衝撃風洞における極短時間力計測技術に関する研究

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論文内容要旨

1 Introduction

Impulse facilities are the only ground test facilities to simulate hypervelocity flow, although their test duration is in the order of ms to hundred ms. Since 1997, a large-scale free piston shock tunnel HIEST1 has been available at the National Aerospace Laboratory in Japan for a scramjet study. HIEST can simulate flow equivalent to flight Mach number 8 or higher, and large-scale scramjet models of three-meters in length can be installed, although their test time is in the order of ms. In the case of aerodynamic force measurement such as the drag, lift and pitching moment of a large scale scramjet in HIEST, the authors have tried to use the direct acceleration measurement technique called the free-flight technique. By this method, test models were weakly-restrained (suspended) with low rigidity support such as thin wires or springs, so that the effect of the restorative force caused by model support can be neglected within a short test period. Theoretically, aerodynamic force can be hence obtained simply as a product of measured acceleration and weight of the models. However, measured force shows messy oscillations, which were caused by mechanical vibrations coming from the insufficient rigidity of test models. Since these oscillations do not decline within a short test time, they disturb accurate measurement. Increasing the rigidity of test models is a way to avoid these oscillations. However, from the engineering point of view, it is impossible to obtain sufficient rigidity with large-scale scramjet models of 3 meter length. Thus, a new measurement technique was required to remove the effect of these oscillations for large-scale scramjet force measurement within ms order test time.

In this study, aiming for force measurement with large scale models in HIEST, a force measurement technique with miniature accelerometers for a short test time was developed. First, basic research of free-piston shock tunnel and force measurement technique within short test duration was conducted. Second, force measurement technique with miniature accelerometers was proposed and was evaluated with large-scale model in a free-piston shock tunnel. Third, The technique was applied on unsteady drag force measurement of a sphere model(80mm diameter) in a shock tube(test duration 600 μ s). The shock tube result showed the technique is also effective for force measurement in μ s order test time. At the last, the technique was applied on the large-scale scramjet with hydrogen fueled combustion test in a free-piston shock tunnel. The test result demonstrated that scramjet ground testing with large scale model under hypervelocity flow condition can be performed with sufficient reliability for scramjet research.

2 Basic research on free-piston shock tunnel

For the force measurement, basic research on free-piston shock tunnel was conducted to extend performance; stagnation condition and test duration. First experimental study for free-piston driver was performed to evaluate an optimum operation theory (tuned operation theory) and to estimate a numerical simulation code. The experimental result showed the theory and the code was reliable. With the theory and the code, large scale free-piston shock tunnel was constructed. Additionally, force measurement technique within ms order short test duration was carried out. A high stiffness aerodynamic force balance was developed. The balance was used for drag force measurement of a hemi-sphere model in a free-piston shock tunnel HEK. A stress wave force balance was also developed to measure skin friction force of a scramjet combustor. Although these balances were effective for small size test model, these are useless for large-scale test model.

3 Force measurement technique with miniature accelerometers

A force measurement technique has been developed for large-scale aerodynamic models with a short test time. The technique is based on direct acceleration measurements, with miniature accelerometers mounted on a test model suspended by wires. Measuring acceleration at two different locations, the technique can eliminate oscillations from natural vibration of the model. The technique was used for drag force measurements on a three-meter long supersonic combustor model in the HIEST free-piston driven shock tunnel. A time resolution of 350 μs is guaranteed during measurements, which resolution is enough for ms order test time in HIEST. To evaluate measurement reliability and accuracy, measured values were compared with results from a three-dimensional Navier-Stokes numerical simulation. The difference between measured values and numerical simulation values was less than 5. We conclude that this measurement technique is sufficiently reliable for measuring aerodynamic force within test durations of a millisecond.

4 Application on un-steady drag force measurement in shock tube

Shock wave interaction with a sphere is one of the benchmark tests in shock dynamics. However, unlike wind tunnel experiments drag force measurements on a sphere installed in a shock tube have not been carried out. Hence an experimental and a numerical studies of measuring unsteady drag forces acting on a 80 mm diameter sphere was conducted. In the experiment, the sphere was suspended vertically along the center line of a 300 mm $¥times$ 300 mm vertical shock tube and loaded with a planar shock wave at shock Mach number of 1.22 in air. Unsteady drag forces exerted on the sphere were measured with an accelerometer installed inside it. Output data out of accelerometer was evaluated by means of de-convolution data processing so as to be comparable with those obtained numerically by solving the Navier-Stokes equations. Good agreement was obtained between measured time variation of drag force and numerical one. In order to interpret the interaction of shock wave with the sphere, high speed video recordings and double exposure holographic inter-ferometric observation were conducted. It is found that a maximum drag force appeared not at the time instance when the shock arrived at the equator of the sphere but at sometime after the transition of reflected shock wave from regular to Mach reflection. A negative drag force was created even though only for very short duration of time when the transmitting shock wave focused at the rear stagnation point of the sphere.

