THE CHARACTERISTICS OF A CYLINDRICAL PROBE AT HIGH SUBSONIC SPEEDS

PART 2. THE CASE HAVING INCLINATION ANGLES*

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Abstract

In measuring high subsonic internal flows which are observed in high speed turbomachines such as transonic or supersonic compressors, authors planned to use a cylindrical probe which was supported at both ends, and got satisfactory results in the case of zero inclination angle.

Futhermore, the inclination characteristics of this probe were investigated experimentally and it was revealed that the yaw angle of flow could be easily obtained independently of both Mach number M_∞ and inclination angle α. It was also revealed that the flow component normal to the probe axis could be obtained with a fair accuracy from the characteristics of zero inclination angle within the range of not too large inclination angles (about $\pm 15°$).

1. Introduction

In measuring high subsonic internal flows which are observed in high speed turbomachines such as transonic or supersonic compressors, authors planned to use a cylindrical probe which was supported at both casing walls (outer and inner), and got satisfactory results on the characteristics at high speeds in the case of zero inclination angle[1].

Since the real flows in turbomachines, even in axial-flow type ones, have radial components, we must know the characteristics of the probe in such inclined flows (flows having attack angles).

Although the cylindrical probe is convenient for the measurement of flows in the plane normal to its axis, it is generally supposed to be inconvenient in the case having an inclination angle. This experimental investigation on the characteristics in the case having inclination angles is to reveal that the flow component normal to the probe axis can be obtained, provided inclination angles are not too large (about $\pm 15°$).

We can say consequently this type of cylindrical probe may be very useful for the measurement of flows having not too large inclination angles.

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2. Symbols

M_∞ : free stream Mach number
$\overline{M}_\infty$: Mach number of flow component normal to the probe axis ($\overline{M}_\infty = M_\infty \cos\alpha$) (see Fig. 2)
P : pressure measured on a cylindrical probe with one hole
P_0 : total pressure
$\overline{P}_0$: total pressure of flow component normal to the probe axis (see Fig. 2)
P_S : static pressure
P_A, P_B, P_C: pressures on three pressure holes of a cylindrical probe (see Fig. 2)
Y_θ : direction coefficient
Y_S : static pressure coefficient
Y_T : total pressure coefficient
$\overline{Y}_T$: total pressure coefficient defined by $\overline{P}_0$ in place of P_0
ΔY_S : difference between Y_S at any other Mach number and Y_S at a base Mach number
$\Delta Y_{S\,\mathrm{mean}}$: mean value of ΔY_S at various θ
α : inclination angle (attack angle) (°)
θ : yaw angle or peripheral angle (°)

Subscripts
b : value at a base Mach number
m : mean value to various Mach numbers

3. Apparatus

A rough sketch of the wind tunnel used in this experiment is shown in Fig. 1. Two nozzles having discharge areas of 200×25 mm² (Nozzle I) and 100×50 mm² (Nozzle II) were prepared. Figure 2 shows a three-hole cylindrical probe used in this experiment. A device shown in Fig. 3 was employed in order to vary inclination angles. The center of rotation of the turn table was made to coincide with the pressure hole position of the probe.

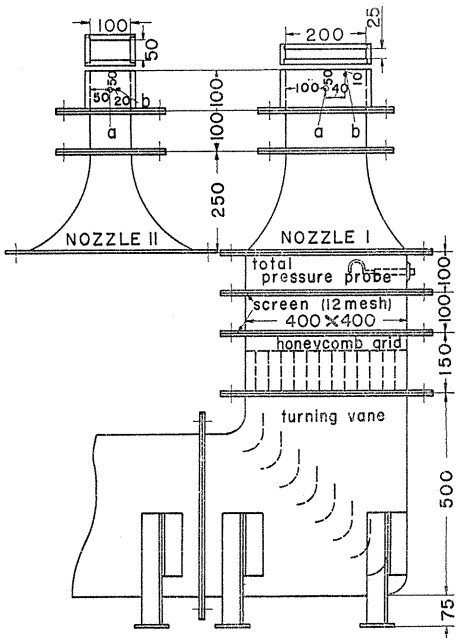


FIG. 1. Wind tunnel.

