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Orbiter Approach and Landing Tests—Correlation of Flight and Predicted Performance Data

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The development of modern, conventional aircraft includes an extensive flight test program to verify the predicted flight characteristics and design capabilities. Such flight test programs exercise the aircraft through the full range of its capabilities over a lengthy time span. This paper presents the results of a program in which a flight test vehicle was flown for a limited number of flights. The vehicle was the NASA Space Shuttle Oribiter. The vehicle was configured with a tailcone both on and off during the flight test program; however, the data presented in this paper represents the tailcone-off flights. The total free-flight time for the entire flight test program was less than one-half hour. The flight regime tested represented only the approach and landing phase of the vehicle's planned flight capability. The Space Shuttle Orbiter program relied heavily on an extensive wind-tunnel test program to predict the aerodynamic performance data over the complete flight range, as well as to predict data tolerances. During the flight test program short maneuvers were performed to provide flight motion data. A data extraction program was developed to produce flight-derived aerodynamic performance data in coefficient form from the motion data. The resultant flight test data were correlated with the predicted data and fell within the predicted data tolerances for all phases of the subsonic flight test regime, including ground effects.

Nomenclature

A_x, A_y, A_z	= vehicle translational accelerations, g units
b	= span, ft
C_A	= axial force coefficient
C_D	= drag coefficient
C_L	= lift coefficient
C_ℓ	= rolling moment coefficient
C_m	= pitching moment coefficient
C_n	= yawing moment coefficient
C_N	= normal force coefficient
C_Y	= side force coefficient
$\bar{c}$	= mean aerodynamic chord length, ft
FF	= free flights
I_{xx}, I_{yy}, I_{zz}	= moments of inertia, slug-ft^2
I_{xy}, I_{xz}, I_{yz}	= products of inertia, slug-ft^2
L/D	= lift-to-drag ratio
M	= Mach number
M_x, M_y, M_z	= moments, ft-lb
p, q, r	= vehicle angular rates, rad/s
$\dot{p}, \dot{q}, \dot{r}$	= vehicle angular accelerations, rad/s^2
$\bar{q}$	= dynamic pressure, lb/ft^2
S	= reference area, ft^2
W	= weight, lb
α	= angle of attack, deg
Δ	= incremental data
δ_{BF}	= body flap deflection, deg
δ_e	= elevon deflection, deg
δ_{SB}	= speed brake angle deflection, deg

Subscripts

FLT	= flight data
GE	= ground effect
LG	= landing gear
$PRED$	= predicted data

Introduction

DURING the approach and landing phase, the Space Shuttle Orbiter is a large, unpowered, gliding flight vehicle; therefore, obtaining flight data over a wide range of flight conditions through a conventional extensive flight test program was not feasible. Because of these limitations, an extensive wind-tunnel test program and analysis effort were undertaken to provide specified tolerances, thus insuring that the shuttle vehicle would have acceptable flight characteristics. The flight test phase, limited in altitude to less than 27,000 ft and to low-subsonic speeds, could then be utilized to verify that the subsonic aerodynamic performance predictions were within tolerances and, hence, establish additional confidence in the overall wind-tunnel test program and analysis effort.

The task of obtaining aerodynamic performance data from the flight tests was accomplished through the development of an aerodynamic data extraction program where careful attention was given to techniques, such that usable flight-performance parameters were produced. The aerodynamic performance correlations of flight and predicted data presented herein represent Approach and Landing Test Program flights 4 and 5. The Shuttle Orbiter vehicle was configured with the tailcone off for these flights.

Predicted Data Base

The aerodynamic design data for the Space Shuttle Orbiter vehicle was based on an extensive wind-tunnel testing program and analysis effort. The program was undertaken in order to minimize the requirements for an extensive flight program and was designed to provide confidence in the aerodynamic predictions within specified tolerances to insure the desired flight characteristics of the vehicle. The wind-tunnel testing in the subsonic flight regime was largely done with models of 0.03, 0.0405, and 0.36 scale in facilities such as the Rockwell NAAL low-speed tunnel and the NASA Ames Research Center 40×80 ft tunnel. The test data derived from

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the 0.36 scale model in the Ames 40×80 ft facility is the basic low-speed portion of the predicted data base. These data were tested at the conditions most closely simulating flight Reynolds number and, due to the relatively large scale of this model, unknowns resulting from scale effects were minimized. Ground effects and landing gear incremental data were derived from tests utilizing the 0.0405 scale model in the Rockwell NAAL low-speed tunnel. All testing and analysis results were published as the "Orbiter Aerodynamic Design Data Book" from which all predicted data presented herein are derived.[1]

Flight Data Extraction

The data extraction program utilizes flight data from several sources: the Aerodynamic Coefficient Identification Package (ACIP), the Backup Flight Control System (BFCS), the Operational Instrumentation/Developmental Flight Instrumentation (OI/DFI), and the General Purpose Computer (GPC). The data from each source were recorded onboard for post flight analysis in addition to any other additional function for which the data source was scheduled.

