THE CHARACTERISTICS OF A CYLINDRICAL PROBE AT HIGH SUBSONIC SPEEDS

(Part 1: The Case of Zero Inclination Angle)*

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Abstract

In using the probe to measure the direction and the speed of high subsonic internal flows which are observed in high speed turbomachines such as transonic or supersonic compressors, the characteristics of the probe must be known beforehand.

As a first step, the characteristics of a cylindrical probe at high subsonic speeds were investigated in the case of zero inclination angle.

The experiments were carried out over a range of flow Mach numbers from 0.3 to 0.79. Yaw angles were varied from $-20°$ to $+20°$.

Both the direction and the total pressure coefficients obtained were independent of Mach numbers. Hence, in the practical application of the probe as a yawmeter, the direction of wind velocity and the total pressure can be obtained directly from simple calibration curves.

Although the static pressure coefficient obtained was a function of Mach number, a simple relation was observed within yaw angles of $\pm 10°$, and the static pressure and the Mach number can be easily obtained in this range by the successive approximation method.

1. Introduction

In measuring the direction and the speed of high subsonic internal flows which are observed in high speed turbomachines such as transonic or supersonic compressors, several difficult problems exist.

Things to be considered are enumerated as follows.

(1) The substantial part and the support of a probe must be as small and thin as possible. This condition is required to make the choking effect being minimum, and make the disturbance exerted by the probe in upstream and downstream as small as possible. The small size is also important for the requirement to insert the probe into the narrow space between blade rows.

(2) The structure of a probe must have enough strength. This is important because the support must be thin from the condition (1).

(3) A probe must be able to measure the flow close to the casing wall. This arises from the requirement to measure the boundary layer of the wall which is very important from the standpoint of secondary flows.

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(4) The shape of support must not have a great effect on the flow. The flows in turbomachines have different directions at each radial station. Therefore, if a simple streamline type support is inserted the direction of flow will be disturbed.

(5) The effects of inclination (attack) angle on the characteristics of the probe must be known clearly. Because the flows in turbomachines have often radial components, the possibilities are required that the measurement of the inclination angle is possible or the effect of inclination angle is clear.

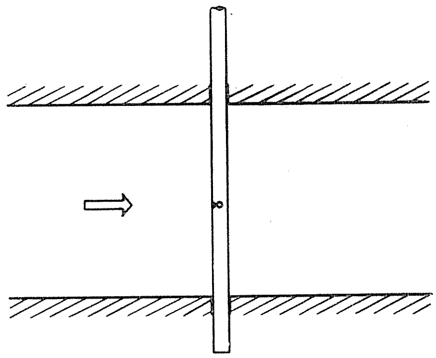

FIG. 1. Cylindrical probe in the flow passage.

(6) High speed characteristics of the probe must be good. If the variation of characters with Mach number is not mild, inconveniences will be felt in data analyses.

Because of reasons mentioned above, a cylindrical probe supported at both side walls was planned to use as shown in Fig. 1. In this case, conditions (1), (2), (3) and (4) are seemed to be satisfied fairly well. About the condition (5), the cylindrical probe has a convenient character at low speed[1], but further experiments will be needed whether this character will be kept at high speed. In this report discussions on it are not included. About the condition (6), although it was thought to be inadequate that the cylindrical probe is inserted into high subsonic flows, the result is not so bad as feared. It is also one of the objects of the experiment to investigate on this condition in detail.

2. Symbols

- M' Mach number calculated from the static pressure at the station f, 2 (Nozzle I in Fig. 3)
- M_∞ free stream Mach number
- P wall pressure or pressure measured by a cylindrical probe with one hole
- P_O total pressure
- P_S static pressure
- P_A, P_B, P_C pressures on three pressure holes of a cylindrical probe (Fig. 4)
- P_a atmospheric pressure
- Y_θ direction coefficient
- Y_S static pressure coefficient
- Y_T total pressure coefficient
- ΔY_S difference between Y_S's at a Mach number and base Mach number (see Eq. 5)
- α inclination angle (attack angle), (degree), ($\alpha=0°$ in this report)
- θ yaw angle, (degree)

subscripts

- b value at base Mach number
- i value when a cylinder was inserted
- m mean value to various Mach numbers

