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Engineering Notes

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Aerodynamic Characteristics of Frustum-Shaped Elastic Membrane Aeroshells in Supersonic Flow

Kazuhiko Yamada* and Kojiro Suzuki†
University of Tokyo, Tokyo 113-8656, Japan
and
Motoyuki Hongo‡
Japan Aerospace Exploration Agency, Kanagawa 229-8510, Japan

Nomenclature

C_{AE} = aeroelasticity parameter
E = Young's modulus
h = thickness of membrane
L = reference length
M_∞ = freestream Mach number
q_∞ = freestream dynamic pressure
u_∞ = freestream velocity
α = angle of attack
ρ_∞ = freestream density

Introduction

A MEMBRANE aeroshell shows potential to be used for innovative reentry vehicle concept.[1] Various concepts of membrane aeroshells have been proposed for a decelerator in supersonic flight of reentry or aerocapture vehicles.[2–4] A vehicle with a low mass and large membrane aeroshell can have much smaller ballistic coefficient than conventional reentry vehicles because the ballistic coefficient represents the ratio of the mass to the drag-producing area of the vehicle. For such a vehicle, large deceleration can be obtained during flight at high altitude, where the atmospheric density is very low. This leads to reduction in the maximum aerodynamic heating because a heat flux to a body surface increases with the atmospheric density at the flight altitude. When a membrane aeroshell is used, the cost and weight for thermal protection systems are expected to be dramatically reduced, and a safer and cheaper reentry system will be realized. However, this concept has not yet been used in an actual aerospace mission, except for some test flights.[5] One of the reasons is lack of knowledge of the characteristics of a membrane aeroshell in supersonic flow. In this study, supersonic wind-tunnel experiments were conducted to acquire fundamental understanding on the behavior of the membrane aeroshell and its aerodynamic characteristics in supersonic flow. We considered a capsule-type vehicle with a frustum-shaped membrane aeroshell derived from the tension shell structure.[6] The effects of flow conditions and properties of membrane materials were investigated.

Experimental Setup

Supersonic wind-tunnel tests were conducted to investigate the aerodynamic characteristics of a vehicle with a frustum-shaped membrane aeroshell. These experiments were performed in the 60×60 cm supersonic wind tunnel that belongs to the Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency. These experiments were mainly carried out at Mach number 3.0. The freestream dynamic pressure was varied from 33.2 to 102.9 kPa. The freestream dynamic pressure was expected to affect the characteristics of the membrane aeroshell because a deformation of a membrane aeroshell strongly depends on the aerodynamic force acting on the surface. The unit Reynolds number was varied from 1.53 to 4.74×10^7 1/m with freestream dynamic pressure.

A schematic of the experimental model is shown in Fig. 1. In Fig. 1, model A, which had a 90-mm maximum diameter, and model B, which had a 70-mm maximum diameter, are shown. Model A was mainly used in this experiment. Model B was used for the test only in high dynamic pressure cases, in which the membrane aeroshell of model A was ripped out and smaller aeroshell must be used for the test model to survive. The both models consisted of a

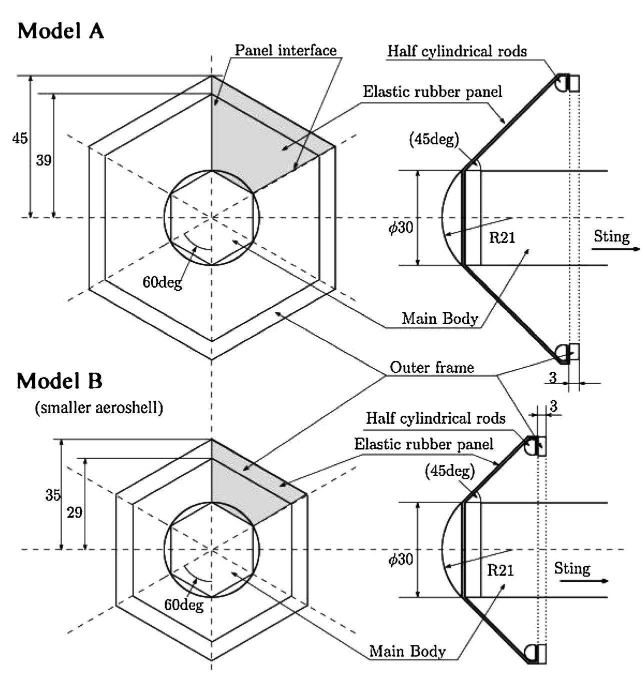

Fig. 1 Schematic of experimental model; dimensions in millimeters.