The ACIP data were the only flight data source dedicated to postflight analysis. It consisted of pulse code modulated (PCM) data and supplied the body axes linear accelerations of the vehicle and the angular rates about these axes. The sample rate in the package was 50 samples/s.

The primary purpose of the BFCS was as its name implies: to supply a backup flight control system. As an analysis data source, the BFCS provided angles of attack and sideslip, Mach number, dynamic pressure, and control surface angles at sample rates of 12.5 and 25 samples/s.

The ability to monitor the flight from the ground was furnished by OI/DFI data. This data source provides angular accelerations and control surface positions at sample rates which vary from 25-1 samples/s.

The GPC, in addition to being a postflight data source, was the primary component in the shuttle fly-by-wire avionics. For postflight analysis, the GPC affords another source of angle of attack, dynamic pressure, vehicle attitudes, and true airspeed. These parameters are sampled at a rate of 1/s, with the exception of the vehicle attitudes which are sampled at a rate of 5/s.

The flight information is collected from these several sources by a data management organization (NASA/JSC Test Division personnel) and converted to engineering units. At that point, it is then ready for use by the data extraction program.

Figure 1 is a simplified diagram which illustrates the flow of the data. The raw data are delivered from onboard the vehicle to data management for conversion to engineering units preparatory for distribution to potential users. Loaded into the data extraction program, the data are first transferred from original measurement locations to the appropriate center of gravity as required (an example would be ACIP accelerations from package locations to the center of gravity). The data are then checked to determine if filtering is required and, if so, to what extent. Inspection is also done to discover any time skews or biases requiring correction. The necessary calibrations and corrections are made to the control surface data and angle-of-attack measurements. The control surface data are further summed and averaged to give elevon, aileron, speed brake, and rudder angles. The aerodynamic coefficients are then calculated.

During the onboard recording of the flight data, the nature of the data sampling and the dynamics of the vehicle in-flight make it imperative for the data extraction program to be able to interpolate, filter, and correct for time skews. The interpolation process, which is straight-line interpolation from point to point, is necessary to put all the collected data at a common time base, and interpolate the data to a selected, common sample rate.

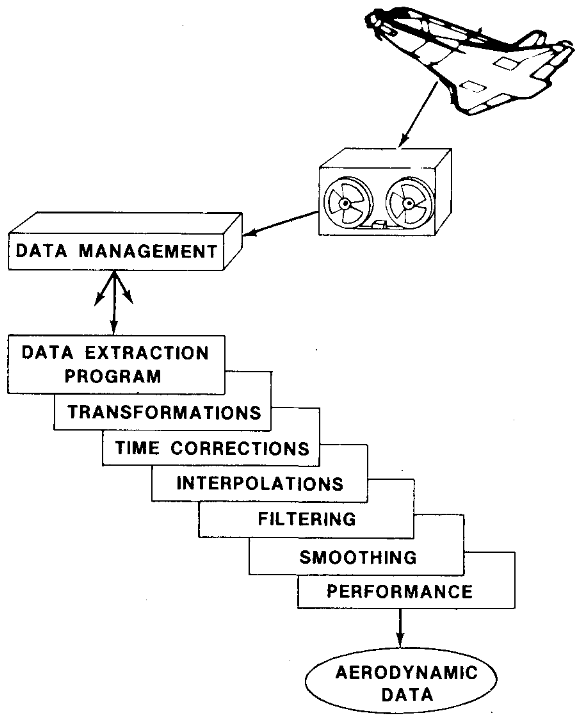

Fig. 1 Simplified diagram of data flow.