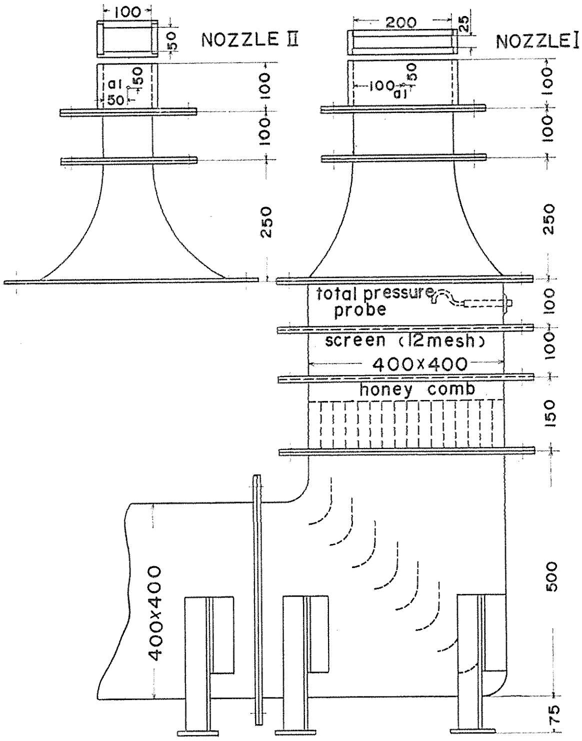

FIG. 2. Wind tunnel.

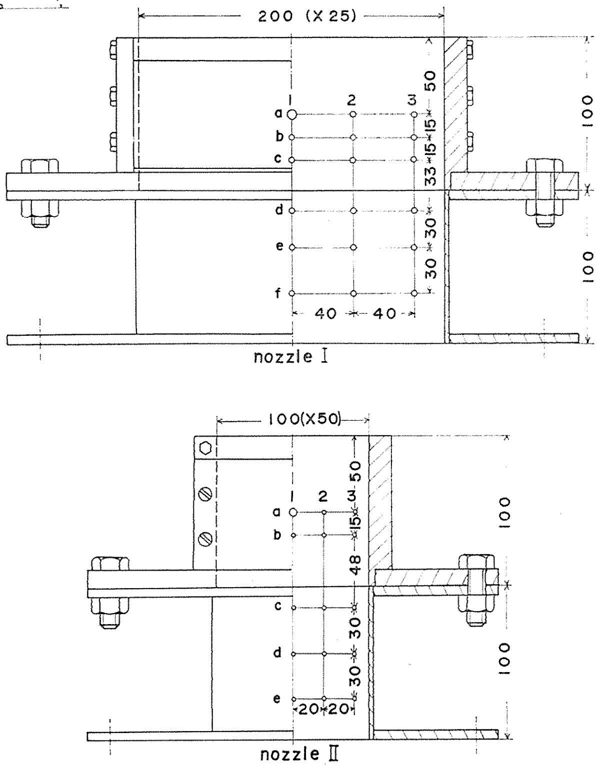

FIG. 3. Nozzle I and Nozzle II.

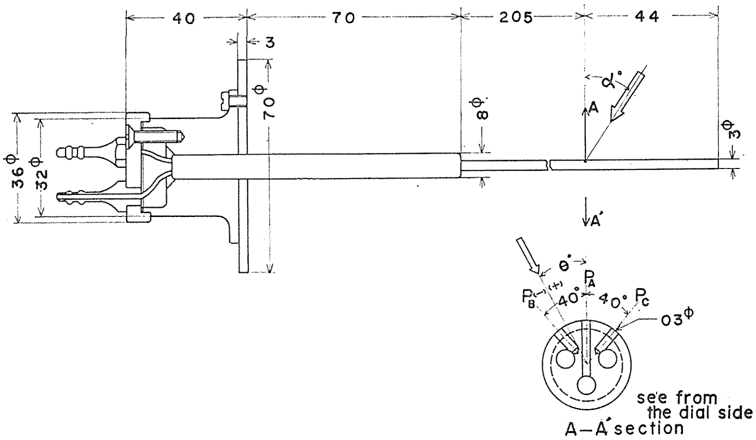

FIG. 4. Three-holes cylindrical probe.

