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Wind tunnel test comparison between JAXA-HIEST and ONERA-S4MA with HYFLEX lifting-body

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Abstract
Hypersonic aerodynamic characteristics of a lifting body were measured in the free-piston driven shock tunnel JAXA-HIEST. The novel three-component force-measurement technique "Free-flight in wind tunnel" was implemented, which enables high-precision multi-component force measurement within the short test duration on the order of milliseconds. The test model was a 10%-scaled HYFLEX Japanese lifting body reentry vehicle, which had successful reentry test flight in 1997. During the test campaign, the model angle of attack was varied from 30 to 50 degrees with elevon (body flap) deflection angle of 0 degrees and 20 degrees. To evaluate the measurement uncertainties of the present free-flight technique, the comparison was conducted on the aerodynamic coefficients obtained with the conventional force-balance technique in the blow-down type Hypersonic wind tunnel ONERA-S4MA. The comparison revealed that the drag, lift and the lift-drag ratio agreed quite well with both measurements above. However, a significant difference of pitching moment characteristics, especially on trim angle was detected at a flap deflection of 0 degrees.

1. Introduction

Since 1998, JAXA-Kakuda has been operating the free-piston high-enthalpy shock tunnel HIEST (Fig. 1) [1]. One of the primary aim of the facility is a production of high-fidelity aerothermodynamic data for design of lifting reentry vehicles. Although high-enthalpy impulsive facilities can duplicate high-temperature real-gas flow, their short test duration was a serious drawback for aerodynamic force measurement. During a decade of research on new force measurement techniques in HIEST, a new free-flight technique we successfully developed in JAXA Kakuda Space Center [2]. The free-flight (or free-fall) technique, which involved the test model being completely non-restrained for that short test duration, is based on onboard instruments instead of conventional optical tracking techniques. Through a previous three-component force measurement test campaign [3] with a cone model, the technique showed its high measurement precision even for the pithing coefficient, which is more difficult to measure than drag or lift coefficient. In this work, this free-flight force measurement technique was applied to the aerodynamic test campaign of a lifting body reentry vehicle in HIEST. A Japanese lifting body vehicle HYFLEX [4], was selected as the test model, which vehicle successfully performed Hypersonic gliding flight in 1997. Drag, lift and pitching moment coefficients were obtained under the following two test flow condition; (1) perfect gas condition and (2) high-temperature real-gas condition. Moreover, the measurement precision of the present free-flight technique was also estimated, followed by the discussion of the measurement accuracy comparing with the conventional blow-down Hypersonic wind tunnel ONERA-S4MA.

Figure 1: Free-piston high-enthalpy shock tunnel HIEST

2. Free-flight force measurement technique for shock tunnel

Instead of the conventional free-flight optical-tracking technique described by Bernstein [5], a new technique in HIEST is based on an on-board acceleration measurement system. In the technique, test models are released from a magnetic holder installed on the wind-tunnel ceiling so that it lies in the nozzle core synchronized with the arrival of the test flow. Thus, throughout the entire test, the model is completely

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unrestrained by any support system and is not interfered with aerodynamically or mechanically. For a comparatively heavy model can be used using this technique, variation in model position and attitude can be virtually eliminated during the test period even high free-stream dynamic pressure in HIEST. Moreover, acceleration measurement accuracy can be ensured with on-board accelerometers, the outputs of which were stored on an on-board miniature data recorder. After the termination of the test flow, the model falls into a soft-landing system placed on the floor, enabling the model and instruments to be reused. This sequence of events is shown in Fig.2.

2.1 Free-flight test model

The HYFLEX is a Japanese lifting body reentry test vehicle, which successfully conducted Hypersonic flight in 1996. The special feature of the HYFLEX test flight was a Hypersonic maneuver with two elevons aft of the fuselage. The flight data was the unique benchmark for the uncertainty analysis of the present force measurement technique in HIEST. For this test campaign, a 1:10 scale HYFLEX model was manufactured as shown in Fig.3. The specifications of the model are described in Table 1. In the table, the moment of inertia around y-axis *Iyy* is an important parameter for the measurement accuracy of pitching moment. Two-support wires torsional pendulum method was applied to determine the *Iyy* of the HYFLEX model.
In the free-flight technique in HIEST, two electromagnets were used to hold and release the model. The model was thus made of SUS420 magnetic stainless steel, which suits to increase the model weight. Inside a model, three JAXA in-house data recorders and 16 miniature Piezoelectric type accelerometers (PCB352A07) are on-board, with which the aerodynamic force applied to the model is measured as acceleration. Furthermore, in order to measure model surface pressure, eight high-speed Piezo-resistive pressure transducers (Kulite XCQ-093) were instrumented. In the whole wind tunnel test, the elevon (body flap) deflection angle was fixed to 0 degrees or 20 degrees. The angle of attack of the model was varied from 30 to 50 degrees.