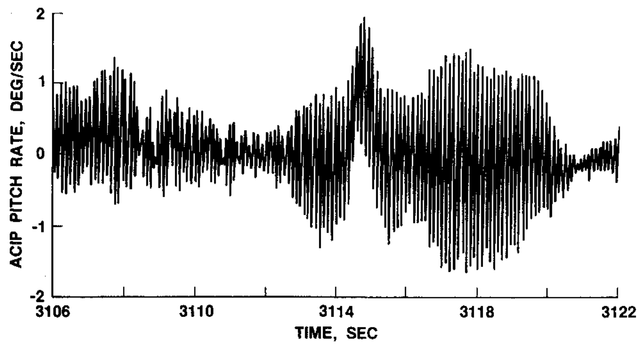

Fig. 2 Unfiltered pitch rate vs time.

Filtering or smoothing of the data is utilized to eliminate any undesired noise in the data. Noise may be the result of structural vibrational modes of a low-frequency noise resulting from the dynamics of controlling the vehicle. In any event, the options exist to either smooth or filter the data. A power spectral density analysis can be done on the parameters to determine their frequency content.[2] From this, a determination of the extent of desired filtering may be made. Figure 2 illustrates the unfiltered pitch rate data from an early flight (flight 1). The apparent high-frequency vibration resulted from a poor mounting of the ACIP in the vehicle for that flight. The power spectral density plot in Fig. 3 indicates the presence of a definite frequency of 5-6 Hz resulting from the structural vibration. It was necessary to remove this to make the data usable for further analysis. The data extraction program contains a Butterworth low-pass filter which was utilized to eliminate that type of noise.[3] To prevent the introduction of a time lag in the data, the data are filtered forward and backward. The result of filtering the pitch rate data with a cutoff frequency of 3 Hz is shown in Fig. 4.

The selection of the cutoff frequency determines the apparent smoothness of the filtered data. A high cutoff frequency eliminates the structural vibration, whereas a much lower frequency reduces dynamic motion to an apparent trim time history. A technique for smoothing flight data found in Ref. 4 provides a similar capability. The amount of

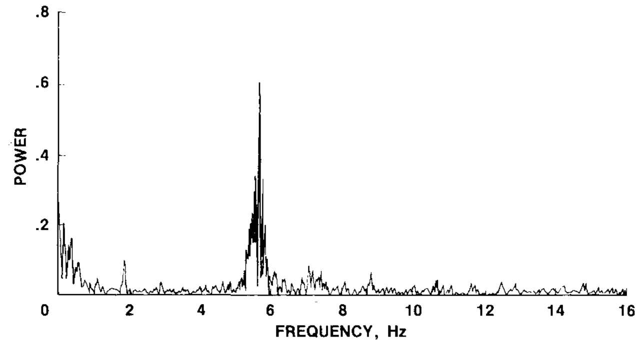

Fig. 3 Power spectral density analysis of pitch rate data.

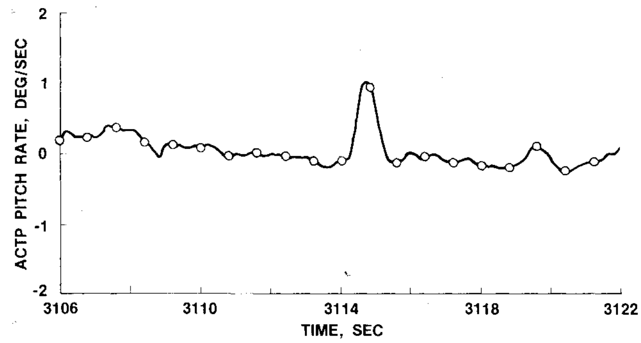

Fig. 4 Filtered pitch rate vs time.

smoothing here is controlled by the number of passes made through the smoothing routine and the number of data points from which the smoothed data pont is obtained.

The inherent nature of the several data sources makes it possible that timing differences or time skews can be present in the data. Since there are alternate sources of some data parameters (such as elevon postion from both the BFCS and the OI/DFI), these time skews can be identified by the program.[5] Once any time skew is located, the correction for it can be made during the interpolation process.