3. Apparatus

A rough sketch of the wind tunnel used in this experiment is shown in Fig. 2. Two nozzles with discharge areas of 200 × 25 mm and 100 × 50 mm were prepared (Fig. 3). Notations of *a*, *b*, *c*, *d*, *e*, *f* and 1, 2, 3, represent static pressure hole locations. *a*, 1 is the inserting position of a cylindrical probe. Figure 4 shows a three-hole cylindrical probe used in this experiment.

4. Preliminary investigations

4.1. The pressure distribution around a cylinder and the location of pressure holes

The pressure holes of a cylindrical probe must be apart properly from the point of view of sensitivity, but are desired not to enter into the separation region and the region behind a shock wave at yaw angles to some degree.

And so, pressure distributions around a cylinder were surveyed over five

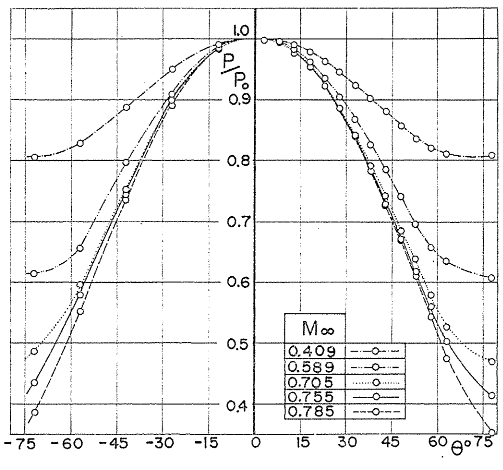

FIG. 5. Pressure distribution around a cylinder in Nozzle I.

Mach numbers (calculations of those are described hereafter) using Nozzle I and a 3 mm-diameter probe with a 0.3 mm-diameter hole (Fig. 5).

At each Mach number, the pressure distribution is smooth at $|\theta| \leqq 60°$ and therefore the flow is seemed not to separate in this region. Seeing from the pressure distribution, the supersonic speed portion is supposed to exist at $M_\infty = 0.705$ and above, but shock wave existence is not clear. This may suggest that in spite of shock wave existence, its intensity is very weak, the boundary layer is pretty thick, the flow on the cylinder surface separates immediately just behind the shock, or the pressure hole may be large compared with the diameter of the cylinder.

Anyway, within yaw angles of $|\theta| \leqq 60°$, the flow around a cylinder can be thought not to be singular. Therefore, three pressure holes were located 40° apart, and this probe was thought to be usable over a range of yaw angles $-20° \leqq \theta \leqq +20°$.

4.2. The problem in measuring the static pressure at the wind tunnel wall

In calibrating a cylindrical probe, the flow Mach number can be obtained from the static pressure measured at the wind tunnel wall. But some problems existed about its station. The following two conditions were taken into account.

(1) Effects exerted on the surrounding by the cylinder. Since the flow near the cylinder is affected by the existence of the latter, a precise flow Mach number cannot be obtained from the static pressure hole in the vicinity of the cylinder.

(2) The effect of the wall boundary layer. As frictional losses and the boundary layer growth exist along the flow passage, the static pressure taken from a hole far upstream of the cylinder cannot be directly used for the calculation of Mach number.

At first, using Nozzle I the static pressure distributions on the wall were surveyed without a cylinder inserted, and then the same experiment was done with it (Fig. 6). The volume flows were controlled to give same Mach numbers at sufficiently upstream of the cylinder in both experiments. Although the static pressure gradient was found to exist along the flow passage from these results, it was clarified that the pressure gradient little depended on whether a cylinder existed or not (except in the neighborhood of the cylinder). Now, when the pressure without a cylinder is subtracted from the one with a cylinder at

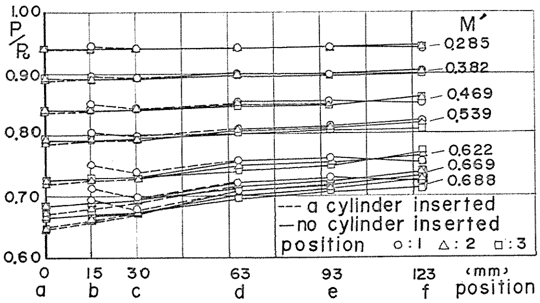

FIG. 6. Pressure distribution along the wall of Nozzle I.