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*Graduate Student, Department of Aeronautics and Astronautics, Graduate School of Engineering, Engineering Building 7, Hongo 7-3-1, Bunkyo. Student Member AIAA.

†Associate Professor, Department of Advanced Energy, Graduate School of Frontier Sciences, Engineering Building 7, Hongo 7-3-1, Bunkyo. Member AIAA.

‡Technical Staff, Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara.

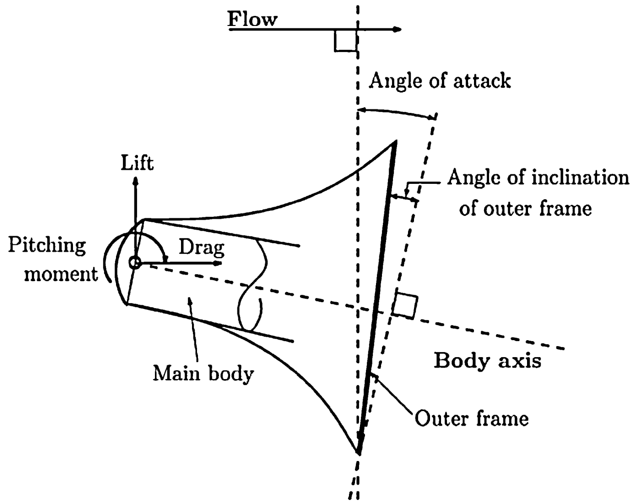

Fig. 2 Definition of aerodynamic coordinate system.

metal main body, elastic membrane aeroshell, and hexagonal metal outer frame. The main body had a spherical nose and a cylindrical body. It was attached to a sting balance system. The membrane aeroshell consisted of the six thin trapezoidal panels made from an elastic rubber sheet. The inner ends of the membrane panels were attached to the main body. Each membrane panel was fastened to the neighboring ones with small patch plates and screws. The outer ends of the membrane panels were attached to the hexagonal outer frame. The outer frame was a rigid body but was free to move in all directions because it was attached to the main body via the flexible membrane. Two kinds of elastic rubber sheets (hard rubber and soft rubber) were used in these experiments. The thickness of both kinds of rubber sheets was 1 mm. For comparison, the rigid aeroshell made from aluminum panel was also tested. Young's modulus was evaluated as 20 and 2.0 MPa for the hard rubber and soft rubber, respectively, by the simple tension tests made beforehand. When it is considered that the membrane aeroshell will be potentially used for a reentry vehicle, high-temperature membrane materials, such as Zylon® textile or Kapton® film, should be used. However, the rubber sheet was used for the present experiment because the main objective of the present study is to clarify the effect of the deformation of the membrane aeroshell on the aerodynamic characteristics, and a larger deformation is obtain by the rubber sheets with much smaller Young's modulus than those high-temperature materials.

In these experiments, the aerodynamic forces were measured using a sting balance system. The flows around the model were visualized by the schlieren method. Definition of the aerodynamic coordinate system is given in Fig. 2. For the reference area of the aerodynamic coefficients, the area surrounded by the outer frame was used.

Results

Zero Angle of Attack

The models with the rigid metal, hard-rubber membrane, and soft-rubber membrane aeroshell in supersonic flow, $M = 3.0$, are shown in Fig. 3. The freestream dynamic pressure and angle of attack were 37.7 kPa and 0.0 deg, respectively. The membrane aeroshells were quite stable in the supersonic flow and did not oscillate in all of the cases. The magnitude of the fluctuation for the drag force was less than 1.0%. The elastic membrane aeroshells were deformed to a concave shape and stretched in the downstream direction, as shown in Fig. 3. On the other hand, at the panel interface, the deformation was restricted. The displacement of the outer frame in the downstream direction became large when Young's modulus of the membrane was small, that is, in the case of the soft-rubber membrane aeroshell. A similar trend was observed when the freestream dynamic pressure became high.