Having completed all the preliminary processing, the flight data are then ready for use in calculating the flight performance parameters. These calculations are performed using the force and moment equations, where the force equations are[6]:

$$C_A = -WA_x/\bar{q}S$$

$$C_Y = WA_y/\bar{q}S$$

$$C_N = WA_z/\bar{q}S$$

and the moment equations are[6]:

$$M_x = \dot{p}I_{xx} - \dot{q}I_{xy} - \dot{r}I_{xz} + q(rI_{zz} - pI_{xz} - qI_{yz}) - r(qI_{yy} - rI_{yz} - pI_{xy})$$

$$M_y = \dot{q}I_{yy} - \dot{r}I_{yz} - \dot{p}I_{xy} + r(pI_{xx} - qI_{xy} - rI_{xz}) - p(rI_{zz} - pI_{xz} - qI_{yz})$$

$$M_z = \dot{r}I_{zz} - \dot{p}I_{yz} + \dot{q}I_{yz} + p(qI_{yy} - rI_{yz} - pI_{xy}) - q(pI_{xx} - qI_{xy} - rI_{xz})$$

$$C_\ell = M_x/\bar{q}Sb \qquad C_m = M_y/\bar{q}S\bar{c} \qquad C_n = M_z/\bar{q}Sb$$

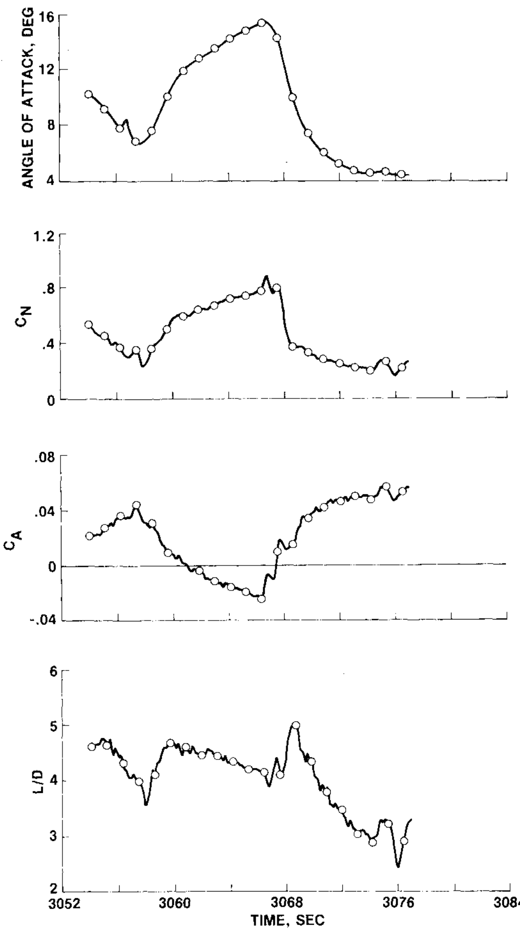

Fig. 5 Calculated performance parameters for flight 4.

An example of the performance parameters derived from free-flight 4 data is seen in Fig. 5. At this point, the analyzed data are ready for comparison with the vehicle's predicted data base.

Aerodynamic Performance Correlations

Flight 4 of the Approach and Landing Test Program included a pullup/pushover maneuver which yielded flight data over an angle-of-attack range of 4.6-15.5 deg. The Mach number, dynamic pressure, and speed brake deflection were near constant throughout the maneuver. The elevon deflection utilized throughout the maneuver was not constant; however, it was possible to select flight data points at an elevon deflection of 4.5 deg for analysis purposes. The vehicle was in the tailcone-off configuration shown in Fig. 6 for both flights 4 and 5. Data presented herein will represent those flights only.

Predicted data were generated for given flight attitudes, Mach numbers, and control surface deflections through the use of an aerodynamic data analysis program. The predicted aerodynamic data base of Ref. 1 has been digitized and stored on computer files, and the aerodynamic data analysis program is utilized to extract the predicted data of the specific flight parameters and control surface deflections corresponding to a given flight data point.

The flight and predicted normal force coefficient against axial force coefficient comparison shown in Fig. 7 confirms the basic aerodynamic performance. Since flight normal and axial force coefficients are derived directly from the previously mentioned ACIP package, such a comparison does not require knowing angle of attack and is independent of any unknowns in angle of attack. Flight angle-of-attack uncertainties become apparent in Figs. 8 and 9 in that the angle

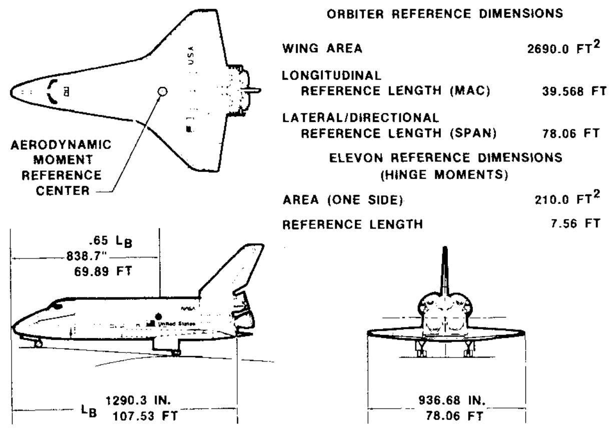

Fig. 6 Space Shuttle Orbiter configuration.