4. Preliminary investigation

From the practical point of view, the calibration of the probe is desired to be done in the flow with the solid walls of nozzle which are similar to ones inside a turbomachine. But because of the technical difficulty to vary inclination angles continuously inside the noz-

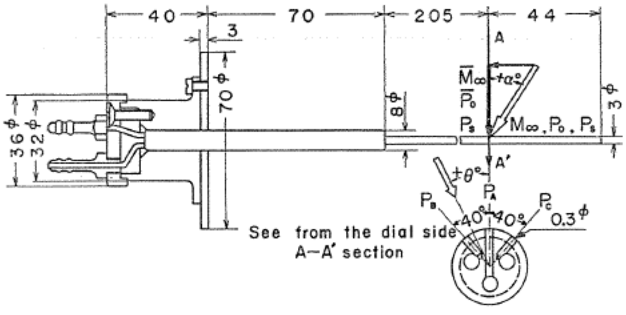


FIG. 2. Three-hole cylindrical probe.

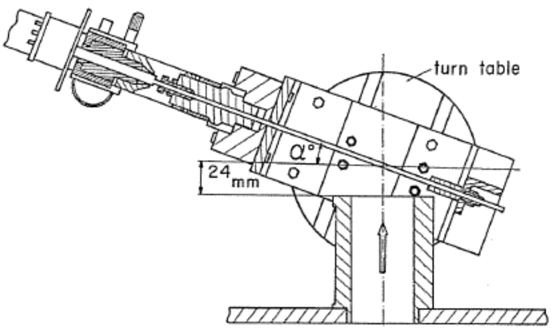


FIG. 3. Three-hole cylindrical probe and wind tunnel.

zle, the experiments were carried out in the jet stream outside the nozzle. Accordingly, it was necessary to confirm the pressure distribution around a cylinder in the jet stream to be the same as one inside the nozzle.

A cylinder was located at the position 24 mm outside the discharge surface of Nozzle I and Nozzle II, and identification of the pressure distribution around the cylinder was examined with the one at inserting position in Nozzle I (same as a-1 position shown in Fig. 1 of Part 1 of the paper[1]). When a cylinder was inserted into the nozzle, the flow Mach number was calculated by the method of the same paper[1]. And when a cylinder was inserted in the jet stream, the calculations of the Mach number needs a value of static pressure at the cylinder. This was obtained by modifying the wall pressure using the relation between the wall pressure without a cylinder (b-position in Fig. 1) and the static pressure at the inserting position.

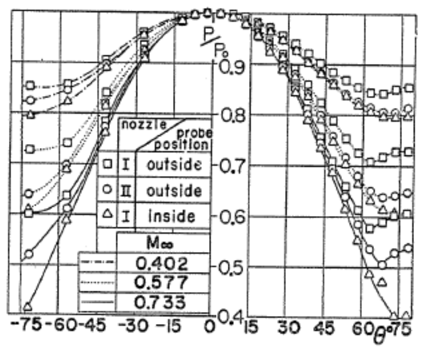


FIG. 4. Pressure distribution around a cylinder.

The results are shown in Fig. 4. When peripheral angles θ are limited to the values from $-60°$ to $+60°$, the pressure distribution around a cylinder in the jet stream of Nozzle II is nearly identical with the one inside the wall of Nozzle I. The large difference between cases inside and outside Nozzle I may be due to the small discharge jet width which is 25 mm. Because almost same flows around the cylinder were expected to be established in the jet stream of Nozzle II and inside the wall of Nozzle I, authors decided to do investigations in the jet stream of Nozzle II (at the 24 mm outside the discharge surface).

5. Test procedure

Seven flow Mach numbers of about 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.82 were taken. The inclination angles α (see Fig. 2 and Fig. 3) were varied from $-30°$ to $+30°$ at intervals of 5° and the yaw angles θ from $-20°$ to $+20°$ at intervals of 2°. According to the results of preliminary investigations mentioned above, Nozzle II was used and the pressure hole position of the probe was set at 24 mm out of the discharge surface.