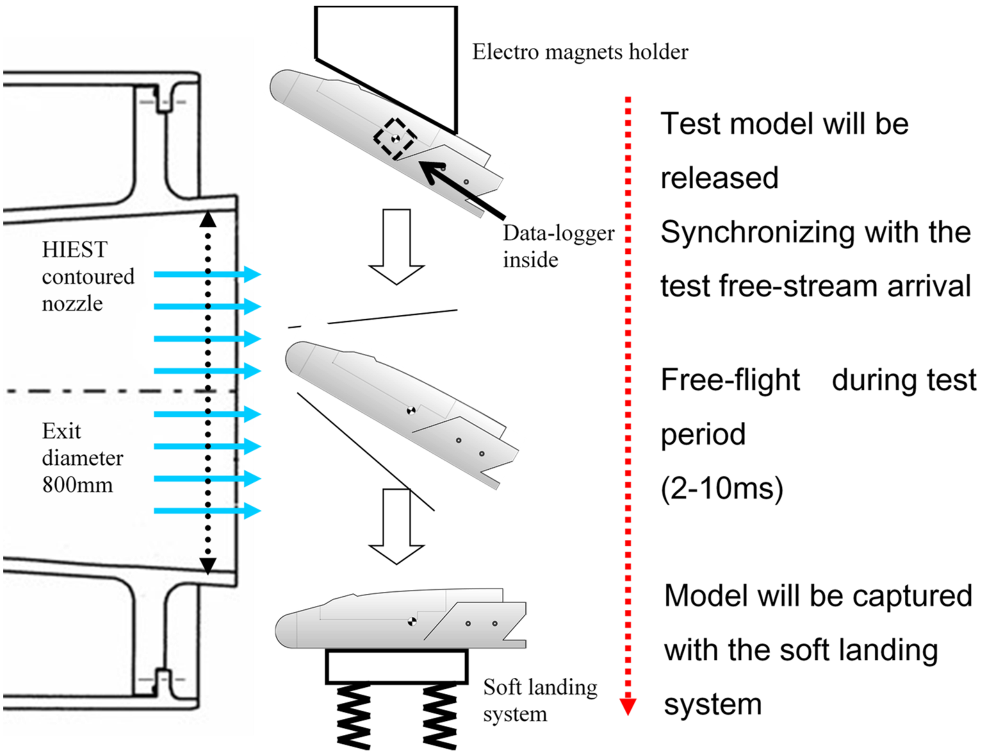

Figure 2: Sequence of events in the free-flight technique

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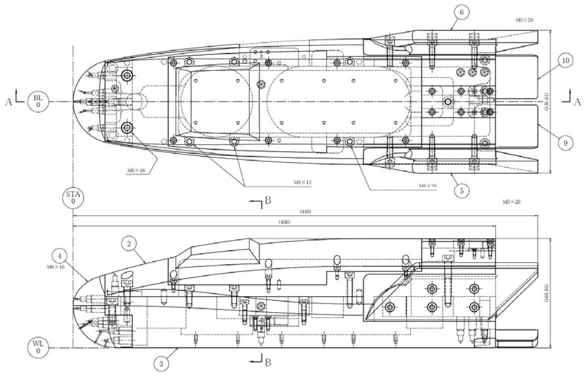

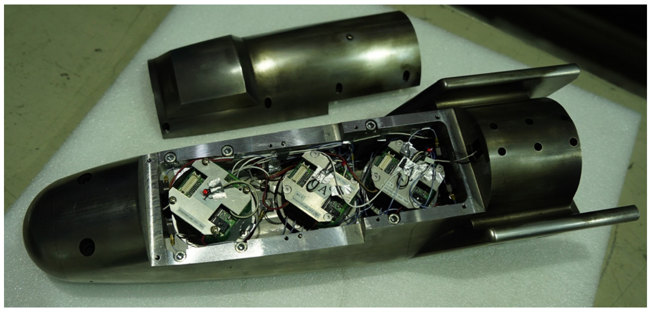

Figure 3: Schematic of HYFLEX free-flight test model (Left). Three data recorders instrumented in the HYFLEX free-flight model (Right).