ORBITER CONDITIONS:
MACH NUMBER (M) = 0.4
ANGLE OF ATTACK (α), DEG = 4.6→15.4
ELEVON DEFLECTION (δ_e), DEG = 4.5
SPEED BRAKE DEFLECTION (δ_{SB}), DEG = 3.7
BODY FLAP DEFLECTION (δ_{BF}), DEG = 0

FLIGHT DATA:
△ FF-4 (PULL UP/PUSHOVER)
□ FF-5

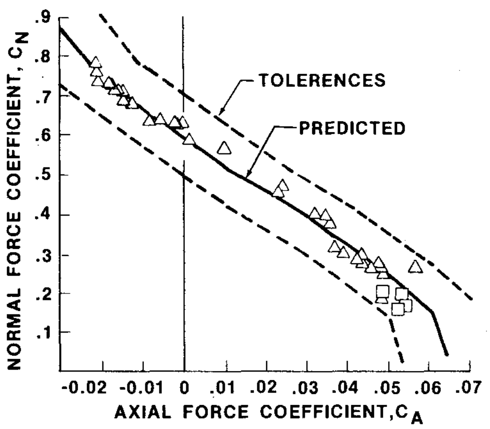

Fig. 7 Comparison of flight and predicted basic aerodynamic performance.

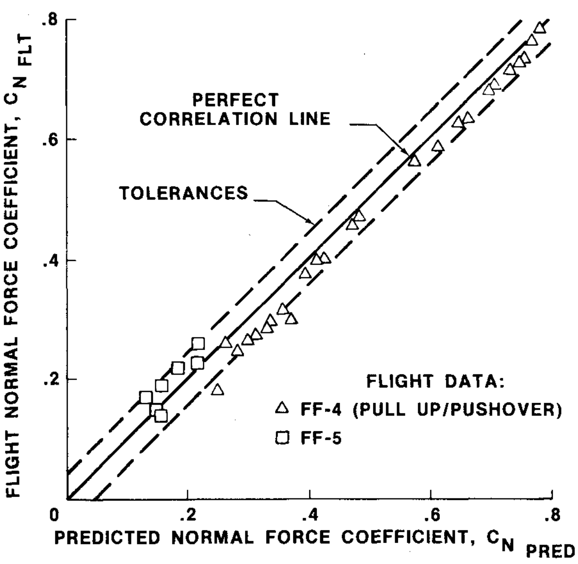

Fig. 8 Flight vs predicted normal force coefficient.

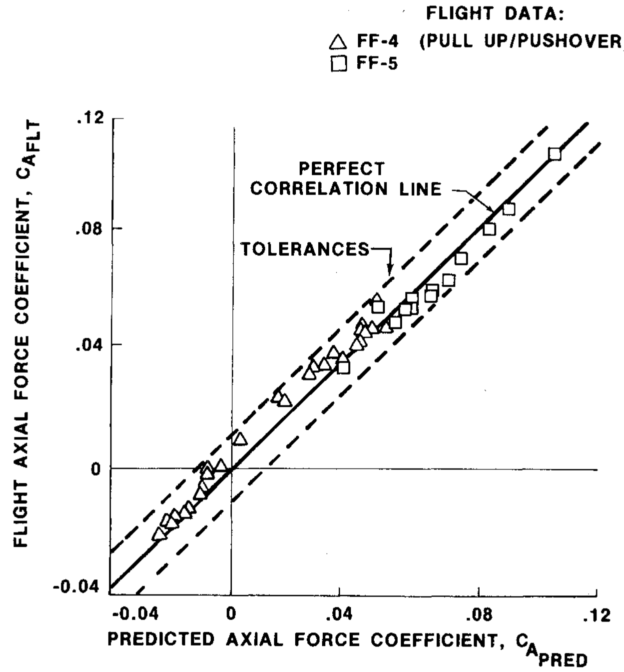

Fig. 9 Flight vs predicted axial force coefficient.