6. Results and considerations

The characteristics of a cylindrical probe were arranged into the following coefficients. These are the same that were used in Ref. 1 except the total pressure coefficient. Although the real flow has an inclination angle to the probe, it is expected that the flow component normal to the probe axis has a primary effect on three pressure holes. For this reason the total pressure coefficient was defined by the total pressure corresponding to the velocity normal to the probe axis.

$$\text{direction coefficient} \quad Y_\theta = \frac{P_B - P_C}{D} \tag{1}$$

$$\text{total pressure coefficient} \quad \overline{Y}_T = \frac{\overline{P}_0 - P_A}{D} \tag{2}$$

$$\text{static pressure coefficient} \quad Y_S = \frac{(P_S - P_B) + (P_S - P_C)}{2D} \tag{3}$$

where

$$D = \frac{1}{2}\{(P_A - P_B) + (P_A - P_C)\} \tag{4}$$

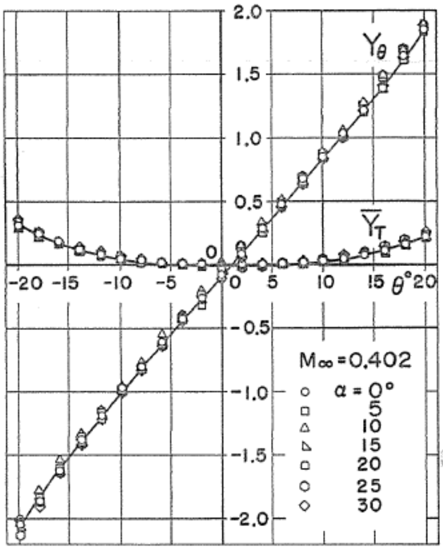
Both Fig. 5 and Fig. 6 show the variations of foregoing coefficients against yaw angles θ, taking an inclination angle as a parameter at each Mach number (Minus parts of α and some parts of M_∞ were omitted).

(1) Direction coefficient Y_θ

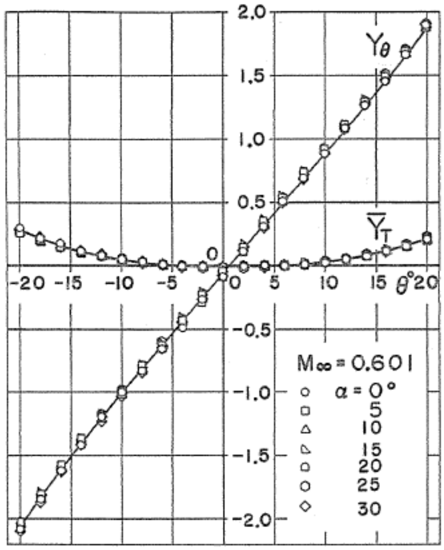
The direction coefficient Y_θ changes little with Mach numbers and inclination angles α except low Mach numbers. Therefore, Y_θ can be represented by only one curve even in an inclined flow. The mean curve which was obtained in this experiment is shown in Fig. 7 (This is a mean for the values at various Mach numbers in the case of zero inclination angle).

(2) Total pressure coefficient $\overline{Y}_T$

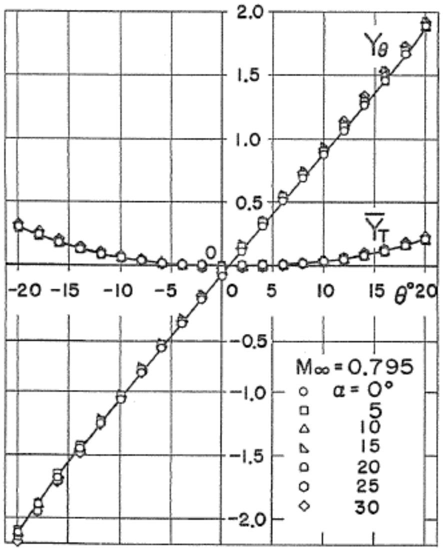
The total pressure coefficient $\overline{Y}_T$ also changes little with Mach numbers M_∞



