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Engineering Notes

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Measurements in the Wake of Blunt Aerobrake Models at 1.8 and 4.9 km/s

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Introduction

MANY proposed NASA missions, such as transfer between low and high Earth orbits and exploration of Mars, may make use of aeroassist technology to achieve payload economy.[1] In an aeroassist maneuver, a spacecraft passes through the Earth's upper atmosphere and uses aerodynamic forces to change its orbit. Figure 1 shows a schematic of a typical aeroassist vehicle, in this case the Aeroassist Flight Experiment (AFE) vehicle. The front surface, or aerobrake, generates the aerodynamic drag and lift forces that decelerate or otherwise change the flight path of the vehicle; in addition, it protects the payload from the intense heat generated as the vehicle passes through the atmosphere. The payload is located behind the aerobrake. One phenomenon important to aeroassist technology is the hypersonic wake flow, because the payload must be protected from the convective and radiative heat generated in the wake. Of particular concern is the possibility that the shear layer, which separates from the frustum (or shoulder) of the aerobrake, will impinge on the payload. Should this occur, experiments by Shieh and Gay[2] have shown that the convective heating rate at the impingement point can be as high as that of the front stagnation point. A more complete discussion of the importance and complexity of blunt aerobrake wake flows is contained in Strawa et al.[3]

To study aeroassist technology, NASA proposed the AFE. Unfortunately, this project was canceled due to budgetary problems. However, because of the potential advantages of using aeroassist technology, the relevant phenomena continue to be studied. Over the last several years, experiments have been conducted in the NASA Ames' ballistic ranges with the objective of studying hypersonic blunt body wake flows in support of the AFE project. Of interest to the vehicle designers and relevant to several of the experiments proposed for the AFE were the angle of shear turning and the location of the wake neck. In the present experiment the shear turning angle ϕ is defined in Fig. 1 as the angle from the back surface of the aerobrake to the observable free-shear layer. Previous experiments were conducted by Wells[4] in a wind tunnel using the AFE shape in air at $M = 10$ and in CH_4 at $M = 6$ at an approximate freestream Reynolds number of 1.53×10^5 (based on model diameter). The model was held in place by a sting protruding from its back. These experiments provided much-needed initial measurements of the shear turning angle from the upper corner of the vehicle. However, the effects of the sting and the test Mach number on the shear turning angle were not known, and the lower shear turning angle and location of the wake neck could not be determined. This Note presents measurements of upper and lower shear turning angles and the wake-neck location that were obtained in the NASA Ames' ballistic range. The upper shear turning angles that were measured in the ballistic range are compared to the wind tunnel results.

Ballistic Range Experiments

The experiments were conducted in the hypervelocity free-flight aerodynamic facility (HFFAF) and the pressurized ballistic range (PBR). A description of these facilities can be found in Ref. 5. Briefly, the PBR can launch models about 4.5 cm in diameter to velocities of 1.8 km/s, and the HFFAF can launch 1.9-cm-diam models to velocities of 4.9 km/s. Scale models of the AFE vehicle were flown at velocities and densities that closely simulate the flight Mach and Reynolds numbers and still yield shadowgraphs of the flow structure. The conditions of the tests conducted in the PBR were 1.83 km/s ($M = 5.4$) in air at a freestream Reynolds numbers of 5.53×10^5 and 7.38×10^5, based on model diameter. Three of these tests were conducted at 1.0, 1.19, and 1.36 km/s, corresponding to Mach numbers of 2.9, 3.5, and 4.0, respectively. The conditions of the tests conducted in the HFFAF were 4.88 km/s ($M = 14.4$) in air at Reynolds numbers of 3.26, 4.59, and 8.70×10^5. Shadowgraphs of the free-flight models were taken, and measurements of the shear turning angle and wake-neck location were made.

