Numerical Study of Flow Angles and Mach Number Measurement Using the Surface Pressure of a Supersonic Aircraft with Nose Cone*

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Numerical simulation of the flow around an air data sensor (ADS), which measures flow angles and Mach numbers using surface pressures on a nose cone, was conducted in this study. Effects of the half-cone angle on the flow angle and Mach number measurements were investigated. Results show that a large half-cone angle achieves high sensitivity of flow angle measurements. Results further demonstrated that a small half-cone angle achieves high-sensitivity of Mach number measurements. To satisfy these conflicting requests, we proposed the use of bi-conic nose cones with two gradients. High sensitivity was achieved for both flow angle measurements and Mach number measurements using this bi-conic nose cone.

Key Words: Supersonic Flow, Computational Fluid Dynamics, Air Data Sensor System, Nose Cone

Nomenclature

- D : body diameter
- K_α : coefficient for calculating the angle of attack
- K_β : coefficient for calculating the sideslip angle
- L : nose cone length
- M_∞ : free stream Mach number
- p : pressure
- p_0 : pressure at nose cone tip
- p_1 – p_4 : pressure at nose cone surface
- p_{ave} : average pressure through p_1 to p_4
- p_s : free stream static pressure
- x : axial distance from the nose cone tip
- γ : specific heat ratio
- ΔM_∞ : Mach number measurement error
- Δp : pressure difference
- α : angle of attack
- β : sideslip angle
- ϕ : circumference angle of nose cone
- ψ : half-cone angle of nose cone

1. Introduction

A development study of a microgravity test vehicle using a balloon was conducted by a group comprising members of the Japan Aerospace Exploration Agency (JAXA) and university researchers.¹⁾ In this system, a microgravity environment is realized by dropping a cylindrical vehicle with a nose cone from 40 km altitude. Figure 1 shows the vehicle. To date, two vehicles have been dropped, and microgravity tests were conducted. There are also plans to use this vehicle

as a test-bed of supersonic flight,²⁾ because it can reach the maximum Mach number of 2.0. When we use this vehicle as the supersonic test-bed, we must measure the flow angles and Mach numbers. Therefore, we are planning to employ an air data sensor (ADS).

ADS is a flow measurement system designed to measure flow angles and Mach numbers. ADS obtains the flow parameters by measuring surface pressure on the vehicle. Figure 2 shows the pressure field of ADS. The surface pressure on the vehicle changes as the angle of attack varies. Generally, the lower surface pressure becomes larger than the upper surface pressure when the angle of attack is positive. In this manner ADS calculates the angle of attack and the sideslip angle as well by comparing the measured pressure distribution with the pressure database produced in advance using CFD or wind tunnel tests.

Generally, as the probe of ADS, a five-hole pitot tube with a spherical^{3–5)} or pyramidal⁶⁾ head is often employed. The head of these types of probes is usually mounted on a long tube. Therefore, the pressure orifices are located far from the vehicle's body. These probes have advantages in accuracy because the flow disturbance from the vehicle's body is reduced. However, due to their length these probes present the disadvantage of making the total body length larger. For the microgravity test vehicle described above, the pitot-type ADS was found to be not feasible due to its length and difficulty in the balloon operation. Instead of the pitot-type, ADS that measures surface pressure on the nose cone is employed.

ADS using the vehicle's surface pressure was employed by the Space Shuttle⁷⁾ orbiter, for example. In Japan, a reentry vehicle with a wing developed by the Institute of Space and Astronautical Science (ISAS) also employed this type of ADS.⁸⁾ In this case, the vehicle was streamlined, and had a

Fig. 1. Microgravity test vehicle using a balloon.

Fig. 2. Pressure field of ADS.

complex shape with a wing. However, the microgravity test vehicle in this study has a simple nose cone, which is advantageous for elucidating the principles of ADS.