the same M', the effects of a cylinder on the upstream can be investigated (assumed that frictional losses along the flow passage are same in both cases) (Fig. 7). We can say that the effects of the cylinder are small in the upstream at position d as shown in Fig. 7. Because d is 63 mm upstream from the cylinder, it may be reasonable to conclude that the effect of a cylinder is small in the upstream 20 times of the cylinder diameter. The flow Mach number in this report was thus calculated by finding the static pressure at the position of the cylinder which was calculated from the static pressure at (d, 2) by the correcting method including the static pressure correction mentioned above.

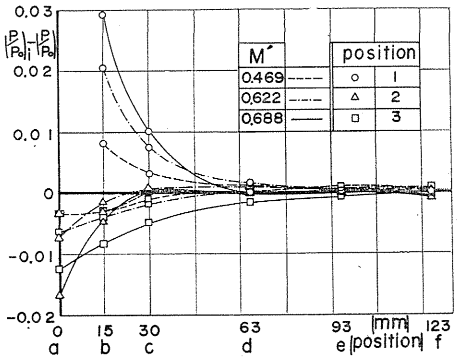

FIG. 7. Effect of cylinder on static pressure along the wall.

4.3. The problem of choking

On the experiment at high subsonic speed with a relatively small exit area, choking of a wind tunnel should be considered. The choking Mach number of 0.87 could be calculated from one-dimensional theory on Nozzle I with a cylinder inserted, but if the boundary layer growth was taken into account, the flow would choke at a lower value and the experiment will be restricted to at lower Mach numbers.

Examination of the increase of Mach number with the increase of tunnel total pressure (shown in Fig. 8) shows us that there is no worry about choking till about Mach number of 0.80.

In order to investigate the effect of choking of a wind tunnel on the pressure distribution around a cylinder, the pressure distributions in Nozzle I and Nozzle

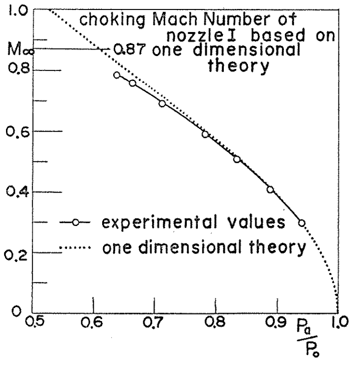

FIG. 8. Mach number variation versus tunnel total pressure.

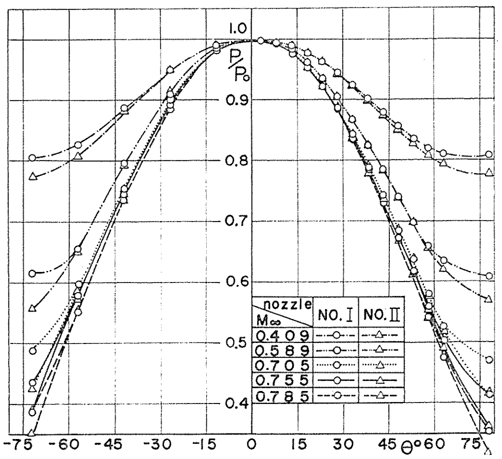

FIG. 9. Comparison between pressure distribution around a cylinder in Nozzle I and Nozzle II.

II were compared (Fig. 9). In Nozzle II the effect of choking is expected to exist strongly and if the difference between both nozzles is large, the pressure distributions in Nozzle I should be reconsidered. Fortunately, within $|\theta|=60°$, the static pressure distributions are thought to be same on both nozzles. Therefore, within this range, the pressure distribution is thought to be little affected by choking and it is concluded reasonably that this probe can be used in Nozzle I without any fear about choking.

5. Test procedure

The experiments were done with zero inclination angle. Seven flow Mach numbers of about 0.3, 0.4, 0.5, 0.6, 0.7, 0.76 and 0.79 were taken. Yaw angle θ was varied from $-20°$ to $+20°$ at intervals of 2°.