The ballistic range models were machined from aluminum on a three-axis computer-controlled milling machine so that the forebody would be an accurate scale model of the aerobrake. The computer program describing the AFE aerobrake shape was supplied by NASA Johnson Space Flight Center. The aerobrake shape is that of an elliptic cone raked off at 17 deg relative to the normal axis. The cone has an ellipsoidal nose. The aerobrake is mounted onto a hexagonal afterbody with a diameter less than that of the aerobrake. Early in the project history the rocket motor was to remain with the spacecraft during the aeroassist maneuver. Later, it was decided to jettison the rocket motor before the aeroassist maneuver. Thus, the early low-velocity ballistic range models and the

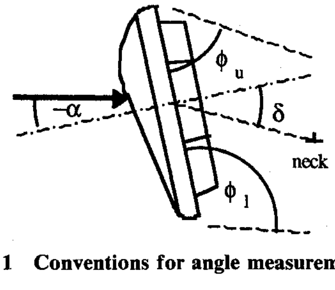

Fig. 1 Conventions for angle measurements.

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model of Ref. 4 had an afterbody that included a rocket motor. During the later high-speed ballistic range tests, the rocket motor was omitted. Since the rocket motor is within the recirculating region of the wake flow where pressures are very low, its presence had little effect on the shear turning angles and wake flow at the angles of attack of interest.

Results and Discussion

Figure 1 shows a sketch of the AFE model flown in the ballistic range tests and the convention used to measure the upper and lower shear layer angles and the wake-neck angle. Note that positive angles of attack are nose up. Using this convention, the vehicle trims at -17 deg in a nose down attitude. Theoretically, the shear-layer turning is defined as the angle between the local freestream velocity vector and the free-shear layer at the point of separation. This angle is very difficult to measure experimentally because the local freestream flow direction cannot be determined from the shadowgraphs. In many cases, the shear layer was curved in the region of the frustum, and an extension of the shear layer back to the plane of the aerobrake did not intersect the frustum. As mentioned, the shear turning angle is measured from the back surface of the aerobrake to the observable free-shear layer. For the wind tunnel data,[4] the shear layer was not visible in the shadowgraphs, and the shear angle was considered to be the angle between the back of the aerobrake and the line connecting the frustum and the point where the shear layer impinged on the sting. Therefore, this angle does not truly represent the shear-layer turning angle, and it is called the shear turning angle. The shear turning angle measured in this experiment is analogous to the angle reported by Wells.[4] The neck angle was measured from the perpendicular to the vehicle base to the center of the wake neck. Of the many shadowgraphs taken

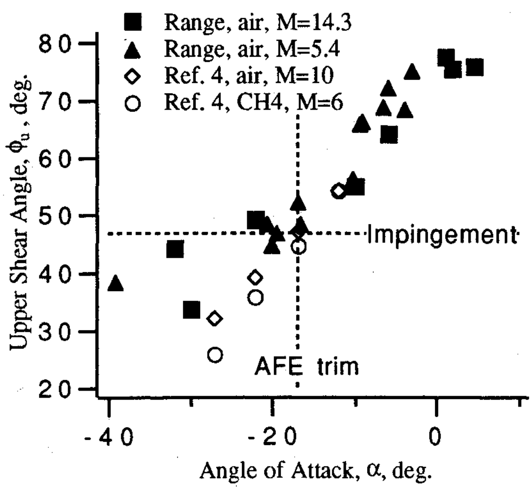

Fig. 2 Upper shear angle vs angle of attack.

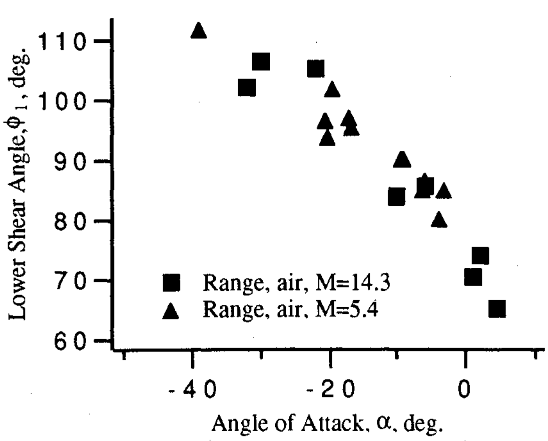

Fig. 3. Lower shear angle vs angle of attack.