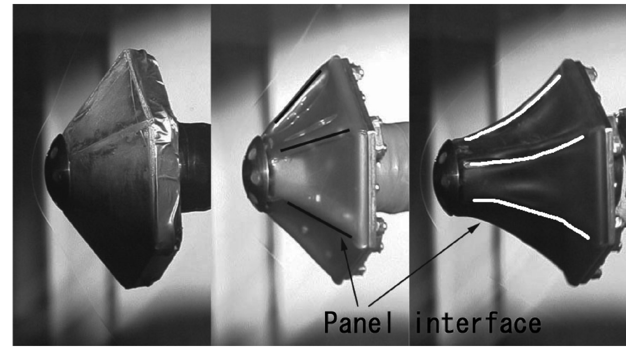

Fig. 3 Model with the membrane aeroshell deformed to a concave shape in supersonic flow, $M_\infty = 3.0$ and $q_\infty = 37.7$ kPa: rigid model (left), hard rubber model (center), and soft rubber model (right).

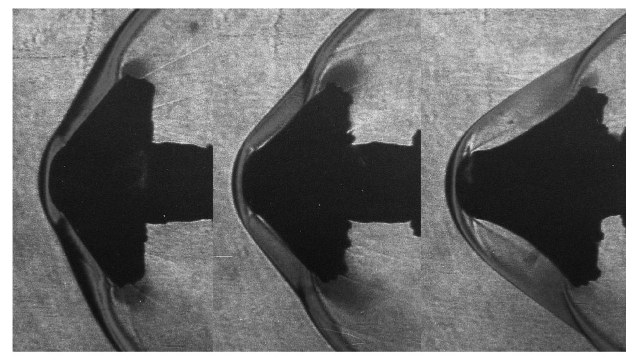

Fig. 4 Schlieren photograph of model with membrane aeroshell in supersonic flow, $M_\infty = 3.0$ and $q_\infty = 37.7$ kPa: rigid model (left), hard rubber model (center), and soft rubber model (right).

The schlieren pictures at the same conditions as Fig. 3 are shown in Fig. 4. The deformation of the membrane induced a global change in the flowfield around the model, especially in the shape of the shock wave over the flare. The fact that the increase in the freestream dynamic pressure led similar results to decrease in Young's modulus of the membrane material implies the presence a single parameter that can describe both factors.

In the present study, we introduce the nondimensional parameter C_{AE} (called an aeroelasticity parameter), which represents the ratio of the aerodynamic force to the elastic force and is given as

$$C_{AE} = L\rho_\infty u_\infty^2 / Eh \tag{1}$$

The relation between C_{AE} and the drag coefficient is shown for the rigid, hard-rubber, and soft-rubber aeroshell models at various dynamic pressures in Fig. 5. The results of model B are also shown in Fig. 5. The length of the panel interface of the aeroshell was used as the reference length to calculate C_{AE}. The horizontal axis is C_{AE} with a logarithmic scale. These results indicate that the variation of the drag coefficient is described by a single curve with respect to C_{AE}. The drag coefficient decreased when the aeroelasticity parameter C_{AE} increased, that is, when the dynamic pressure increased or Young's modulus of the membrane decreased, because the aeroshell was significantly stretched in the downstream direction and the shape of the aeroshell became more slender, that is, the averaged slope angle of the frustum became smaller.

Such a tendency was also observed in the numerical results obtained by the coupling method of the particle-based linear elastic membrane model and laminar Navier–Stokes analysis (see Ref. 7) as also shown in Fig. 5. Both experimental and numerical results indicate that the drag coefficient of the membrane aeroshell model is almost constant at C_{AE} smaller than 0.1 and decreases steeply around $C_{AE} = 0.1 \sim 1.0$, where the aerodynamic force becomes comparable to the elastic force.

