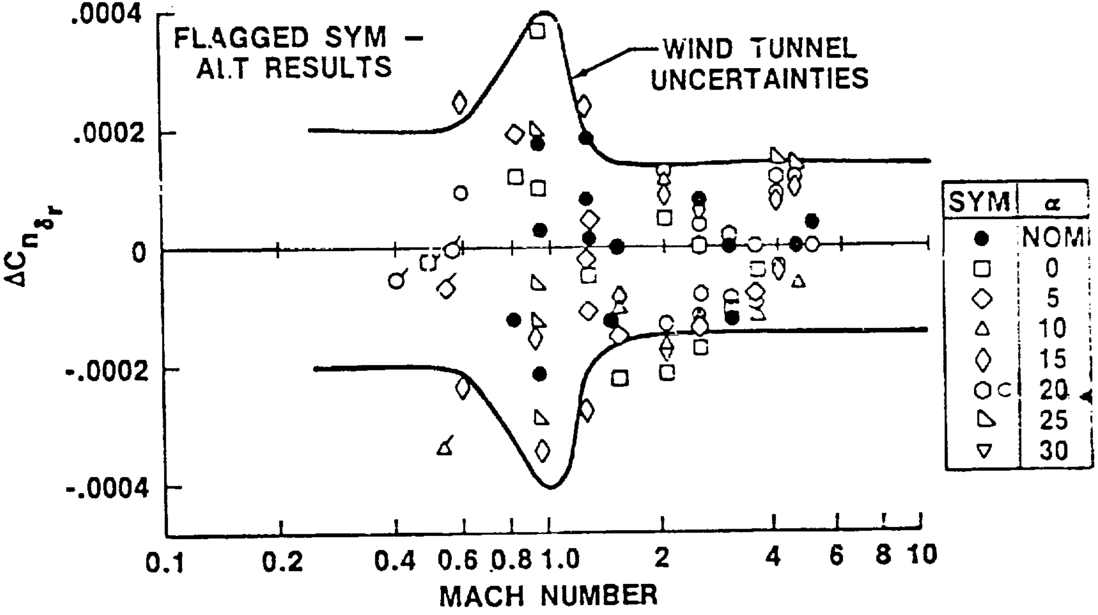


Figure 9.- Orbiter rudder yaw derivatives uncertainty.

