高温衝撃風洞 HIEST での加速度計を用いた極短時間力計測法

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Aerodynamic force measurement technique with miniature-accelerometers for short test duration in the high-enthalpy shock tunnel HIEST.

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概要
大気圏再突入流れに代表される高エンタルピ流れ場を地上で再現できる自由ピストン型衝撃風洞は、従来型風洞を大きく上回る数千気圧、数千度のよどみ点条件を作り出すことが可能である。しかし、その試験時間は極めて短く数 ms から数 10ms 程度しかない。この短い試験時間で空力計測を可能とするには、応答性の高い計測法が必要であり、過去から多くの計測法が研究されてきた。宇宙航空研究開発機構では、従来型空力天秤を用いた計測法に変わる新たな力計測法として、模型をワイヤで保持し、模型加速度を計測する方法の研究を続けて来た。今回の報告では、この方法の HIEST への適用性を実験的に検証するために、極超音速風洞試験の標準模型である HB-2 模型を用いた風洞試験を HIEST で行い、以前に HIEST でおこなった空力天秤計測結果、および長秒時試験が可能な極超音速風洞での計測結果と比較した。

1. Introduction

Free-piston shock tunnel[1)] is one of the ground test facility to simulate high-temperature real gas flow such as external flow around reentry vehicles. The tunnel can produce high stagnation pressure and stagnation temperature up to several hundred MPa and up to several thousand K, respectively. However, ms order test duration of the tunnels is extremely short comparing with conventional blow-down wind tunnels. Hence, conventional force measurement technique, which has been generally used in long duration wind tunnel can not be available because of its time response is not sufficient.

For aerodynamic force measurement in such a short test duration, fast response force measurement technique is required. A direct acceleration measurement technique[2)] was developed by CALSPAN in the 1960s. In this technique, test models were weakly restrained (suspended) with low stiffness support such as thin wires, allowing the effect of restorative force due to model support to be neglected within a short test period. Aerodynamic force can be thus obtained simply as a product of the measured acceleration and mass of a model. However, this technique has the disadvantage of degrading measurement accuracy with messy oscillations. This was caused by mechanical vibrations due to the insufficient rigidity of the test model. Since these oscillations do not damp within a short test time, they overlap with the relevant signal and disturb accurate measurement. With this oscillation, applicable models were restricted to small size models of a few hundred mm. If the effect of the oscillation can be removed, time resolution of the direct acceleration technique will be improved.

In this study, the signal recovery technique was applied to aerodynamic force measurement in the free-piston shock tunnel HIEST. To evaluate the feasibility of the present technique, unsteady drag force measurement was performed with the HB-2 hypersonic standard model. The measurement results were compared with the results obtained with the aerodynamic force balance technique in HIEST[3)]. The results were also compared with the results obtained in a blow-down type hypersonic wind tunnel.

2. Force measurement for aerodynamic model

Signal recovery method

To remove the oscillations caused by mechanical vibrations of the test model, a signal recovery process based on frequency domain de-convolution was applied as follows. If we assume the measurement system to be linear, the relation between output signal $x(t)$, system function $g(t)$ and input force $f(t)$ can be related by the following convolution equation.

$$x(t) = \int_0^t g(t-\tau) f(\tau) d\tau \quad (1)$$

To obtain the loaded force $f(t)$ from measured signal $x(t)$, the integral must be inverted. By applying Fourier transform, Eq. (1) is converted to

$$X(\omega)=G(\omega)F(\omega) \quad (2)$$

where ω is the angular velocity. The capital letters represent the transformed function. Thus, $f(t)$ can be obtained through invert Fourier transform F^{-1} as follows.

$$f(t) = F^{-1}(F(\omega)) = F^{-1}(X(\omega)/G(\omega)) \quad (3)$$

In Eq.(3), G(ω) has to be obtained with an impact test. G(ω) can be determined from

$$G(\omega)=X_c(\omega)/F_c(\omega) \quad (4)$$

Where, $X_c(\omega)$ is output from the accelerometer and $F_c(\omega)$ is output from the impact hammer.