Table 1: Specification of HYFLEX 1:10 scale model

Total mass (including sensors and data recorders)	16.78kg
Total length	0.440 m
Moment of inertia Iyy	0.226 kgm^2
Centre of gravity X_G (from the nose tip)	0.241 m
Centre of gravity Y_G (from the bottom surface)	0.0463 m

2.2 Free-stream test condition

In the HIEST present test campaign, two free-stream test conditions were selected: low enthalpy conditions (H_0=3MJ/kg) and high enthalpy conditions (H_0=14MJ/kg). The first test condition was perfect gas condition and the second one was high-temperature real-gas conditions, under which condition approximately 40% of oxygen molecules were dissociated. Both free-stream conditions, shown in Table 2, which conditions were obtained through calculation with the one-dimensional thermochemical non-equilibrium nozzle code [6,7]. As shown in the Table, the free-stream condition in the conventional Hypersonic blow-down wind tunnel ONERA S4MA was also tabulated as the reference condition. The HYFLEX force measurement test campaign in ONERA S4MA was conducted 20 years ago [8], which measurement results were mainly used for the aerodynamic design of HYFLEX because there was not available Hypersonic wind tunnels in Japan. In this study, the ONERA S4MA results were used to evaluate free-flight force measurement technique in HIEST.

Table 2: HIEST test free stream condition

Facilities	HIEST low H_0	HIEST High H_0	ONERA S4MA
Condition	Perfect gas	Real gas	Reference
Stagnation temperature (K)	$3.0x10^3$	$7.3 x10^3$	$1.1 x10^3$
Stagnation pressure (MPa)	16	32	6.1
Stagnation enthalpy (MJ/kg)	3.7	13.6	N.A.
Static temperature (K)	$2.8x10^2$	$1.4 x10^3$	$5.5 x10^1$
Static pressure (kPa)	1.3	4.7	$1.7x10^{-1}$
Free-stream density (kg/m^3)	$1.6x10^{-2}$	$1.1x10^{-2}$	$1.1x10^{-2}$
Free-stream velocity (km/s)	2.6	4.7	1.5
Free-stream Mach number	7.6	6.0	9.7
Free-stream Unit Reynolds number (1/m)	$2.4x10^6$	$1.0 x10^6$	$8.7 x10^5$
O mass fraction	$3.3x10^{-4}$	$6.9x10^{-2}$	N.A.
O_2 mass fraction	$2.1x10^{-1}$	$1.4x10^{-1}$	N.A.

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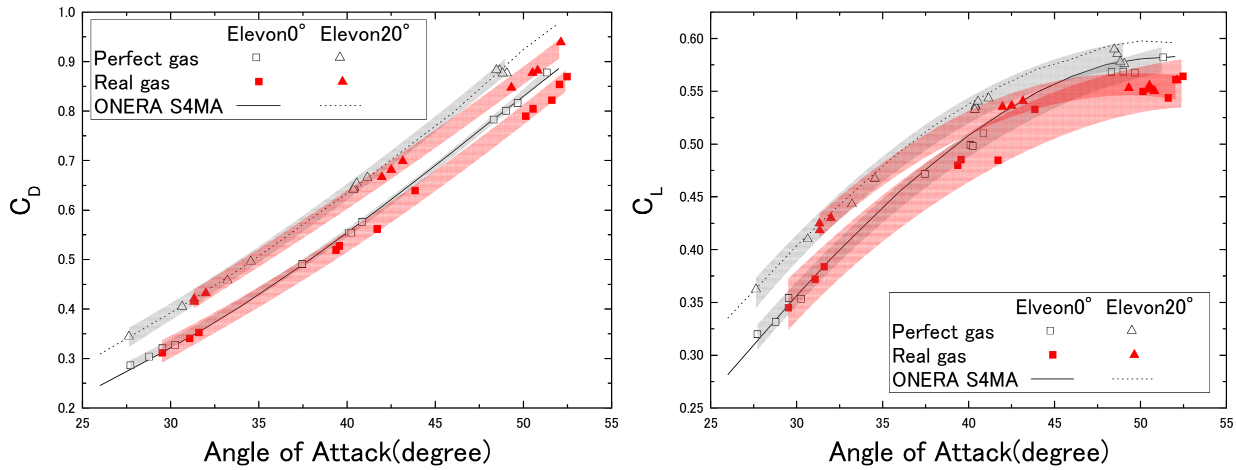