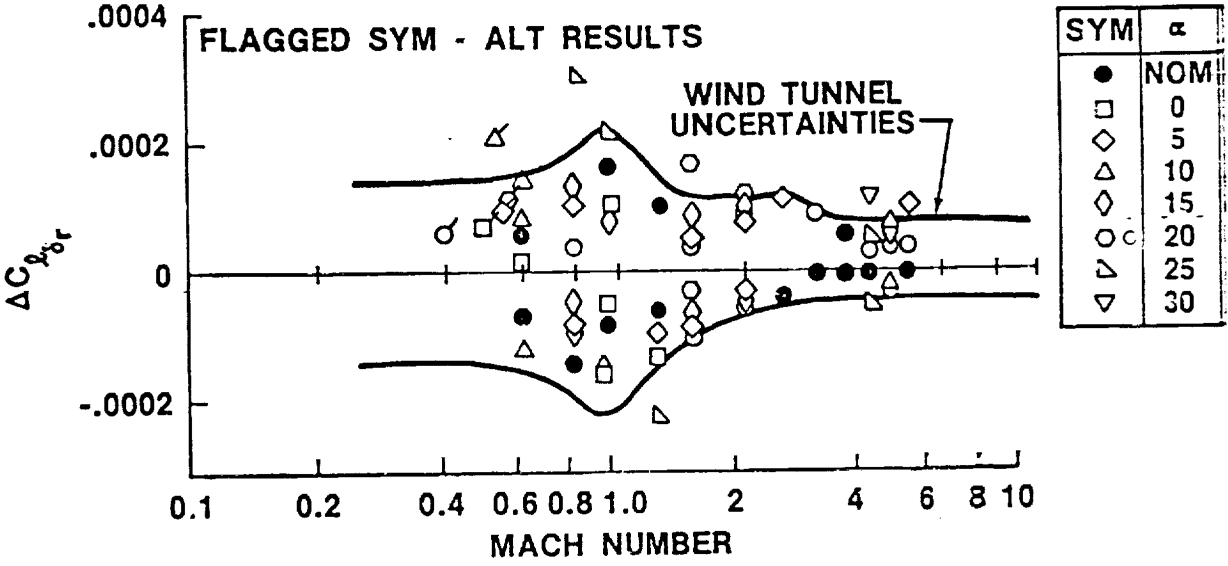


Figure 10.- Orbiter rudder roll derivatives uncertainty.

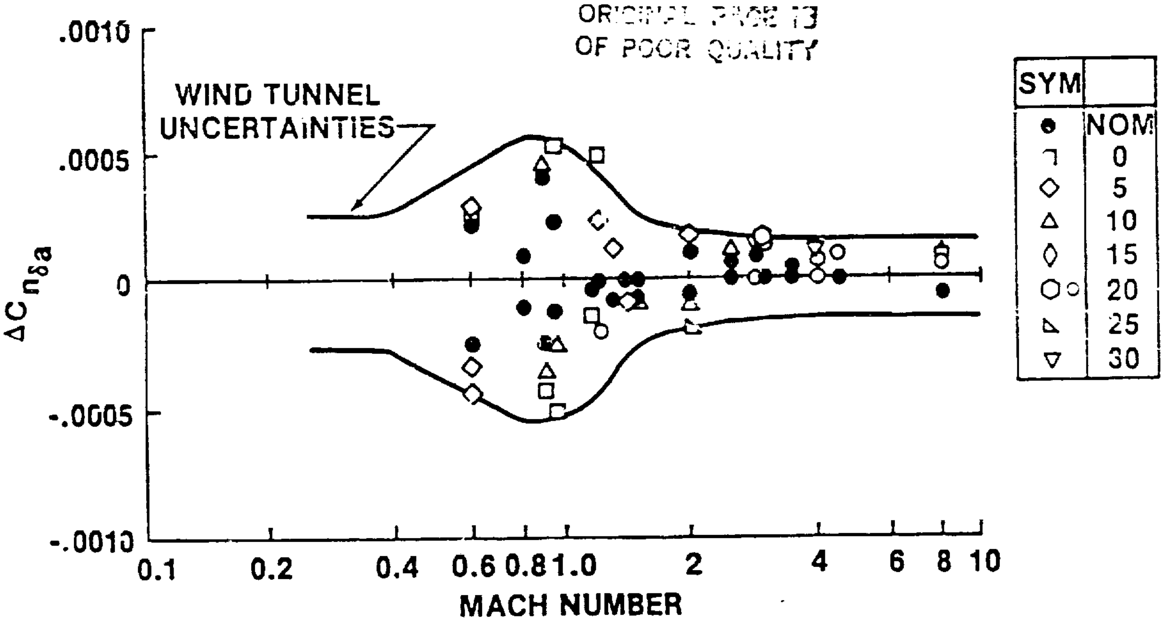


Figure 11.- Orbiter aileron yaw derivatives uncertainty.