HB-2 hypersonic standard model

The HB-2 model is a standard model used for evaluation of test flow characteristics in various supersonic wind tunnels. The HB-2 model used in this study are shown in Fig. 1. This model was made from aluminum alloy (A7075), with a model length and mass of 500mm and 10.88kg respectively. For the installation of piezoelectric type accelerometers (PCB 352C66: resonance frequency of 40kHz), the model has a 50mm × 50mm square open space in the vicinity of the model mass-center. The model was suspended with thin wires 0.5mm in diameter. Although high-stiffness large-diameter sting was not necessary for this measurement, a small diameter sting was required,

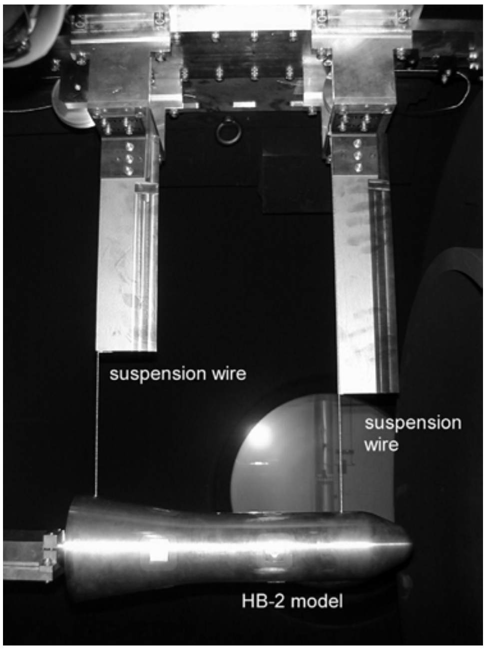

Fig.1 HB-2 standard model installed in the HIEST test section. The model was suspended from thin wires.

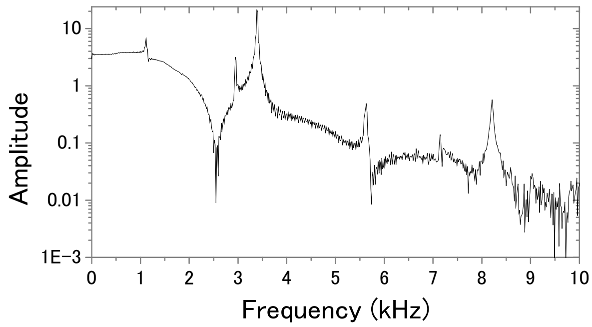

Fig.2 Frequency characteristics of the HB-2 model

protecting the signal cables of the accelerometers from high-enthalpy test flow. This sting was also used as a safety holder for the model, if the suspension wires accidentally broke.

Dynamic characteristics of the test model were obtained through an impact test. An impact hammer (PCB model 086C03) was used to initiate impulse response on the model. Fig. 2 shows the spectrum of the accelerometer output. In the figure, there are a number of peaks that represent the resonance frequency of the mechanical vibrations; the natural mode of vibration of the test model. The figure shows that the 1st vibration mode was 3.35kHz. The higher frequency modes were 5.6kHz and 8.2kHz.

In the signal recovery process, high frequency components will cause messy noise on de-convoluted signals. The noise can be removed with a low-path filter to cut-off higher frequency component in G(ω). This means the time response of the recovery process is determined by the low-path filter characteristics. The cut-off frequency of the low-path filter was set at 10kHz.

3. Wind tunnel test

Throughput the present series of tests, stagnation pressure P_0 was mostly held constant at 20MPa. On the other hand, stagnation enthalpy H_0 was varied from H_0=4MJ/kg to 12MJ/kg. Table 1 shows the test flow conditions, which were calculated with an axis-symmetrical in-house nozzle flow code[4]. Since shock tube operation conditions were slightly under-tailored, the free-stream Pitot pressure history

Table 1. Test flow condition of HIEST

P_0 (MPa)	16	22	18
H_0 (MJ/kg)	3.9	7	12
T_∞(K)	350	710	1290
ρ_∞(10^{-3}kg/m^3)	16	12	8
u_∞(km/s)	2.7	3.5	4.5

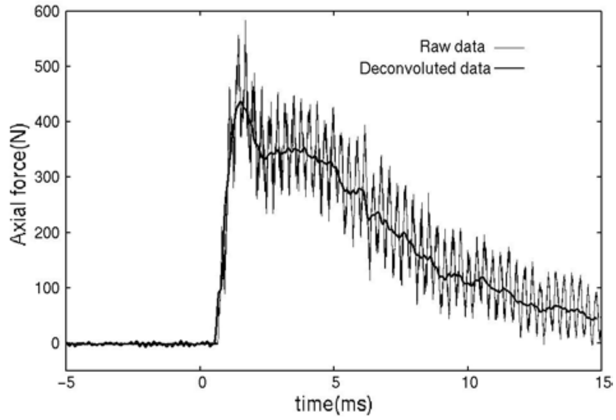

Fig.3 Axial force measurement record of HB-2 standard model. The thin line shows raw data from the accelerometer mounted in the model. The thick line shows signal recovery data through the de-convolution calculation.