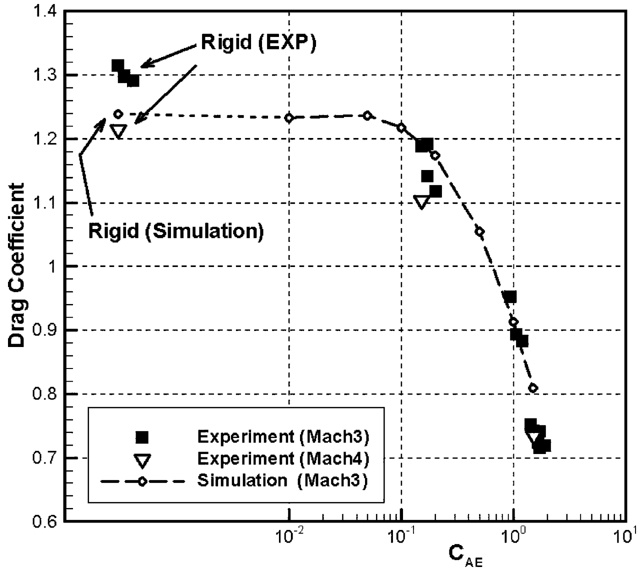

Fig. 5 Experimental results and estimated curve about relation between C_{AE} and drag coefficient.

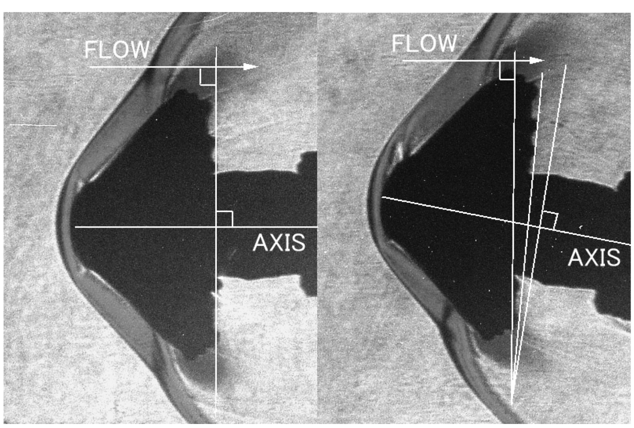

Fig. 6 Schlieren photographs of hard rubber membrane aeroshell model in supersonic flow: $M_\infty = 3.0$ and $q_\infty = 37.7$ kPa: $\alpha = 0.0$ deg (left) and $\alpha = 12.0$ deg (right).

In Fig. 5, the results at Mach number 4.0 are also shown. A similar trend was also obtained, although the drag coefficient at Mach number 4.0 was slightly smaller than at Mach number 3.0. These results lead us to expect the presence of the Mach number independence rule, which is generally applied to the aerodynamic characteristics of a rigid body at high Mach numbers, also to be applicable to the membrane aeroshell. For confirmation, hypersonic wind-tunnel experiments at higher Mach number are necessary.

Effects of Angle of Attack

Schlieren photographs are shown for the hard-rubber model at angle of attack of 0.0 and 12.0 deg in Fig. 6. At 12.0-deg angle of attack, the outer frame inclined against the body axis. This results shows that the membrane aeroshell tends to be deformed to set the outer frame to be normal to the freestream direction, even when the main body is at an attack of angle.

The variation of the drag coefficient with the angle of attack are shown for rigid-metal, hard-rubber, and soft-rubber aeroshell models at $q_\infty = 37.7$ kPa in Fig. 7. These results show that drag coefficients of the membrane aeroshell model are less sensitive to the angle of attack than the rigid aeroshell model. The drag coefficient of the membrane aeroshell model hardly depends on the angle of attack and has an almost constant value. This is because the membrane aeroshell tends to head in the freestream direction as explained in the preceding paragraph. The lift force and pitching moment acting on the model with membrane aeroshell is almost negligible compared to the drag force.