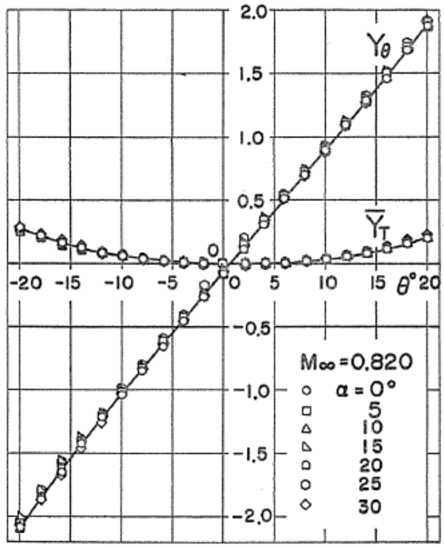
(a) Y_θ, $\overline{Y}_T \sim \theta$



(b) Y_θ, $\overline{Y}_T \sim \theta$



(c) Y_θ, $\overline{Y}_T \sim \theta$



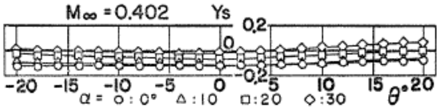
(d) Y_θ, $\overline{Y}_T \sim \theta$

FIG. 5

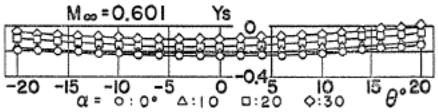
and inclination angles α. Therefore, $\overline{Y}_T$ can be represented also by only one curve. The mean curve which was obtained in this experiment is shown in Fig. 7 (This is a mean for the values at various Mach numbers in the case of zero inclination angle).

(3) *Static pressure coefficient* Y_S

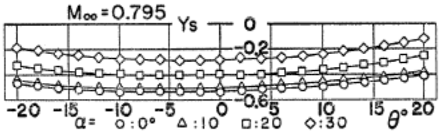
It was described in Ref. 1 that the free stream Mach number M_∞ and the



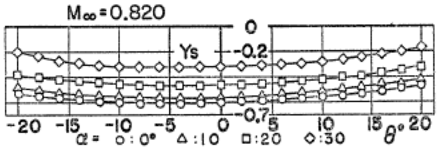
(a) $Y_S \sim \theta$



(b) $Y_S \sim \theta$



(c) $Y_S \sim \theta$



(d) $Y_S \sim \theta$

FIG. 6

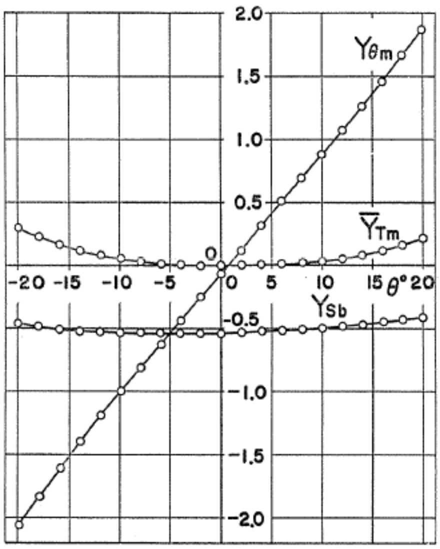
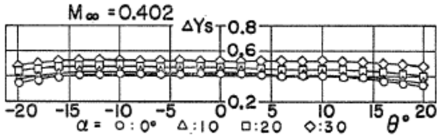
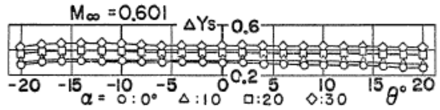


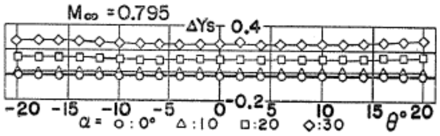
FIG. 7. $Y_{\theta m}$, $\bar{Y}_{Tm}$, $Y_{Sb} \sim \theta$



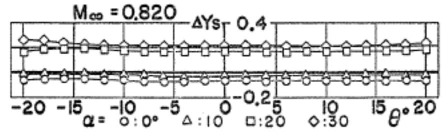
(a) $\Delta Y_S \sim \theta$



(b) $\Delta Y_S \sim \theta$



(c) $\Delta Y_S \sim \theta$



(d) $\Delta Y_S \sim \theta$

FIG. 8

static pressure P_S could be obtained simultaneously by making use of the difference ΔY_S from a base Mach number and by the successive method in the case of zero inclination angle. Authors considered whether the same method as above could be used or not in the case having an inclination angle. It is observed from Fig. 6 that the variation of static pressure coefficient Y_S to inclination angles at a constant Mach number M_∞ can be regarded as a parallel moved one and when an inclination angle was kept constant the variation to Mach numbers M_∞ is also nearly parallel moved one. Therefore, taking a static pressure coefficient at a certain Mach number ($M_\infty=0.795$ in this paper) and an inclination angle ($\alpha=0°$) as a base, the difference from other Y_S was considered (Fig. 8).