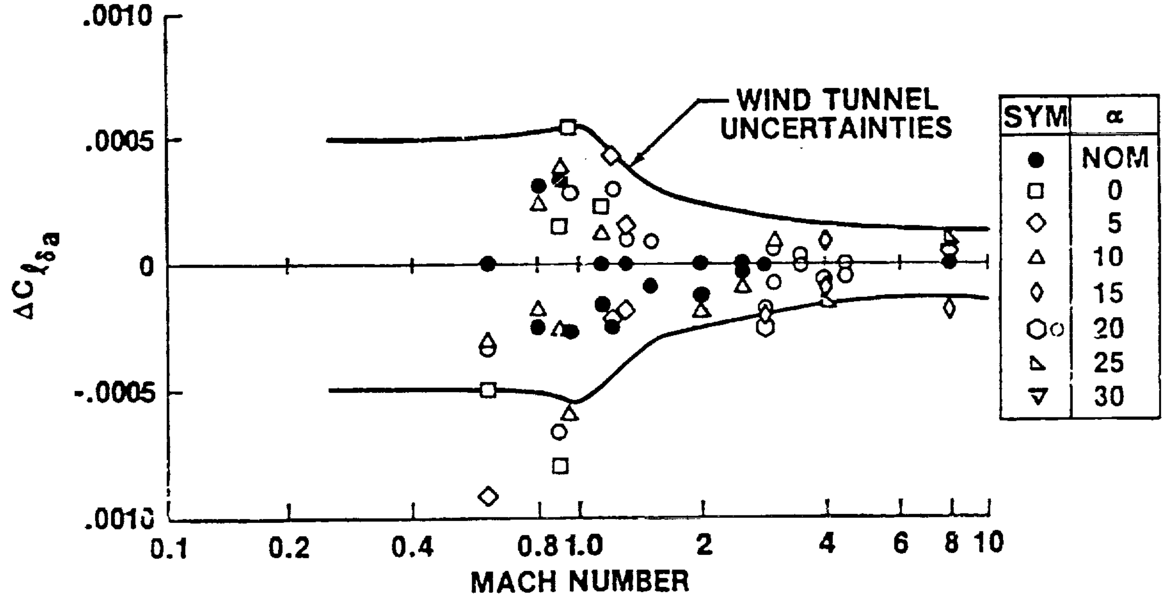


Figure 12.- Orbiter aileron roll derivatives uncertainty.

