HYFLEXの空力特性評価

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HYFLEXの飛行実験において取得された空力特性データと風洞試験およびCFDに基づく予測値を比較することにより、HYFLEXにおいて使用した空力特性予測手法の妥当性を評価する。本稿が対象とするのは、空力係数、縦トリム特性、エレボン・ヒンジモーメントと機体表面圧力分布である。飛行試験と予測値の比較の結果、HYFLEXの空力設計において適用した空力特性予測手法は、全般的に妥当なものであることが検証された。しかし、軸力係数、トリム舵角等については、予測値と飛行結果の間に設計で考慮したUncertainty以上の差異が見られたため、その原因について考察した。

EVALUATION OF HYFLEX AERODYNAMIC CHARACTERISTICS

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HYFLEX - Hypersonic Flight Experiment which was planned for the development of the Japanese unmanned orbiting plane, HOPE, was successfully conducted on Feb. 12, 1996. In this paper, the following flight data in respect to aerodynamic characteristics are presented: aerodynamic force coefficients, longitudinal trim characteristics, elevon hinge moment, and surface pressure distribution. The data are compared with the preflight predictions based on wind tunnel test results and CFD calculations in order to investigate validity of the prediction methods. Through the comparisons, the prediction methods used in the HYFLEX vehicle design are proved to be generally valid while some discrepancies are found in axial force and elevon trim angle.

INTRODUCTION

The HYFLEX project [1] was planned as one of a series of small-scale experimental vehicles for the development of the Japanese unmanned orbiting plane, HOPE. It has been progressed since 1992 as a joint work between National Aerospace Laboratory (NAL) and National Space Development Agency of Japan (NASDA). The purpose of the project is to experience design, manufacturing, and flight of hypersonic lifting vehicle and to acquire hypersonic flight data on aerodynamics, thermal protection system, and guidance and control.

The experiment was successfully performed on Feb.12, 1996 whose trajectory agreed well with the nominal one designed in the final design phase [2]. It suggests that prediction methods of aerodynamic characteristics in the vehicle design are fairly valid. Many flight data were transmitted by telemetry to the ground with almost no problems during the entry flight. In respect to aerodynamics, data categorized below were gathered :

(1) aerodynamic force and moment
(2) stability and control derivatives including aerodynamic effectiveness of aerodynamic control surface called 'elevon'
(3) elevon hinge moment
(4) surface pressure distribution
(5) aerodynamic heating distribution
(6) gas-jet interaction of experimental RCS thrusters located on side stabilizing fins

In this paper, the flight data included in the categories from (1) to (4) are presented in super- to hypersonic speed range, compared with the preflight predictions based on wind tunnel test results and CFD calculations conducted prior to or after the flight.

PREFLIGHT PREDICTION METHOD

To predict aerodynamic characteristics of the HYFLEX vehicle, wind tunnel tests and CFD calculations were performed for the flight configuration, HRV03-540, shown in Fig. 1 and the previous configuration, HRV03-530. Though HRV03-530 is without a forebody upper surface bulge, effects of the configuration difference on aerodynamic characteristics were assumed to be negligible. Reference dimensions to nondimensionalize the measured aerodynamic characteristics are shown in Table 1.

Six-components of aerodynamic force and moment and stability and control derivatives were predicted on the basis of the wind tunnel test results covering Mach number range of the HYFLEX flight. Hinge moments of elevons and surface pressure were also measured in the tests.

On the other hand, the CFD calculations using a Navier-Stokes code were conducted to confirm validity of the wind tunnel test results and to know surface pressure distribution for the design of the vehicle structure.

Data in five wind tunnels were used for aerodynamic characteristics prediction of the flight vehicle configuration and post-flight comparison with the flight data. Test ranges which are covered by the tests are compared with the actual flight range of HYFLEX in Fig. 2. It can be seen that the tests almost cover the flight range of Mach number, Reynolds number, and angle of attack. To acquire force and moment data in hypersonic speed range, the ONERA S4MA hypersonic wind tunnel in France was used. The data was confirmed by Newtonian flow calculations and CFD. The NAL 1.27m hypersonic wind tunnel was also used to measure surface pressure distribution after the flight.