In previous studies, Cooper and Webster⁹⁾ and Centolanzi¹⁰⁾ studied ADS for supersonic flow using surface pressures on a cone. Their works were compiled in an experimental database for the nose cone with a certain half-cone angle. In Centolanzi's report, some important findings for the nose cone selection were as follows: (1) a larger half-cone angle is preferable to suppress the flow separation, and (2) a larger half-cone angle has the advantage of accuracy in flow angle measurement. However, no evidence data were presented in the report.

In this paper, ADS using the surface pressure of the nose cone for the microgravity test vehicle was studied. Numerical calculations were conducted on the flow field of ADS. The improvement in the measurement accuracy is examined based on numerical calculations. In this study, the Mach number range of the flow is limited from 1.5 to 2.0, which is an important range for the test-bed operation. The effects of the half-cone angle of the nose cone are discussed. In addition, a new advantageous shape is proposed for the flow measurements, and its accuracy is analyzed.

Discussion related to the measurement error of the Mach number and flow angle is carried out in this paper. However, the tolerance in the measurement of ADS for a balloon-based supersonic test-bed has not been clearly defined yet. The tolerance should be determined considering the operational purpose, the availability of sensor accuracy and the procurement costs within the project budget. In this study, the error tolerance is set temporarily to 0.1 for Mach number and 0.2 deg for flow angles.

(a) Computational grid layout around the body

(b) Whole computational grid layout

(c) Contour around the apex

Fig. 3. Computational grid layout.

2. Numerical Method

2.1. Numerical setup and conditions

Figure 3 shows a hemispherical grid, where a three-dimensional inviscid flow calculation was conducted. The grid system includes about 600,000 grid points. There are 120 points along the axial direction, 63 points along the circumferential direction, and 80 points along the radial direction. Figure 3(c) shows that the nose cone apex is blunted. The apex curve radius is $(1/80)D$. We used the AUSM-DV scheme¹¹⁾ and a third-order MUSCL approach.¹²⁾ The LU-SGS scheme¹³⁾ was used for calculating the time integration. Test conditions are shown in Table 1. In this calculation, the Mach number varies between 1.5 and 2.0. The angle of attack is varied as well, between 0 and 10.0 deg, which is expected during supersonic flight tests using the vehicle. Figure 4 presents the nose cone shape and the location of the pressure measurement orifices. Four pressure measurement orifices are located at $x =$

Table 1. Parameters of calculation.

Mach number	1.5, 1.6, 1.7, 1.8, 1.9, 2.0
Half-cone angle	16°, 20°, 30°, 40°
Angle of attack	0°, 2°, 4°, 6°, 8°, 10°

Fig. 4. Nose cone dimensions.

$(2/3)L$, $(2/3)L$ downstream from the apex. These orifices are located every 90 deg along the circumferential direction. The pressures of these four orifices are p_1 to p_4 , respectively. Another orifice exists at the nose cone apex. The pressure of this orifice is assigned as p_0 . The ADS in this study uses these five orifices to calculate the Mach number and flow angles. The half-cone angle of the nose cone varies between 16 and 40 deg. The effect of the half-cone angle on the ADS sensitivity is investigated. We used SX-6, a supercomputer at ISAS/JAXA, for calculations. The Mach number, the angle of attack and the half-cone angle are chosen as parameters of the calculations. Approximately 100 cases of numerical calculations were conducted.

2.2. Measurement procedure

Several different measurement methods to measure the Mach number and the flow angles have been proposed in previous studies. Here we introduce one such method, which was employed in the flight test of the reentry vehicle with a wing by ISAS.⁸⁾ First, the Mach number was calculated using surface pressures p_0 and p_1 to p_4 . The procedure for the Mach number measurements is described in section 3.3. Next, the flow angles are calculated using the following equations.

$$\alpha = \frac{p_1 - p_3}{K_\alpha \{(p_0 - p_2) - (p_4 - p_2)/2\}} \quad (1)$$

$$\beta = \frac{p_4 - p_2}{K_\beta \{(p_0 - p_2) - (p_4 - p_2)/2\}} \quad (2)$$

Here p_1 and p_3 are located on the vertical plane along α ; and p_2 and p_4 are located on the horizontal plane along β . Coefficients K_α and K_β represent the functions of the Mach number. The relation between the Mach number and K_α and K_β must be investigated in advance using wind tunnel tests or computational fluid dynamics. According to these data, polynomials are made. In the flight test, the Mach number is measured first by the surface pressures. Next, K_α and K_β are determined using the polynomials. An example of the K_α and K_β coefficients obtained using wind tunnel results can be seen in our previous study.¹⁴⁾

In this study, the effects of the half-cone angle on the flow angles and Mach number measurement are investigated.