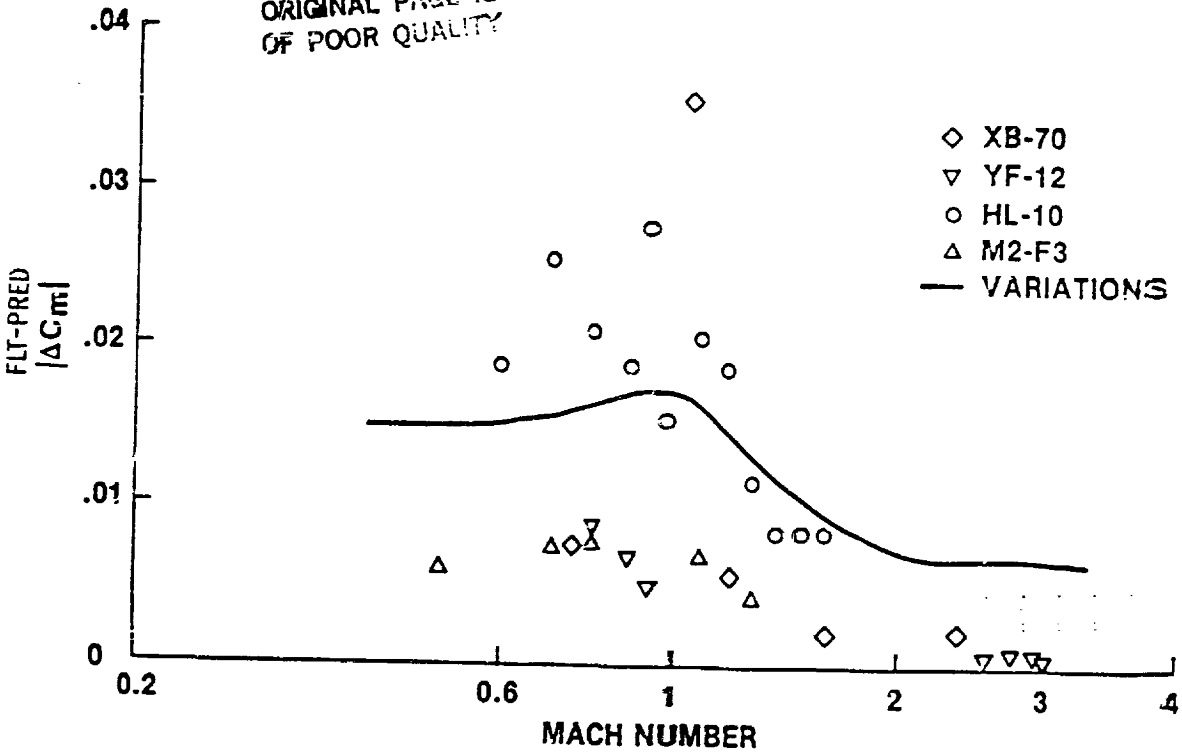


Figure 13.- Correlation of flight and predicted pitching moment.

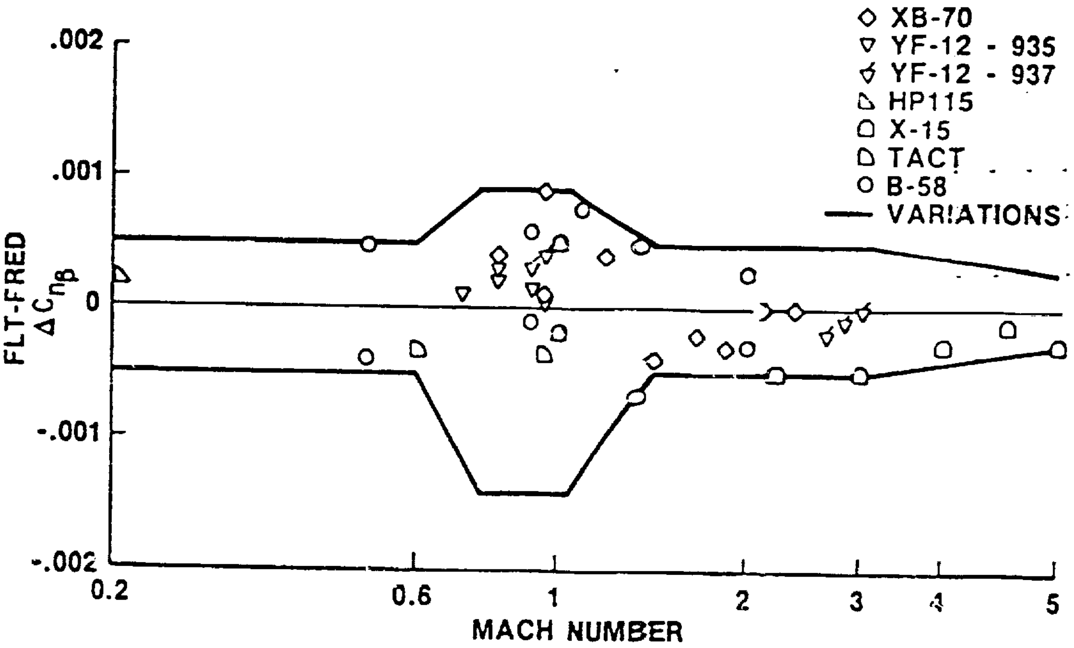


Figure 14.- Correlation of flight and predicted directional stability.