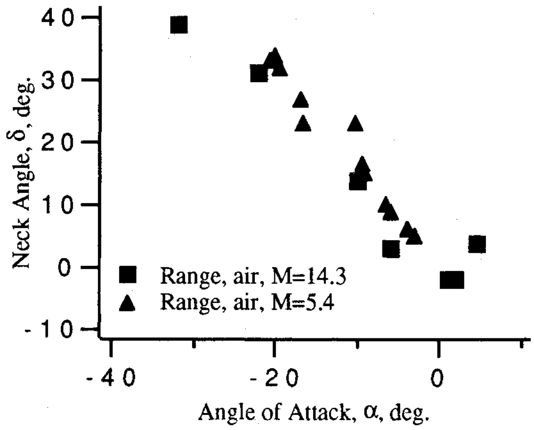

Fig. 4 Neck angle vs angle of attack.

during the range tests, only those with small yaw and roll angles are reported. The uncertainty in the measurements is about ± 1 deg due to the reading errors.

The upper shear turning angle ϕ_u vs angle of attack is shown in Fig. 2 for the $M = 5.4$ and 14.3 ballistic range tests. The data of Ref. 4 is plotted for comparison. There was no discernible effect of Mach number or Reynolds number on the shear turning angle or neck angle measured in this set of experiments. Upper shear layer impingement on the afterbody occurs for shear angles of less than 46.4 deg. The AFE angle of attack limits are between -12 and -22 deg, and, as can be seen in Fig. 2, shear layer impingement could have occurred during portions of the AFE flight.

Figure 3 shows the lower shear turning angle ϕ_l vs angle of attack. It is clear that the lower shear layer does not turn as much as the upper shear layer. This is to be expected since the shear turning angles are affected by the downwash induced by the lifting aerobrake. Positive lift results in downwash toward the lee side, the shear turning angle is reduced, and shear layer impingement does not appear to be a problem for the lee side of the vehicle.

The wake-neck angle δ is defined in Fig. 1 as the angle from the vehicle centerline to the center of the observable neck. Figure 4 shows wake-neck angle δ vs angle of attack. The mean distance to the wake neck was measured to be about one aerobrake diameter.

The scatter of the data in Figs. 2–4 is about ± 5 deg. This scatter is interpreted as resulting from unsteadiness in the wake flowfield. The unsteadiness of the flow can be deduced from the waviness of the recompression shock observed in the shadowgraphs. By measuring the wavelength of the recompression shocks and using the freestream velocity and wake-neck diameter, we obtained Strouhal numbers of about 0.5–0.6. (The Strouhal number is a dimensionless quantity that characterizes frequencies due to fluid mechanical effects and is defined as fd/u, where f is the frequency, u the freestream velocity, and the characteristic dimension d the diameter of the wake neck.) In this case, an estimate of the frequency is obtained by dividing the wavelength by the freestream velocity. For comparison, Behrens and Ko[6] measured the power spectra of wakes of two- and three-dimensional bodies at moderate Mach numbers, about Mach = 6. They measured a Strouhal number of 0.32 in their experiments. The differences in these values may be indicative of Mach number or Reynolds number effects, however, there is insufficient data at present to verify these effects.

Conclusions

Tests of AFE models have been conducted in the ballistic range at velocities of 1.8 and 4.9 km/s. The objective was to study the wake flow of the AFE. The shadowgraphs clearly show the wake structure of interest, in particular the shear turning angles, wake-neck location, and recompression shocks. The data indicate that shear layer impingement may