5 Application on force measurement with large-scale scramjet in a free piston shock tunnel

Large-scale scramjet combustion test was performed in the free-piston shock tunnel HIEST. The model scramjet of 2 m length and of 143 kg mass had integrated configuration, which includes sidewall compression inlet, parallel combustor and sidewall divergent nozzle. Thrust and pressure distribution of the model was measured under flow condition equivalent to flight Mach number 8. Gaseous hydrogen, which equivalence ratio was varied from 0.0 to 2.2 was used as fuel. In order to evaluate testing reliability, comparison with the vitiated air heating wind tunnel RJTF was conducted. The comparison showed un-start characteristics, thrust increment and wall pressure distribution were different between two facilities. A numerical simulation of three-dimensional Navier-Stokes code including combustion and additional wind tunnel tests in HIEST at different stagnation enthalpy were carried out to analyze these differences. The numerical study and the wind tunnel tests showed that (1) un-start characteristics was affected by facility-nozzle boundary layer, which was ingested into the model inlet and (2) thrust increment and pressure distribution was caused by difference of stagnation condition of the test flow between the two facilities. The test result demonstrated that scramjet ground testing with large scale model under hypervelocity flow condition can be performed with sufficient reliability for scramjet research.

6 Conclusion

Research on force measurement technique for short test duration was conducted. In the research new force measurement technique with miniature accelerometers were proposed and evaluated in the shock tube test and in the free-piston shock tunnel test. The shock tube evaluation test revealed that the present technique has enough accuracy and time resolution for phenomena with a duration of hundred μ s. Additionally, the free-piston shock tunnel test showed that the technique enabled the scramjet performance testing on the ground under flight Mach number 8 or higher condition. It can be concluded that the technique is quite effective for basic aerodynamic research and for development of hypervelocity vehicle such as re-entry vehicle and space plane.

論文審査結果の要旨

航空宇宙工学の分野では、スクラムジェットエンジン内の流れおよび宇宙機の大気圏再突入を模擬する高エンタルピー地上実験装置とその短時間力計測法の開発は重要な要素研究である。しかし、短時間力計測に関する様々の手法が提唱されているが、未だ短時間応答特性を有する高信頼性の計測法は確立されていない。本論文は、高エンタルピー衝撃風洞の大型供試模型に加速度計を内蔵させて、マイクロ秒の時間分解能を持つ力計測法を提唱しその原理を衝撃波管実験により検証、さらに大型スクラムジェットエンジンの推力計測に応用した結果をとりまとめたもので、全編6章よりなる。

第1章は緒論である。

第2章では、自由ピストン衝撃風洞の設計理論を展開し、これに基づいて製作した高温自由ピストン衝撃風洞に試作した高剛性空力天秤、応力波天秤を取り付けて力計測の可能性を明らかにしている。これは従来の知見を補完する有用な成果である。

第3章では、高温自由ピストン衝撃風洞の大型供試模型に複数の加速度計を取り付けて、その固有振動の影響を排除した高時間分解の力計測法を提唱し、その計測結果と乱流モデル取り入れた三次元数値解を対比したところ、流れの諸量に最大5％の差しかないことを認めている。これは計測の精度を保証している。

第4章では、縦型衝撃波管に加速度計を内蔵する金属球を吊るし、衝撃波を負荷したときの非定常抗力を計測している。測定した非定常抗力は数値解と非常によく一致し、提唱する力計測の精度と短時間応答性に優れた特性を示している。衝撃波管を用いる検証法は独創的な試みであり、また、抗力の時間履歴に負の抗力が現れることを初めて明らかにしている。これは重要な知見である。

第5章では、以上の力計測法を用いて、高温自由ピストン衝撃風洞およびラムジェット試験装置に取り付けた大型スクラムジェットエンジン模型の抗力を比較し、これらの装置の特性を評価している。得られた知見は、提唱する力計測法の有用性を示すばかりでなく、今後高温自由ピストン衝撃風洞でのスクラムジェットエンジン燃焼試験の実施に重要である。

第6章は結論である。

以上要するに本論文は、高エンタルピー衝撃風洞および衝撃波管内におかれた供試模型に働く力の短時間計測法の確立とその応用例を示したもので、高速空気力学と衝撃波研究に重要な貢献を果たしており、航空宇宙工学および衝撃波工学の発展に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。