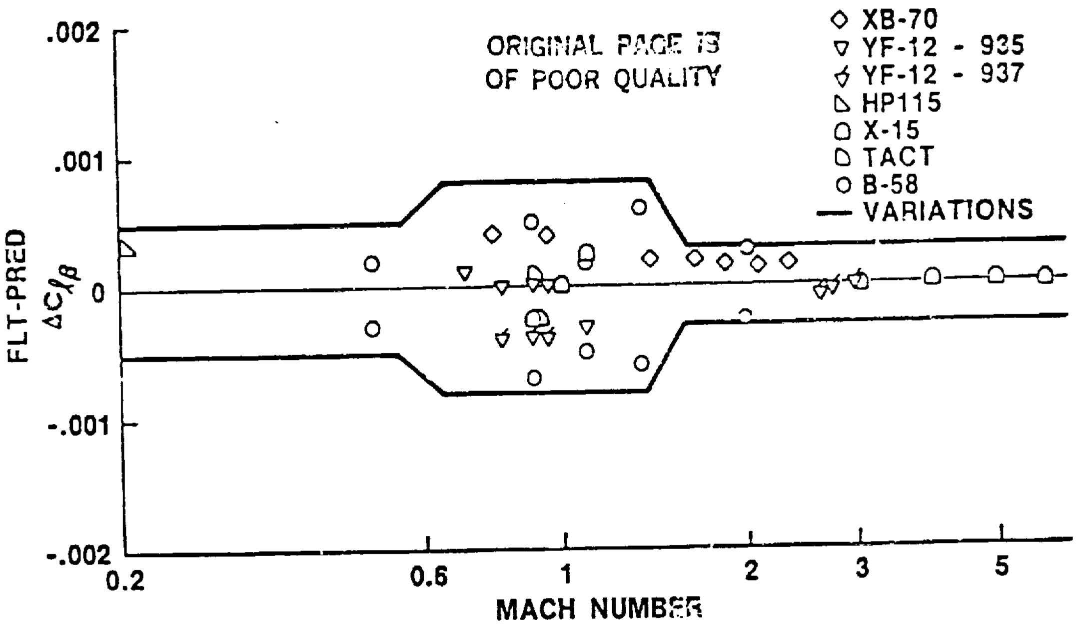


Figure 15.- Correlation of flight and predicted dihedral stability.

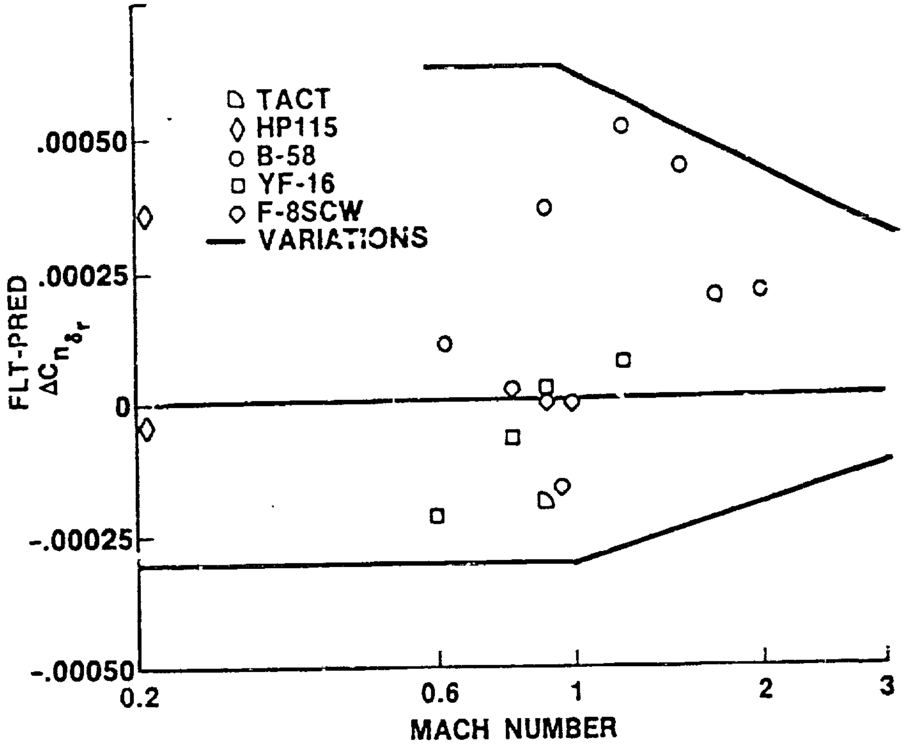


Figure 16.- Correlation of flight and predicted rudder yaw derivatives.