Three wind tunnels in Japan were used for investigating supersonic characteristics: the high-speed wind tunnel in the Fuji Heavy Industries (FHI), the supersonic wind tunnel in the Institute of Space and Astronautical Science (ISAS), and the NAL supersonic wind tunnel. The data were compared with each other to certify data correctness.

In the case of Space Shuttle [3], in order to define uncertainty of the predicted value, many wind tunnel tests for the orbiter were conducted in many different wind tunnels. As the result, "tolerance" which means variation of data among different wind tunnels are determined. Wind tunnel data and flight data for some aircraft in the past were also extensively examined, leading to "variation" which means effects on aerodynamics due to difference between wind tunnel condition and flight condition. In the case of HYFLEX, we use "measurement error" of each individual wind tunnel in place of "tolerance". It is because only one or two tunnels were used for a speed range for the HYFLEX vehicle development. The "measurement error" consists of a force balance error, wind tunnel freestream condition errors, an error due to misalignment of model, repeatability, and so forth.

As Japan did not have any flight data of lifting hypersonic vehicles in the past, "variation" for HYFLEX are estimated on the basis of the space shuttle "variation", taking account of differences in reference area and reference lengths between the HYFLEX vehicle and the Space Shuttle Orbiter. Uncertainty of the prediction is defined as a root sum square of the "measurement error" and the "variation".

REDUCTION OF FLIGHT DATA

Aerodynamic force coefficients are directly reduced from three-axis acceleration data measured by three accelerometers installed in an onboard inertial measurement unit (IMU).

To measure hinge moments of both elevons, strain gages are installed on elevon-actuating link rods. Based on the stress outputs, the moments around elevon hinges are reduced. Hinge moments due to aerodynamic force are extracted with correction of vehicle acceleration effects. It should be noted the effect is significant because acceleration normal to the vehicle axis reaches 5.6g during the entry flight.

As shown in Fig. 3, surface pressure is measured at 29 points located on the whole vehicle surface exclusive of elevon surface. Data at 8 points of them are to know general surface pressure distribution on the body while the remains are for Air data sensor (ADS) and RCS gas-jet interaction experiment [4].

Atmospheric properties for nondimensionalizing the measured aerodynamic force and moment are estimated from remote sensing temperature data obtained by the NOAA Polar-Orbiting Satellite on the day of the flight. The estimation method were validated four times before the flight in comparison with data of the sounding rockets in the Tohoku area of Japan. The results show that root mean square of the differences in pressure and temperature are less than 3 % and 10 K, respectively below an altitude of 55 km.

COMPARISONS OF FLIGHT DATA WITH PREFLIGHT PREDICTIONS

Aerodynamic Force Coefficients and Longitudinal Trim

Figure 4 shows comparisons of normal force coefficient, C_N and axial force coefficient, C_A between the flight data and the predictions.

Through the whole flight Mach range, the flight C_N agrees very well with the prediction. The flight C_A is greater than the prediction below Mach 5 and above Mach 12. The discrepancy in the high Mach number range seems to be viscous interaction effect as observed in the Space Shuttle flight [5-6]. Figure 5 shows a predicted C_A with the viscous interaction effect correction which is proposed for the Space Shuttle Orbiter [6]. It should be noted that the prediction with the viscous effect correction agrees well with the flight data in spite of the configuration difference between the HYFLEX vehicle and the Space shuttle Orbiter.

The C_A difference below Mach 5 is caused by a use of a unsuitable prediction method of base drag for HYFLEX. In the prediction, C_A is obtained as a sum of forebody drag based on the wind tunnel test data and base drag estimated from a base pressure correlation based on turbulent axisymmetric body experiments in the past [7]. Figure 6 shows a comparison of base pressure coefficient among the flight, the prediction, and the wind tunnel tests. It can be found that the predicted base pressure is too high relative to the wind tunnel test data even if considering sting support interference effects. It indicates limitation of the base pressure prediction method based on cone, cylinder, and ogive data with zero angle of attack. If the base pressure measured in the wind tunnel tests is used for prediction, agreement between the flight and the prediction becomes better as seen in Fig. 4 (b).

Figure 7 shows a comparison of lift-to-drag ratio, L/D. In the case using the wind tunnel base pressure, agreement between the flight and the prediction is almost good below Mach 12 while flight L/D is a little smaller than the prediction from Mach 3 to 8.