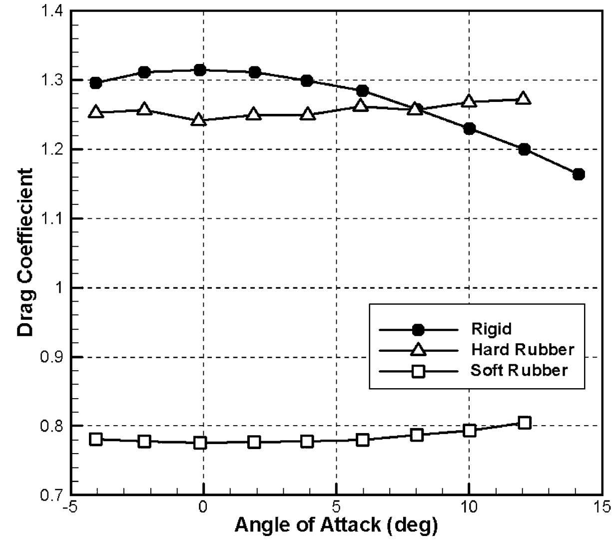

Fig. 7 Experimental results of drag coefficient as function of angle of attack for rigid, hard rubber, and soft rubber aeroshell models, $q_\infty = 37.7$ kPa.

Conclusions

The membrane behavior and aerodynamic characteristics of a capsule model with an elastic membrane aeroshell were investigated by the supersonic wind-tunnel experiments. The results show that the deformation of a membrane aeroshell is governed mainly by the nondimensional aeroelasticity parameter C_{AE} (which is defined as the ratio of the aerodynamic force to the elastic force) in the supersonic flow regime when the Mach number is given. Also a capsule-type vehicle with a membrane aeroshell in combination with a rigid outer frame has some unique characteristics that a rigid vehicle does not have. When C_{AE} increases, the shape of the averaged slope angle of the frustum becomes smaller due to elastic deformation of the membrane, and the drag coefficient decreases. The drag coefficients of the membrane aeroshell model are less sensitive to the angle of attack than the rigid aeroshell model because the membrane aeroshell tends to incline its outer frame to be normal to the freestream direction.

When the unique characteristics of the membrane aeroshell are used properly, it would be possible to design innovative vehicles that have self-adaptive aeroshells, whose shape is automatically deformed to realize a required performance in compliance to the change in the flow conditions. For example, when the atmospheric density abruptly increases, such type of aeroshell can diminish the increase in the drag force because the aeroshell can change its shape to have smaller drag coefficient by stretching its surface to the downstream direction and reducing the averaged frustum.

Knowledge about a membrane aeroshell obtained in this study will contribute to the development of a robust inexpensive, and innovative reentry or planetary-entry capsule using a membrane aeroshell.

References

[1]Iannotta, B., "Down-to-Earth: Transport for Space Cargo," *Aerospace America*, Vol. 38, No. 7, 2000, pp. 39–42.

[2]Mikulas, M. M., Jr., and Bohon, H. L., "Development Status of Attached Inflatable Decelerators," *Journal of Spacecraft and Rockets*, Vol. 6, No. 6, 1969, pp. 654–660.

[3]McRonald, A. D., "A Light-Weight Inflatable Hypersonic Drag Device for Venus Entry," American Astronomical Society, AAS Paper 99-355, March 1999.

[4]Hall, J. L., "A Review of Ballute Technology for Planetary Aerocapture," International Academy of Astronautics Conf. on Low Cost Planetary Missions, Paper IAA-L-1112, May 2000.

[5]Gräßslin, M., and Schöttle, U., "Flight Performance Evaluation of the Reentry Mission IRDT-1," International Astronautical Federation Congress, Paper IAF-01-v.3.05, Oct. 2001.

[6]Anderson, M. S., Robinsion, J. C., Bush, H. G., and Fralich, R. W., "A Tension Shell Structure for Application to Entry Vehicles," NASA TN D-2675, March 1965.

[7]Yamada, K., and Suzuki, K., and Hongo, M., "Aerodynamic Characteristics of Three-Dimensional Membrane Aeroshells in Supersonic Flow," AIAA Paper 2003-3924, June 2003.

P. Weinacht
Associate Editor