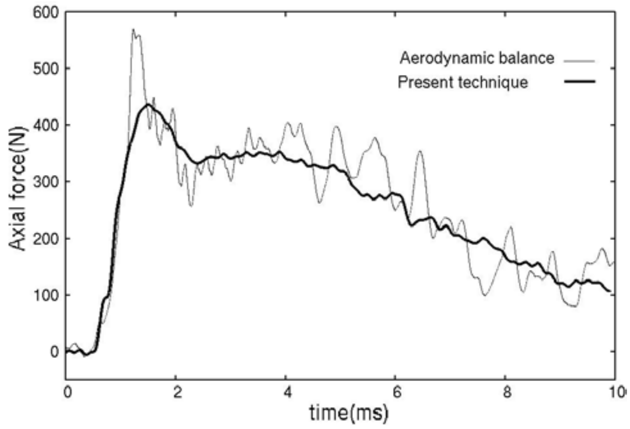

Fig.4 Axial force record of the HB-2 standard model. The thin line and thick line show the balance measurement technique and present measurement technique.

showed over-shoot at the test flow initiation. However, pressure seems steady after this nozzle starting process. The test time in this study was specified as 2 to 4ms, when the flow seems to be established.

Fig. 3 shows an example of the measured axial force record. The thin line and thick line show the raw data and signal recovery data, respectively. The fluctuation caused by mechanical vibration of the model in the raw signal record can be removed with the signal recovery process as shown by the thick line. It should be noted that the cut-off frequency of the low-path filter applied in this study is 10kHz. Hence, the measurement guaranteed the analysis of the phenomena, with a time-constant of less than 0.1ms.

Fig. 4 shows a comparison between the present measurement technique and the aerodynamic force balance technique, which was previously performed in HIEST[7]. The cut-off frequency of the low-path filter in the balance technique was less than 500Hz. The figure clearly shows that the balance results still had heavy fluctuation, caused by irrelevant high frequency components. However the present method does offer a faster time response without high-frequency noise.

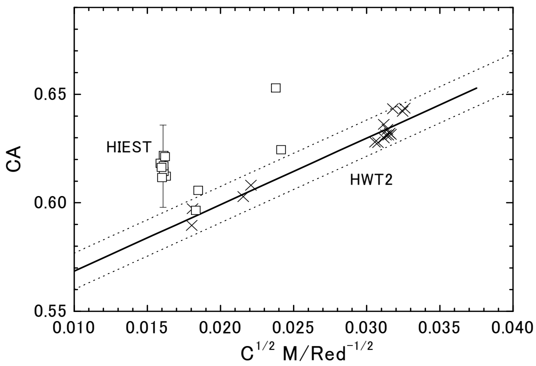

Fig.5 Comparison of the CA with viscous interaction parameter $M/Re^{-1/2}$. The solid line shows the results obtained in HWT2 (the hypersonic wind tunnel at JAXA Chofu). The dotted line shows 95% uncertainty. The open square shows the present results. The error bar shows 95% uncertainty.

To evaluate the present measurement uncertainty, a comparison with other wind tunnel facilities was conducted as shown in Fig. 5. In this comparison, reference data was used that had been obtained in the blow-down type hypersonic wind tunnel HWT2 located at JAXA Chofu[5)]. Since the Mach number and Reynold's number differed between the facilities, the viscous interaction parameter $M_\infty/\sqrt{Re}$ was applied to compare the tunnel results. The uncertainty of the HWT2 results is less than 3%. On the other hand, the uncertainty of the HIEST is less than 6%. The number of data in HIEST was not enough to evaluate the uncertainty in detail. However, the figure shows that the results were 5% higher than that of HWT2 measurements.

4. Summary

The latest results on hypersonic combustion obtained in the free-piston high-enthalpy shock tunnel HIEST are reported. A new scramjet engine model, named M12-03, was developed and tested in HIEST under hypervelocity corresponding to a flight Mach number over 10. The combustor performance at the stagnation enthalpy condition of 7MJ/kg or higher was improved. The results supported the theory that high pressure at the combustor entrance and reduced combustor length help to achieve high combustor performance under hypervelocity conditions.

A new force measurement technique for short duration was also evaluated in HIEST. The evaluation showed that the present technique is feasible for measuring aerodynamic force in free-piston shock tunnels. Since the measurement technique can guarantee a fast time response to the order of sub-msec, it is expected to be a useful tool for observing aerodynamic phenomena in a hypervelocity flow field. This measurement technique can be easily extended to a multi-component system.

References

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