Fig. 5. Typical example of the pressure contours around the nose cone for $M_\infty = 1.72$, $\psi = 20^\circ$ and $\alpha = 9.4^\circ$. Fig. 6. Surface pressure profiles at $x = (1/2)L$.

The sideslip angle β is set at 0 deg to simplify the discussion. Data at $\beta = 0$ are the most important because, in our supersonic flight test, the sideslip angle is managed as 0 by the control system.

3. Results

3.1. Example of flow field

Figure 5 presents an example of the flow field. The Mach number is 1.72 and the flow angle is 9.4 deg in this case. The half-cone angle of the nose cone is 20 deg. Figure 6 portrays the surface pressure distribution along the circumference direction at $(1/2)L$ downstream from the apex. In the figure, the dots represent the experimental results obtained in a previous study.¹⁰⁾ The surface pressure peaks at a certain point. Its minimum value is at the location 180 deg opposite when the vehicle has an attack angle. When the sideslip angle is 0, ADS detects the flow angle by the pressure difference between these two points. As the numerical results in Fig. 6, two results, which are calculated by inviscid flow and viscous flow calculations, are shown. For the viscous flow calculation, the Reynolds number based on the cylinder diameter is 8.11×10^4 , which is consistent with the experimental results in Fig. 6. No turbulence model is used. The

(a) $\psi=16^\circ$ (b) $\psi=40^\circ$

Fig. 7. Pressure and Mach number contours at the half-cone angles of 16 and 40 deg for $M_\infty = 1.5$ and $\alpha = 10.0^\circ$.

results of the viscous flow calculations are slightly larger than those of the inviscid flow calculation because the existence of the boundary layer increases the flow deflection angle. However, the difference is small (approximately 0.02). The ADS detects the flow angles by the pressure difference. Even if the pressure distribution drifts to a higher value, the pressure difference does not change. In Fig. 6, where the angle of attack is 9.4 deg, the maximum pressure difference $\Delta p/p_s$ as measured by the inviscid flow calculation is 0.786. The $\Delta p/p_s$ as measured by the viscous flow calculation is 0.792. Considering these facts and the calculation cost, the inviscid flow calculation was used for this study. The $\Delta p/p_s$ of the experimental study is 0.78. It differs from the inviscid flow calculation result by 0.01. As described later, $\Delta p/p_s$ increases linearly with increased α . According to the linear approximation, the $\Delta p/p_s$ difference of 0.01 causes a 0.1 deg error of the flow angle measurement.

3.2. Effect of the half-cone angle

Figure 7 shows the pressure and Mach number contours around the nose cone at the half-cone angle of 16 deg (Fig. 7(a)) and 40 deg (Fig. 7(b)). The color variation shows the pressure distribution, and the lines show the Mach number contours. In this case, the Mach number is 1.5 and the angle of attack is 10 deg. According to one report,¹⁵⁾ the minimum half-cone angle where the shock is detached is 25 deg under that condition. In Fig. 7(a), where the half-

(a) $M_\infty=1.5$ (b) $M_\infty=2.0$

Fig. 8. Effect of the half-cone angle on the gradient of the pressure difference.

cone angle is 16 deg, the angle of attack is 10 deg. In this case, the deflection angle is 26 deg at the upper part of the cone and 6 deg at the lower part. Detachment of the shock is not observed. In contrast, in Fig. 7(b) where the half-cone angle is 40 deg, the deflection angles at the upper part and the lower part are 50 and 30 deg, respectively. The shock is detached in this case. The sonic line is plotted as a dotted line in Fig. 7(b).