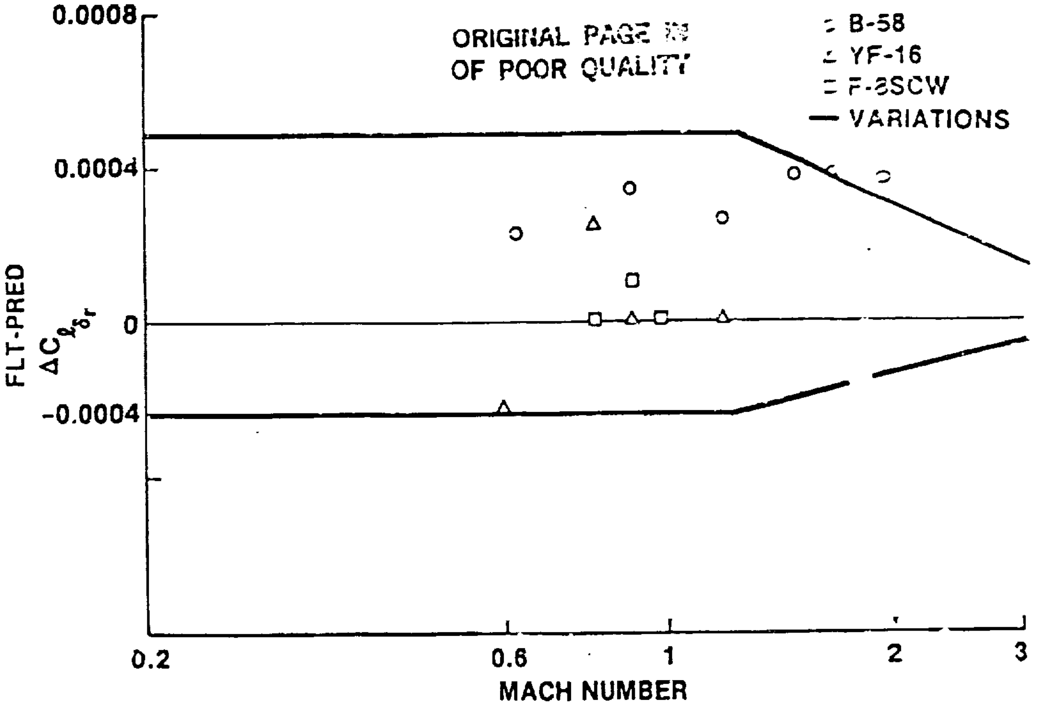


Figure 17.- Correlation of flight and predicted rudder roll derivatives.

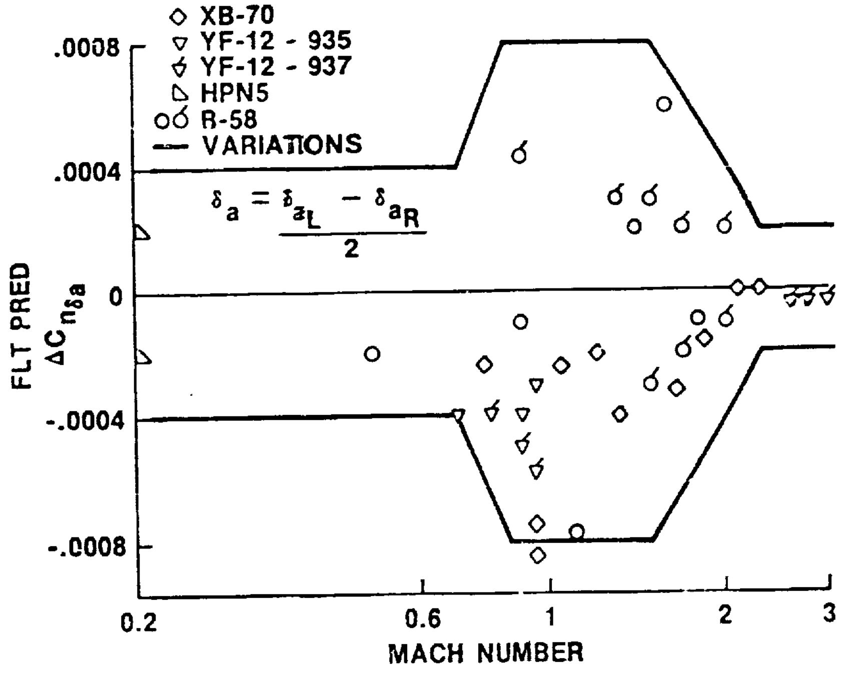


Figure 18.- Correlation of flight and predicted aileron yaw derivatives.