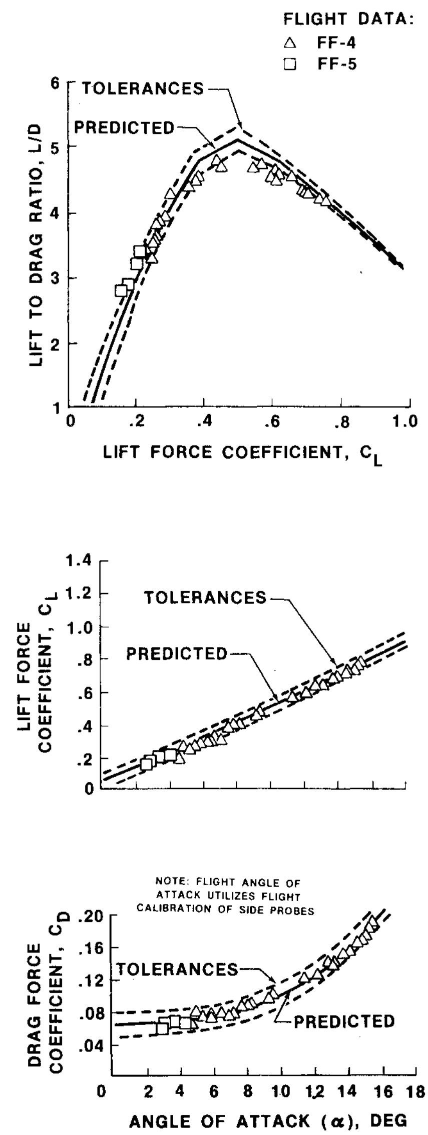

Fig. 10 Stability axis data.

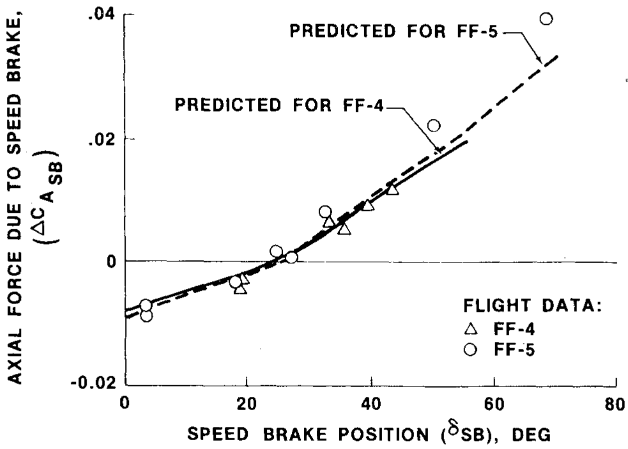

Fig. 11 Speed brake effectiveness.

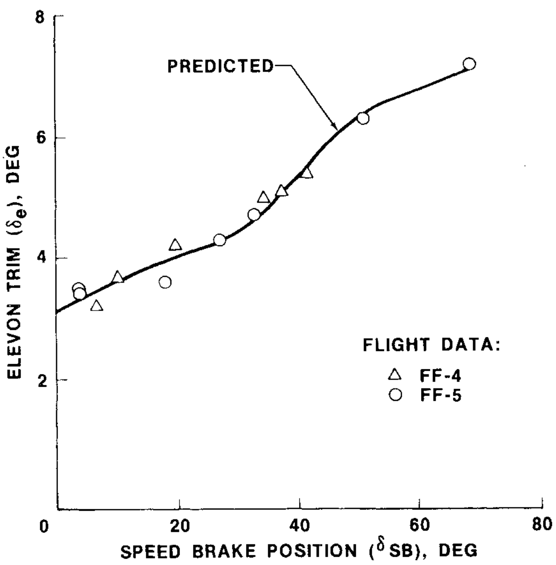

Fig. 12 Elevon trim against speed brake deflection.