Elevon deflection angle as elevators, δe, for longitudinal trim is shown in Fig. 8. In this case, the uncertainty shown includes both effects of pitching moment coefficient uncertainty and uncertainty of the center of gravity (see Table 1). In a supersonic speed range and above Mach 8, flight δe is lower - that is, the upward deflection - than the prediction by maximum 3 deg. The cause is not known at this time while some reasons such as sting support interference are being investigated.

Elevon Hinge Moments

Elevon hinge moment coefficients of both elevons are presented in Fig. 9. Agreement between the flight data and the prediction is good, especially above Mach 5. It should be noted that Mach number effects on hinge moment are very small above Mach 5 because the prediction based on the test data at Mach 9.9 is valid in the entire Mach number range.

Surface Pressure

Surface pressure on middle of the lower body surface, PS23 and 24, are shown in Fig. 10. Prediction by the wind tunnel test in NAL SWT and CFD calculations is almost reasonable while resolution of the flight-measured pressure is insufficient, especially in a supersonic speed range.

CONCLUDING REMARKS

Some comparisons of the HYFLEX aerodynamic characteristics between the flight data and the predictions are presented. The results indicate that the prediction methods based on wind tunnel test results and CFD calculations are generally valid for hypersonic high-angle-of-attack vehicle design. However, some discrepancies are found in axial force and elevon trim angle. The cause of them will be investigated in detail, and the experience should be utilized in the future design of HOPE-X and HOPE.

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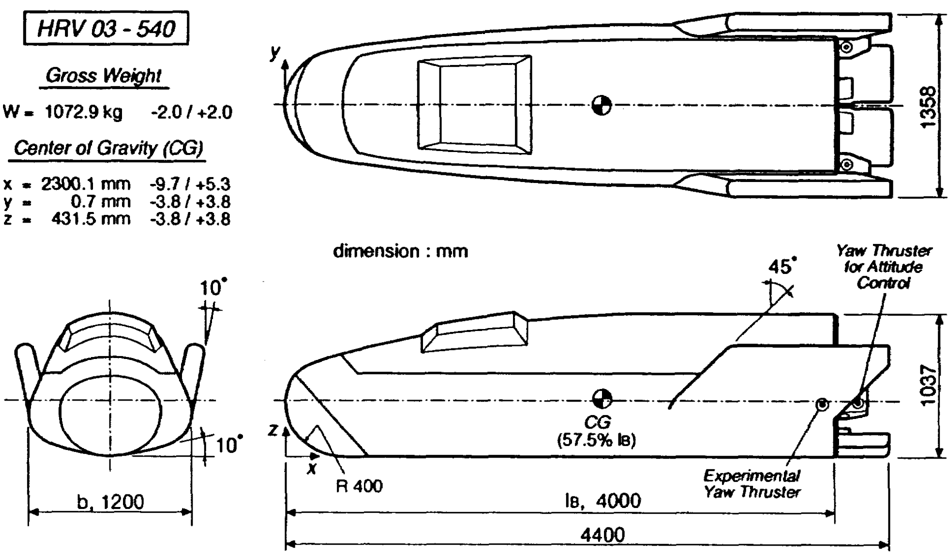
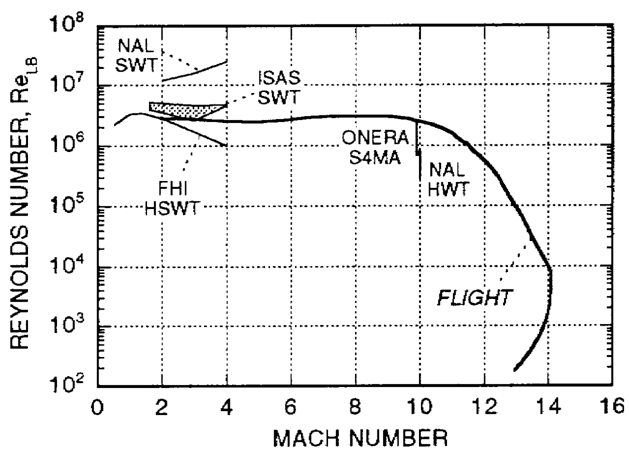