$$\text{Namely,} \quad \Delta Y_S = Y_S - Y_{Sb} \tag{5}$$

where,

$$Y_{Sb} = Y_S \ (M_\infty = 0.795, \ \alpha = 0°)$$

Within a range of $|\theta|<15°$ at a low Mach number ($M_\infty=0.402$) and $|\theta|<20°$ at higher Mach numbers, ΔY_S is almost constant with respect to θ at every inclination angle α. Therefore, ΔY_S at each inclination angle can be represented by the single mean value for the values at yaw angles within ranges noted above. This is named $\Delta Y_{S\,\text{mean}}$.

Because the flow which the probe can perceive in the case having an inclination angle is thought to be the flow component normal to the axis as stated above, $\Delta Y_{S\,\text{mean}}$ is expected to be on one smooth curve if we plot it against the Mach number $\overline{M}_\infty$ normal to the axis in place of the real Mach number M_∞ (Fig. 9). The results show that $\Delta Y_{S\,\text{mean}}$ departs from the curve of zero inclination angle as the inclination angle increases. This probably arises from the fact that the flow perceived by the probe contains not only the normal component but also the parallel component. But within a range of small inclination angles α (about $\pm 15°$) the character of $\alpha=0°$ may be substituted for others. The flow direction θ, the total pressure $\overline{P}_0$, the Mach number $\overline{M}_\infty$ and the static pressure P_S can be calculated from the coefficients obtained above as follows.

(*1*) *Direction θ and total pressure $\overline{P}_0$*

Yaw angle θ can be calculated readily from Eq. 1 and Fig. 7. Since $\overline{Y}_T$ is also obtained from Fig. 7 at the same time, $\overline{P}_0$ can be calculated easily from Eq. (2).

(*2*) *Mach number $\overline{M}_\infty$ and static pressure P_S*

In order to calculate $\overline{M}_\infty$ and P_S the successive approximation method must be used. Y_{Sb} can be obtained from Fig. 7 using θ which is obtained beforehand. As a next step, assuming $\overline{M}_\infty$, we can get ΔY_S from Fig. 9 and Y_S from Eq. (5).

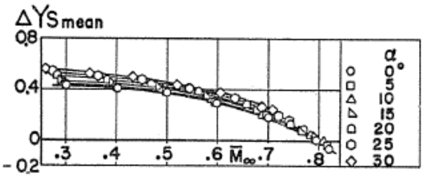


FIG. 9. $\Delta Y_{S\,\text{mean}} \sim \overline{M}_\infty$

Since P_S can be obtained from Eq. (3), $\overline{M}_\infty$ can be obtained from this P_S and $\overline{P}_0$ which was calculated beforehand. The Mach number $\overline{M}_\infty$ and the static pressure P_S can be calculated by repeating this procedure till $\overline{M}_\infty$ converges. $\overline{M}_\infty$ can be obtained with an accuracy of 0.01 within the inclination angles of $|\alpha|<15°$.

7. Conclusions

The following conclusions were revealed as the characteristics of a cylindrical probe in the case having inclination angles at high subsonic speeds.

(1) The yaw direction of the flow can be readily obtained regardless of Mach number and inclination angle.

(2) The real total pressure P_0 cannot be obtained. But total pressure $\overline{P}_0$ which corresponds to the velocity component normal to the probe axis can be obtained regardless of Mach number and inclination angle.

(3) The static pressure coefficient is a function of Mach number M_∞ and inclination angle α. But if $|\alpha|$ is less than 15°, the static pressure P_S and the normal component of Mach number $\overline{M}_\infty$ can be obtained with a considerable accuracy by using the characteristics in the case of zero inclination angle.

Acknowledgement

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