The wind tunnel used for this experiment consists of Nozzle I, and the position of a cylindrical probe is $(a, 1)$ which are shown in Fig. 2 and Fig. 3.

The definition of yaw angle is shown in Fig. 4.

6. Results and considerations

It is convenient to represent the characteristics of the probe in forms of coefficients. In this report the following coefficients were used.

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

$$\text{total pressure coefficient } Y_T = \frac{P_O - P_A}{D} \tag{2}$$

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

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

These coefficients are same as those which were used in Ref. 1. Although the use of other type of coefficients was tried, satisfactory results could be obtained by coefficients mentioned above. Variations of each coefficient with yaw angles are illustrated in Fig. 10 in taking Mach number as a parameter.

(1) Direction coefficient Y_θ and total pressure coefficient Y_T.

Variations with Mach numbers are small. Therefore, only one curve for Y_θ or Y_T which is the mean value of curves is thought to be sufficient to express Y_θ or Y_T characteristic. These results are shown in Fig. 11.

Thus the direction and the total pressure can be obtained easily without regard to Mach numbers.

(2) Static pressure coefficient Y_S.

Variations with Mach numbers are large. But except at low Mach numbers, Y_S curve at each Mach number may be regarded as a parallel-moved one over a range of small θ's. Taking Y_S at a certain Mach number as a base, say Y_{Sb}, differences between it and Y_S's at other Mach numbers were calculated.

$$\Delta Y_S = Y_S - Y_{Sb} \tag{5}$$

$$\text{where } Y_{Sb} = Y_S \ (M_\infty = 0.759)$$

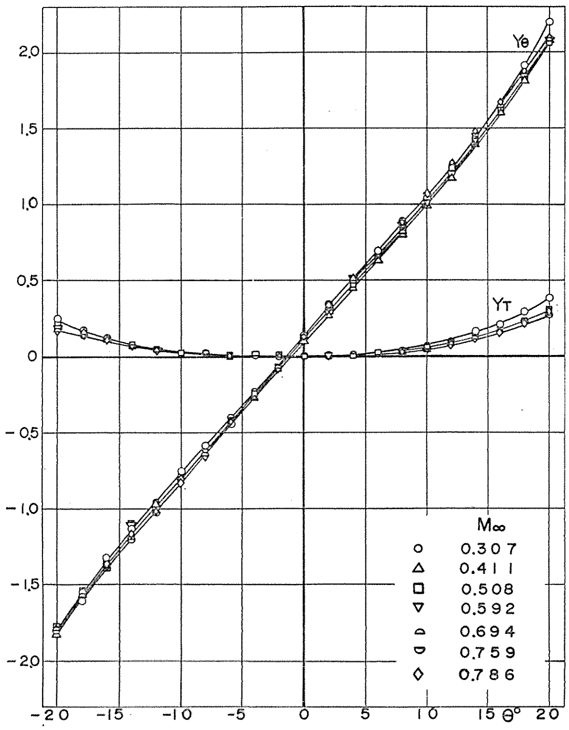

FIG. 10 (a). Y_θ, $Y_T \sim \theta$.

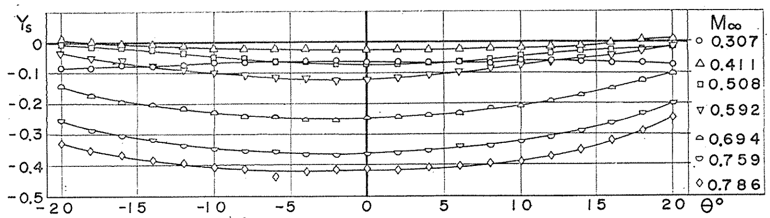

FIG. 10 (b). $Y_S \sim \theta$.

The relation between ΔY_S and θ is shown in Fig. 12. From this figure, ΔY_S is thought to be constant, within $|\theta| = 10°$ at $M_\infty = 0.508$ and within $|\theta| = 20°$ at higher Mach numbers, but appearances are different at $M_\infty = 0.307$ and 0.411. Therefore, ΔY_S, except at low Mach numbers, can be a function of only M_∞. The relation between ΔY_S and M_∞ are shown in Fig. 13.

The methods of calculating the direction, total pressure, static pressure and Mach number of flow from three values P_A, P_B and P_C of pressure holes of the probe are as follows.