Figure 8(a) shows $\Delta p/p_s$ at $x = (2/3)L$ with variation in the angle of attack. The Mach number is 1.5 and the half-cone angles are 16 to 40 deg in Fig. 8(a). Along with the increase in the angle of attack, $\Delta p/p_s$ increases linearly. The angle of attack is calculated using $\Delta p/p_s$ when β is 0. Therefore, the slope of $\Delta p/p_s$ should be large to enable sensitive measurements. As shown in Fig. 8(a), when the half-cone angles are 16, 20 and 30 deg, the slope of the $\Delta p/p_s$ increases along with the increase in the half-cone angle. However, at the half-cone angle of 40 deg, the slope of $\Delta p/p_s$ decreases; it becomes smaller than that at 20 deg or 30 deg. This tendency is the same at the Mach number

Fig. 9. Pressure profiles of the nose cone surface along the x direction.

of 2.0 (Fig. 8(b)). This decrease in the slope results from detachment of the shock. According to that detachment of the shock, the pressure difference decreases because the high pressure at the upper part can affect the lower part. The flow behind the normal shock wave becomes subsonic, and the surface pressure along to the generatrix of the nose cone decreases gradually from the apex. Figure 9 shows the surface pressure profile along to the x direction. The Mach number is 1.5, the half-cone angles are 16 deg and 40 deg, respectively and the angle of attack is 10.0 deg. The circumference angles ϕ are 0 deg and 180 deg. The x coordinate is non-dimensionalized by the nose cone length L . According to the theory of the flow around a cone, if no shock detachment exists, then the surface pressure is constant along to the generatrix. However, if the shock is detached, the surface pressure decreases along to the generatrix, as in the case of a half-cone angle of 40 deg as depicted in Fig. 9. This pressure decrease can decrease the $\Delta p/p_s$ slope.

Consequently, we arrived at the following conclusion: the increase in the half-cone angle provides sensitive measurement, as pointed out by Centolanzi.¹⁰⁾ However, a limit exists. The slope of the $\Delta p/p_s$ decreases and the sensitivity becomes worse if the half-cone angle increases beyond the limit. The half-cone angle should be large as long as it does not cause detachment of the shock.

3.3. Mach number measurement

In this section, we discuss a way to detect the Mach number using the orifice pressures. Generally, the following equation is used to calculate the Mach number from the pressures. In this equation, the pressure variation by the normal shock is considered.

$$\frac{p_0}{p_s} = \left(\frac{\gamma + 1}{2} M_\infty^2 \right)^{\frac{\gamma}{\gamma-1}} \left\{ \frac{\gamma + 1}{2\gamma M_\infty^2 - (\gamma - 1)} \right\}^{\frac{1}{\gamma-1}} \quad (3)$$

However, in the case of the ADS for the microgravity test vehicle, we cannot place the pressure orifice on the surface parallel to the flow because of the restriction from the vehicle design. Therefore, we cannot measure the static pressure directly. In addition to that, if we can place the pressure

(a) $\alpha=4^\circ$

(b) $\alpha=10^\circ$

Fig. 10. Pressures measured at each pressure orifice with the variation in the roll angle for $M_\infty = 1.5$ and $\psi = 16.0^\circ$.

orifice there, then the measured pressure varies along with the flow angle variation. Therefore, we use the surface pressures of the nose cone to calculate the Mach number. Specifically, we use p_{ave} , the averaged value of p_1 to p_4 , which are the pressures at $x = (2/3)L$. The polynomial of p_{ave} is used for calculating the Mach number.