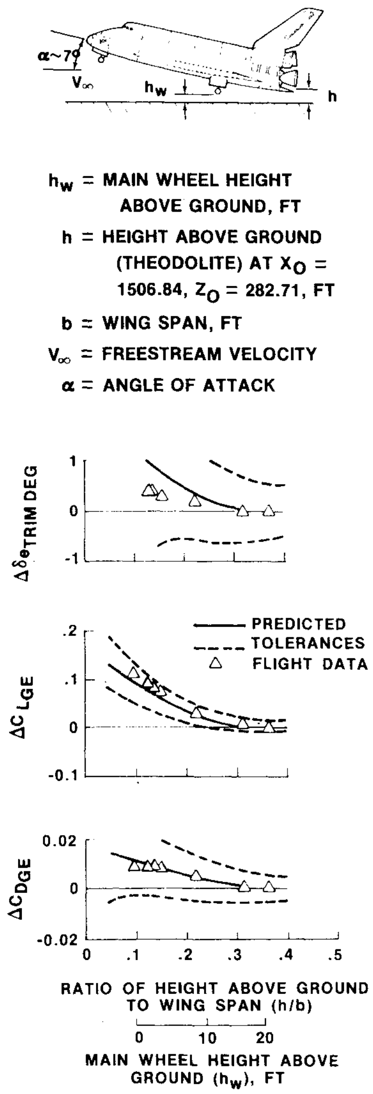

Fig. 13 Free-flight 4 ground effects.

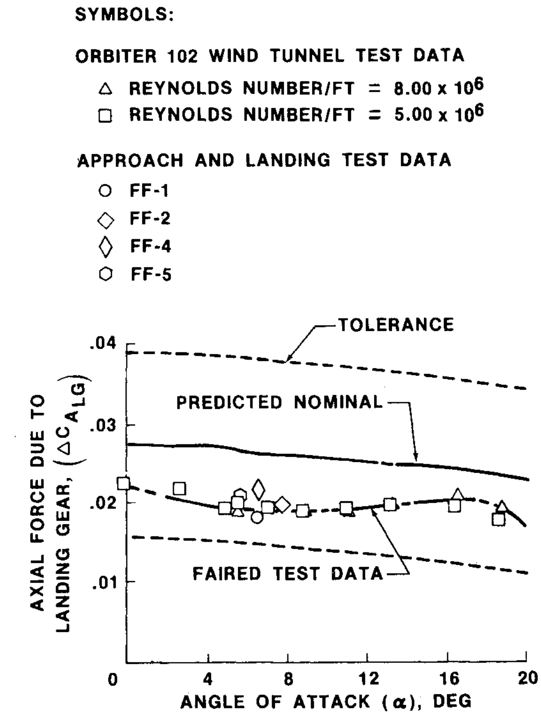

Fig. 14 Axial force due to landing gear.

of attack is required for predicted lookup, and further affects the stability axis data (Fig. 10) through the transformation process from body axis to stability axis. However, the majority of the stability axis data, even with the angle-of-attack unknowns, are within the predicted tolerances.

The comparisons of speed brake axial force effectiveness from both flights 4 and 5 are shown in Fig. 11 and confirm the predicted effectiveness. Excellent correlation of flight and predicted elevon trim deflection against speed brake deflection is indicated in Fig. 12.

An area of concern which has been verified by the flight data is ground effects. The lift and drag coefficients are presented in Fig. 13 as incremental change due to the presence of the ground against height of the vehicle above the ground. The height above ground is presented as both height of main landing gear wheels and height of a reference point on the aft fuselage nondimensionalized by the vehicle span. Both incremental lift and drag coefficients from flight data are well within the predicted data tolerances. The ground effects on pitching moment appear to have been overpredicted, as indicated by the change in elevon deflection required to trim shown in Fig. 13. Preflight predictions indicated an increasing nose-up moment as height above the ground decreased, which is indicated by both flight and predicted elevon requirements for a more positive, or trailing-edge down, deflection. Although flight data indicate less elevon deflection required than predicted, the results are well within the predicted data tolerances.

Estimates of flight landing gear axial force and drag indicate that the incremental effect of landing gear was overpredicted, probably due to not correcting the low-speed, low-Reynolds number wind-tunnel test results to flight Reynolds number conditions. A postflight wind-tunnel test was conducted utilizing a large (0.05 scale), high-fidelity scale model at a high Reynolds number. The results of that test are shown in Fig. 14 and agree well with the landing gear axial force and drag coefficients as derived from the Approach and Landing Test flights.

Conclusions

The Space Shuttle Orbiter vehicle was flown with the tailcone off in flights 4 and 5 of the Approach and Landing Test Program. Based on preliminary flight-derived aerodynamic performance data, the correlations of flight data with predicted data indicate flight data are within the predicted data tolerances, including ground effects. The flight-derived landing gear axial force and drag indicate that the incremental effect of the landing gear was overpredicted, probably due to not correcting the low-speed, low-Reynolds number wind-tunnel results to flight conditions.

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