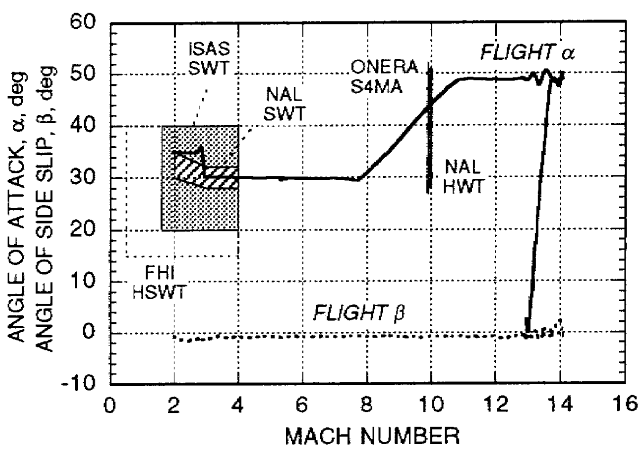
Fig. 1 HYFLEX vehicle configuration.

Table 1 Reference dimensions of HYFLEX vehicle.

Reference area (Planform area), S	4.270 m ^{2}
Body base area, S_B	0.931 m ^{2}
Longitudinal reference length (Body length), l_B	4.000 m
Lateral / directional reference length (Body width), b	1.200 m
Moment reference center (CG),	
x_{CG} (57.5% l_B)	2.3001 m
y_{CG}	0.0007 m
z_{CG}	0.4315 m
Reference area for hinge moment, S_e	0.1677 m ^{2}
Reference length for hinge moment, l_e	0.400 m
Moment reference center of hinge moment, x_{HG}	4.025 m



(a) Freestream Reynolds number.



(b) Angle of attack and side-slip angle.

Fig. 2 Flight condition and vehicle attitude.

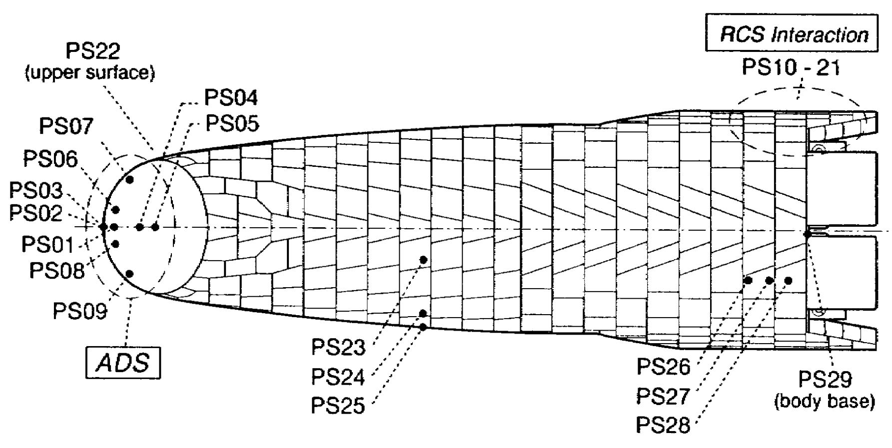
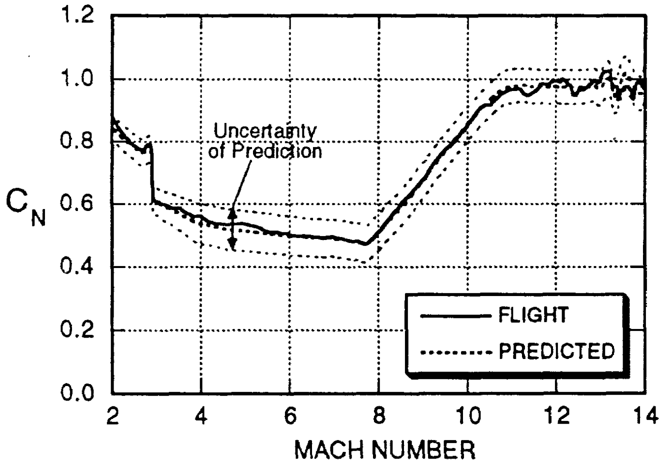
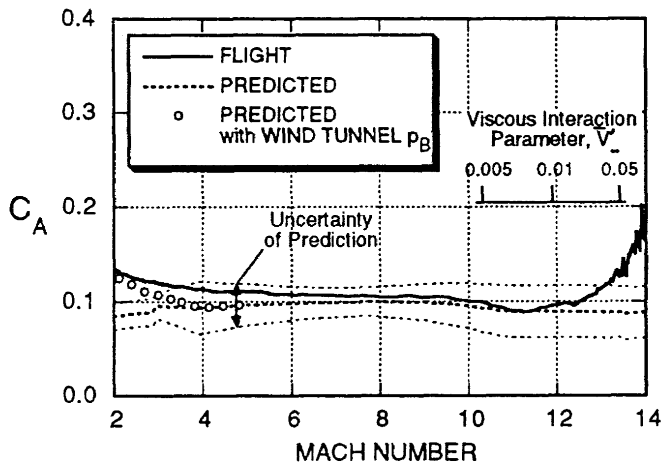