Figure 10 depicts pressures measured on the four orifices (see Fig. 4) and the averaged pressure when the Mach number is 1.5, the half-cone angle is 16 deg and the roll angle ϕ varies between 0 and 360 deg. The pressure distribution shape resembles that of a sine curve (Fig. 6). When the roll angle ϕ varies, each pressure orifice measures the pressure distribution whose phase is different by 90 deg. The averaged value p_{ave} does not vary with variation in the roll angle. Therefore, the Mach number measurement is not affected by the roll angle. In addition to that, the effect of the flow angle on the averaged value is small. Figure 11 portrays the variation of the p_{ave}/p_s against α . The p_{ave}/p_s decreases slightly with the increase in the angle of attack. The amount of the decrease is 0.02 at a Mach number of 1.5, where the amount

Fig. 11. Effect of α on p_{ave}/p_s . Fig. 12. Slope of p_0/p_{ave} against Mach number.

is the maximum. The effect of the decrease in p_{ave} on the Mach number measurement is discussed later.

Next, we obtain the polynomial to correlate p_{ave} with the Mach number. In previous studies, Centolanzi¹⁰⁾ considered the Mach number as a function of p_0/p_{ave} . Hirotsu et al.⁶⁾ regarded the Mach number as a function of $(p_0 - p_{ave})/p_{ave}$. However, this is also the function of p_0/p_{ave} ; that is, no fundamental difference exists. Based on these studies, we regard the Mach number as a function of p_0/p_{ave} in this study.

Figure 12 portrays the variation of p_0/p_{ave} according to Mach number variation. Here the angle of attack is 0, and the half-cone angle is 16 to 40 deg. The slope of p_0/p_{ave} should be large for sensitive measurement of the Mach number. The graph shows that the smaller half-cone angle provides the larger slope. Therefore a small half-cone angle is desirable for Mach number measurements. In particular, for a half-cone angle of 40 deg, the value of p_0/p_{ave} varies only slightly with variation of the Mach number. In this case, the error of the measurement becomes large and the measurement becomes unreliable.

Table 2. Coefficients in Eq. (4).

Half-cone angle	a_0	a_1
16°	0.322	0.490
40°	-7.58	6.74

Here we evaluate the error of the Mach number measurement with variation of the half-cone angle. The errors of 16 and 40 deg in the half-cone angle are compared. The plotted lines shown in Fig. 12 approximate the line using the least-squares method. The following equation is obtained.

$$M_\infty = a_0 + a_1 \left(\frac{p_0}{p_{ave}} \right) \quad (4)$$

The constants in the equation are presented in Table 2. We assume that p_{ave}/p_s has error of 0.02, which results from the variation of α , as described above. The following equation is used to calculate the error of the Mach number measurement.

$$\Delta M_\infty = a_1 \Delta \left(\frac{p_0}{p_{ave}} \right) \quad (5)$$

The error is 0.02 at the half-cone angle of 16 deg, and 0.22 at the half-cone angle of 40 deg. The error at the half-cone angle of 40 deg is more than ten times greater than that at 16 deg.

The Mach number measurement sensitivity becomes greatest if we place the pressure orifice on the horizontal part of the cylinder at $x > L$. However, one problem is placement of the pressure orifice there. When the vehicle has an angle of attack, some place on the cylinder must have a negative deflection angle. Consequently, the flow expansion occurs and flow separation might occur. The flow separation makes ADS difficult because the surface pressure on the separated points is unstable. The ADS using the nose cone surface pressures presents the important benefit that flow separation does not occur easily because the negative deflection angle does not appear until the angle of attack becomes greater than the half-cone angle.

Section 3.1 described that the effect of the viscous terms on the flow angle measurement is small. Regarding the Mach number measurement, the viscous terms slightly affect the measurement because a boundary layer exists in the case of the viscous calculation, which makes the deflection angle large. Results show that the surface pressure increases. For example, when the Reynolds number is 8.11×10^4 , the half-cone angle is 20 deg and the angle of attack is 0; the viscous calculation shows a difference of 0.02 in p_0/p_{ave} . This difference produces measurement error of 0.02 in the Mach number. However, we neglect this error because it is too small to affect the results of this study.