Figure 4: Drag coefficient (Left) and lift coefficient (Right) of the HYFLEX test model at angle of attack from 30 to 50 degrees. Results measured in the conventional blow down wind tunnel ONERA S4MA were superimposed.

3. Test results

3.1 Drag and Lift Coefficient

Measured drag coefficient, lift coefficient and lift-drag ratio related to angle of attack were shown in Fig.4 and Fig.5. In all the figures, square and triangle showed the results with elevon deflection angle 0 degrees and 20 degrees, respectively. Moreover, the open items and closed items were the results under perfect gas conditions and high-temperature real-gas conditions, respectively. The results measured in the conventional Hypersonic wind tunnel ONERA S4MA were also overlaid in all the figures as the solid (elevon 0 degrees) and dotted lines (elevon 20 degrees) to estimate the measurement accuracy of the present free-flight force measurements in HIEST. To estimate the measurement precision of the HIEST data, 95% (2-σ) prediction bands for the perfect gas condition and for the high-temperature real-gas condition were also plotted as the hatched area in the figures.
As shown in these figures, S4MA measurements are inside the 95% (2-σ) prediction bands of HIEST measurements. It means that the measurements in HIEST agreed quite well with those of S4MA. These results revealed that drag force and lift force are insensitive to a stagnation enthalpy, namely flight speed in Hypersonic flow. These results also demonstrated the high-accuracy and precision of the present HIEST force measurement technique. However, as shown in Fig. 4, there was a tendency that the C_D and C_L under high-temperature real-gas condition were slightly lower than those under perfect gas condition or S4MA results. This tendency became remarkable when the angle of attack increased over 40 degrees. The mechanism of this phenomenon is still unknown, however, uncertainty of dynamic pressure is suspected as a cause, because the lift-drag ratio does not indicate the trend as shown in the Fig.5.

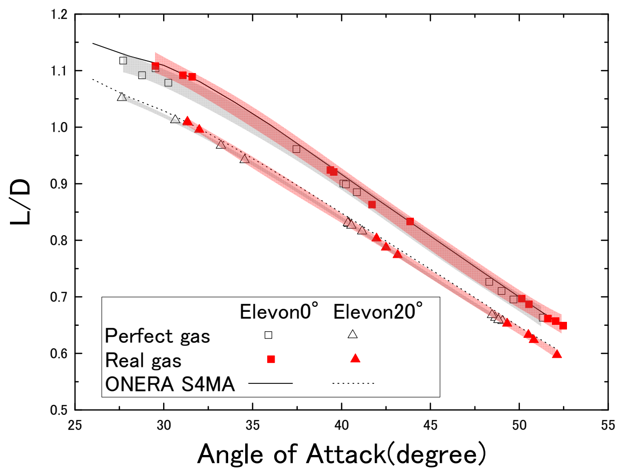

Figure 5: Lift-Drag ratio of HYFLEX test model at angle of attack from 30 degrees to 50 degrees. Results measured in the conventional blow down wind tunnel ONERA S4MA were superimposed.