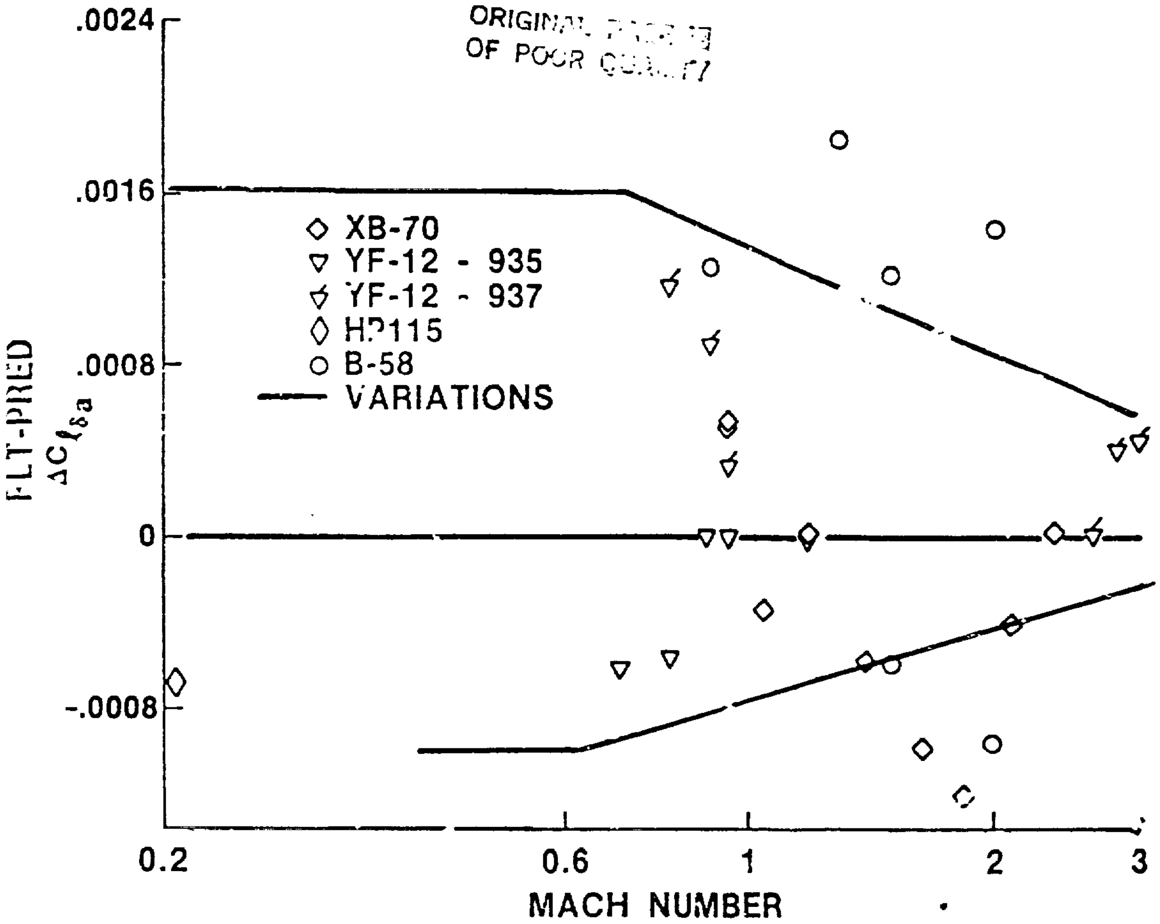


Figure 19.- Correlation of flight and predicted aileron roll derivative.