3.4. Measurement using a bi-conic nose cone

According to the discussions described above, results showed that a large half-cone angle is preferred for measuring flow angles, and that a small half-cone angle is preferred for measuring Mach number. These contradictory requirements must be satisfied to achieve high accuracy in both measurements. Therefore, we propose use of a bi-conic nose

Fig. 13. Bi-conic nose cone.

Fig. 14. Dimensions of the bi-conic nose cone.

cone which has two different gradients. Figure 13 depicts such a nose cone. The large gradient part of the nose cone is used for the measurement of the flow angles; the small gradient part is used for the measurement of the Mach number. The nose cone dimensions are presented in Fig. 14. The location of the border between the large and small gradient parts is set at $x = (1/5)L$. The pressures at $x = (1/10)L$ are used for the flow angle measurement, and the pressures at $x = (2/3)L$ are used for the Mach number measurement. The apex is blunted, as shown in Fig. 3. The entire length of the nose cone is set as equal to a simple nose cone whose half-cone angle is 16 deg. When we set the gradient of the first stage as 30 deg, the gradient of the second stage becomes approximately 12 deg.

Figure 15 depicts the pressure difference between the maximum pressure and the minimum pressure at $x = (1/10)L$ with variation in the angle of attack. Similar pressure differences of the simple nose cone are also presented in Fig. 15. For the simple nose cone, the pressure differences presented in Fig. 15 are those at $x = (2/3)L$. Although the pressure difference of the bi-conic nose cone is slightly different at high angles of attack, the graph is almost identical to that of the simple nose cone whose half-cone angle is 30 deg. Therefore the bi-conic nose cone sensitivity is the same as that of the simple nose cone whose half-cone angle is 30 deg. Figure 16 portrays the gradient of the p_0/p_{ave} with variation in the Mach number. To calculate the values of bi-conic nose cone, the pressures at $x = (2/3)L$, where the gradient of the surface is 12 deg, are used. Therefore the slope of p_0/p_{ave} , which is relative

Fig. 15. Difference between the maximum and minimum pressure at $x = (1/10)L$.

Fig. 16. Sensitivity of Mach number measurement.

to the sensitivity, is greater than that of the simple nose cone whose half-cone angle is 16 deg. Results show that the bi-conic nose cone provides high sensitivity of measurements of both the Mach number and the flow angle.

The bi-conic nose cone merits are not confined to its high sensitivity for ADS, but also include the low aerodynamic drag. For example, we compared the drag coefficient of the nose cone under conditions where the angle of attack is 0 deg and Mach number is 1.5. The drag coefficient of the simple nose cone whose half-cone angle is 16 deg is 0.252. However, the drag coefficient of the bi-conic nose cone, which has the same length as the simple nose cone, is 0.223. Therefore, the drag coefficient of the bi-conic nose cone is smaller by almost 10%. Notably, this calculation is inviscid. Therefore, the friction drag is not included in this drag coefficient. Similarly, a blunted tangent ogive nose cone gives good sensitivity if the Mach number is measured using the downstream part where the gradient is small. The flow angle is measured using the upstream part, where the gradient is large. In this case, the drag coefficient can be smaller than that of the bi-conic nose cone.

4. Conclusions

A numerical study of the air data sensor system, which uses the surface pressure of the nose cone, was conducted. The background of this study is the supersonic flight test vehicle, which uses free fall from a high-altitude balloon. The ADS measures the Mach number and flow angles via the surface pressures. Calculations were conducted under conditions where the Mach number is 1.5 to 2.0 and the angle of attack is 0 to 10 deg. Effects of the half-cone angle of the nose cone on measurement of the Mach number and the flow angle were investigated. The following results were obtained.

1) The half-cone angle should be large for sensitive measurement of the flow angle. However, the shock is detached if it becomes too large, thereby worsening the ADS sensitivity.

2) The half-cone angle should be small for sensitive measurements of the Mach number.

3) We proposed the use of a bi-conic nose cone whose surface has two gradients. Using such a nose cone, we can achieve sensitive measurements of both the Mach number and the flow angle.

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