3.2 Pitching moment

Fig. 6 (Left) showed all the measured pitching moment coefficients in the present HIEST test results, which agreed reasonably well with those of S4MA. Although the precision of the pitching moment was degraded than the drag or the lift force measurements, it was enough to determine the vehicle trim angle. For the discussion of the high-temperature real-gas effect on the longitudinal stability, HIEST measurements with an elevon deflection angle of 0 degrees are the focus. The regression analysis

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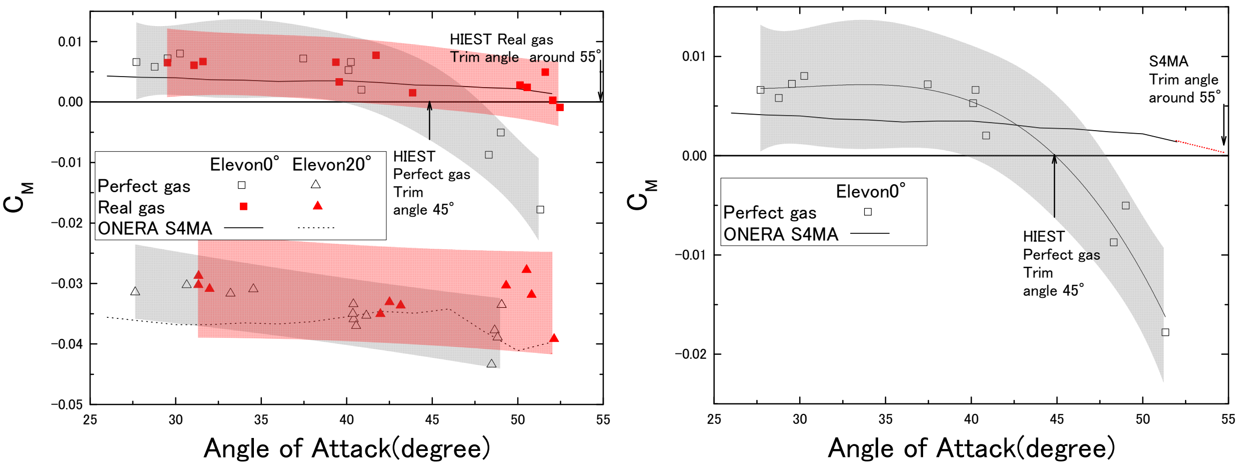

Figure 6: Pitching moment coefficient of HYFLEX test model at angle of attack from 30 to 50 degrees (Left). Results measured in the conventional blow down wind tunnel ONERA S4MA were superimposed. Results under HIEST perfect gas condition with elevon deflection angle 0 degrees were plotted (Right).

of the HIEST results indicated that the trim angle for HIEST perfect gas condition was estimated to 45 degrees. In contrast, it increased to about 55 degrees for the high-temperature real-gas condition. Forward movement of the pressure center as a high-temperature real-gas effect was believed to be the cause of this significant difference of trim angle between the two free-stream test conditions in HIEST.
As shown in the Fig.6 (Right), it should be also noted that the pitching moment coefficients under perfect gas condition in HIEST agreed reasonably well with those of ONERA S4MA at a low angle of attack (40 degrees or smaller). However, a huge discrepancy was found at a high angle of attack (45 degrees or larger). The figure clearly showed that the trim angle of HIEST under perfect gas condition (approximately 45 degrees) was much smaller than that of S4MA (approximately 55 degrees). A report of the HYFELX flight test results [8] said that the body flap deflection angle in flight was -2 degrees at Mach 10 or higher, which deflection angle was less than that of the pre-flight prediction (+2degees). In accordance, it implied that the trim angle of the real flight vehicle was expected to be smaller than that of pre-flight prediction. The trend of the smaller trim angle observed in the flight test was consistent to the HIEST present measurement. Since the longitudinal stability of HYFLEX was designed based only on the S4MA wind tunnel test results, the uncertainty of the wind tunnel measurements should be discussed again.

4. Conclusion

The three-component aerodynamic force measurement test campaign with a HYFLEX lifting body model was carried out under high-temperature real-gas condition in the impulsive facility HIEST. The free-flight force measurement technique developed specially for shock tunnels applied on the present study Comparison with the conventional blow down wind tunnel ONERA S4MA showed that the present free-flight force measurement technique has high-precision and accuracy, which was sufficient to characterize the longitudinal stability of reentry vehicles under high-temperature real-gas condition. The present study revealed the followings.
(1) There was a significant high-temperature real-gas effect on the pitching moment (trim angle increment). However, numerical studies are required for detailed analysis of the Mach number effect and Reynolds number effect
(2) The measurement implied a cause of the elevon anomalies observed in HYFLEX flight test. Uncertainty analysis of the wind tunnel measurement or numerical studies are required.

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