Fig. 3 Location of surface pressure measurement ports.



(a) Normal force coefficient.



(b) Axial force coefficient.

Fig. 4 Longitudinal force coefficients comparison.

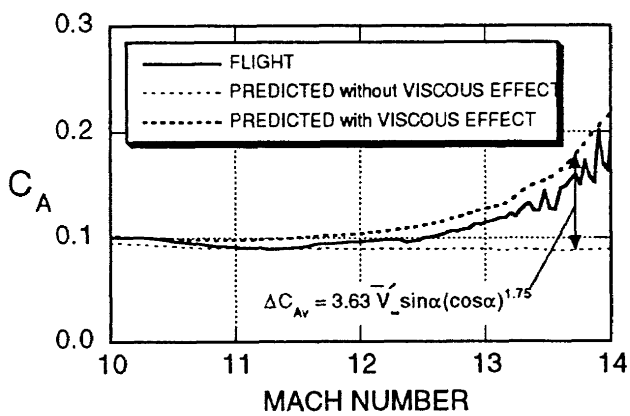


Fig. 5 Viscous interaction effects on axial force coefficients.

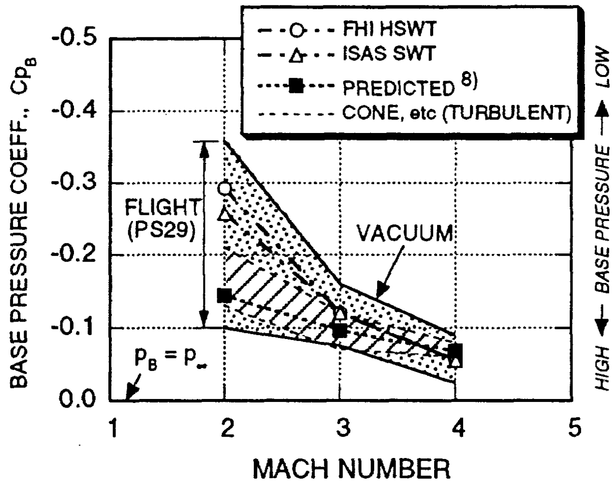


Fig. 6 Base pressure comparison among flight, wind tunnel test and prediction.

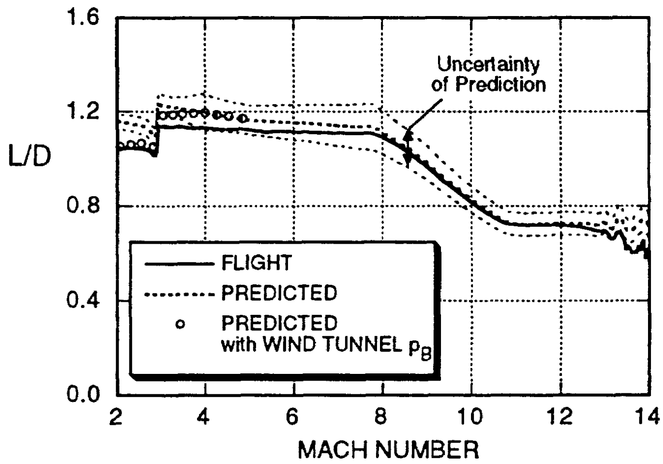


Fig. 7 Lift-to-drag ratio comparison.