(1) Direction and total pressure.

θ is obtained from Fig. 11 after calculating Y_θ in accordance with Eq. (1) by use of P_A, P_B and P_C measured. Y_T is also got from Fig. 11, and P_O can be obtained immediately from Eq. (2).

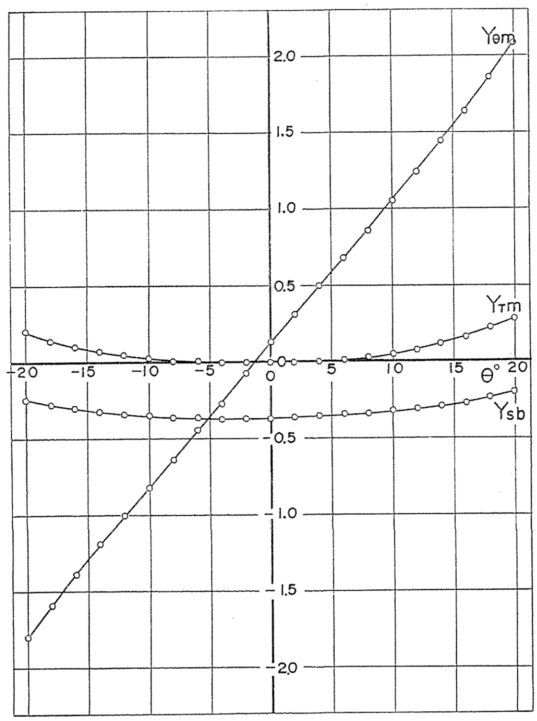

FIG. 11. $Y_{\theta m}$, Y_{Tm}, $Y_{Sb} \sim \theta$.

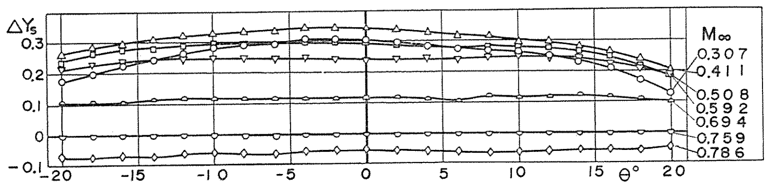

FIG. 12. $\Delta Y_S \sim \theta$.

(2) Static pressure and Mach number.

P_S and M_∞ are not obtained immediately, and the successive approximation method must be used.

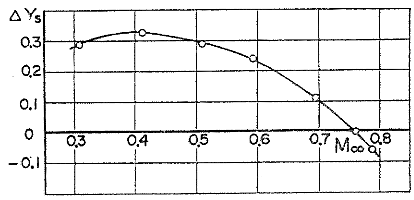

FIG. 13. $\Delta Y_S \sim M_\infty$.

Y_{Sb} at θ which was calculated beforehand is given by Fig. 11. In the next step, assuming the flow Mach number M_∞, ΔY_S is obtained from Fig. 13. And then Y_S can be calculated from Eq. (5). P_S can be obtained from Eq. (3) by use of this Y_S. Using this P_S and P_O which was obtained beforehand M_∞ can be calculated.

Final P_S and M_∞ can be obtained repeating this procedure until M_∞ converges to a definite value. It was confirmed that θ and M_∞ calculated in this way were given within accuracy of 0.5° and 0.01 respectively.

From these results we have found that the characteristics of a cylindrical probe at high subsonic speeds in the case of zero inclination angle are as follows.

(1) About the direction and the total pressure, very simple and convenient coefficients were obtained.

(2) About the static pressure, although we needed somewhat troublesome treatment of the successive approximation comparing with other two coefficients, it was revealed that the coefficient represented was very useful.

7. Conclusions

The results obtained are summarized as follows.

(1) The disturbance exerted by a cylinder affects far up to the upstream about 20 times of its diameter at high subsonic speeds.

(2) On the characteristics of a cylindrical probe at high subsonic speeds, we found the direction and the total pressure coefficients which are independent of Mach numbers and very convenient, and the static pressure coefficient which is also useful within yaw angles of $\pm 10°$ except at low Mach numbers. But the static pressure and the Mach number must be calculated by the successive approximation method.

References

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