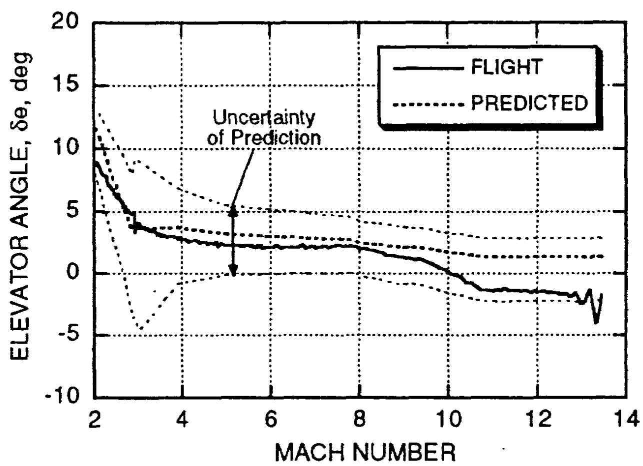


Fig. 8 Longitudinal trim comparison.

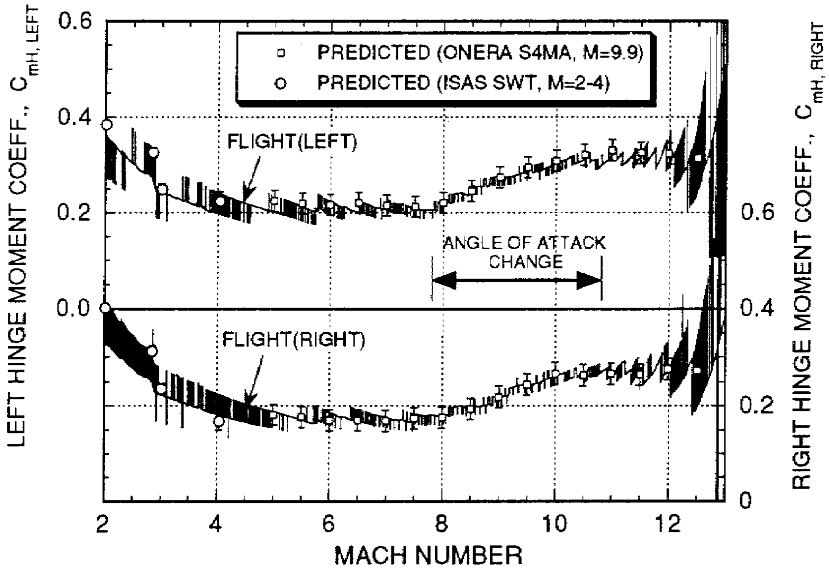


Fig. 9 Elevon hinge moment comparison.

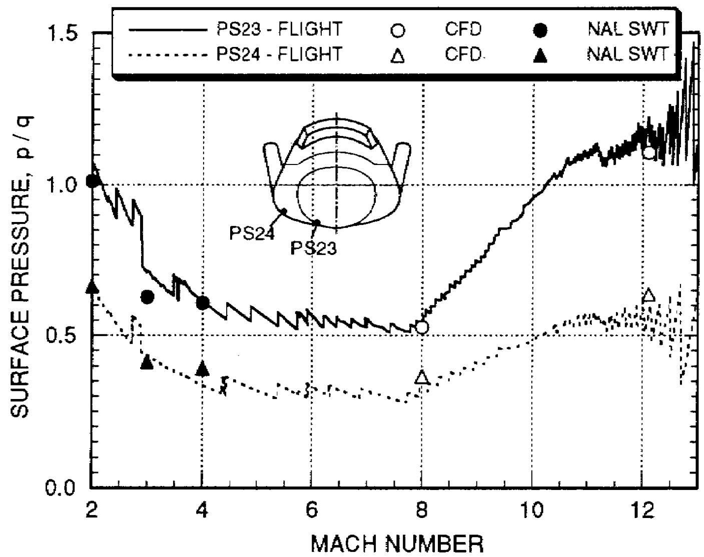


Fig. 10 Body lower surface pressure comparison.