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Calibration of a Three-Hole Probe Employed in Measuring the Performance of a Wind Tunnel Compressor Cascade

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ABSTRACT

Calibrating three-hole probes before using them to obtain measurement data from turbomachines has become imperative. Calibration of the three-hole probe prior to its use in any turbomachinery measurement is crucial due to manufacturing inaccuracies during production. This study presents the calibration of a three-hole probe used to measure the performance of a suction wind tunnel compressor cascade. A transonic wind tunnel with a diameter of 203 mm was used to calibrate the three-hole probe. Other equipment employed during the calibration included a pitot-static tube, five micromanometer transducers, a barometer, and a thermometer. Micromanometers 1 and 2 were used to obtain the values of the wall static and total pressures from the pitot tube, while micromanometers 3, 4, and 5 measured the total, static 1, and static 2 pressures from the three-hole probe. The results show that the total pressure coefficient at the stagnation point around zero yaw angle decreases at lower and higher yaw angles. For the plot of static pressure coefficient, it was observed that it is nearly independent of the flow angle. However, at higher flow angles, some points in the static pressure coefficient plot fluctuated significantly across different Mach numbers investigated. The study demonstrates that the relationship between the flow angle and the directional coefficient is linear for small angles, but at higher negative and positive flow angles, the probe's sensitivity in the flow direction becomes greater.

KEYWORDS: Compressor Cascade, Directional Coefficient, Mach Number, Total Pressure Coefficient, Yaw Angle

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1.0 INTRODUCTION

A three-hole probe is usually employed in two-dimensional flow analyses of compressor cascade blades, to obtain velocity vectors in the regions around the trailing edge, where there are vortices and wakes due to boundary layer separation (Diaz, 2003). Calibration of the three-hole probe prior to employing it for any turbomachinery measurement is very important. This is because of manufacturing inaccuracies associated with it during production. When calibrated, the three-hole probe can be made to cover the operating range and accurate results can be obtained. Treaster and Yocum (1978) stated that in many complex flow fields such those encountered in Turbomachines, the experimental determination of the steady state and three-dimensional characteristics of the flow field are frequently required. Yao *et al.* (2022a) conducted the calibration of a hemispherical 7-hole probe using a subsonic low speed wind tunnel. Flow parameters such as inflow velocity and flow angles were adjusted during the calibration. The authors reported that the results obtained from the calibration were similar to the numerical simulation results, as speed and angle measurement deviations recorded were 5% and 1° respectively.

Bachner *et al.* (2022) conducted the calibration of five-hole and six-hole probes for radial flow angles up to 32◦ and Mach numbers up to 1.3. Mach number measurement deviations were performed at the calibration wind tunnel, and different evaluation methods were examined. Over 210 randomly distributed points were reduced by

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66% using sample standard deviation when compared to similar probe design without the base pressure hole. A new method of calibrating a cylindrical three hole in a non-nulling operating mode was presented (Diaz *et al.*, 2009). A normalization factor used in the calibration coefficient of the probe was used in carrying out the new method of calibration. The authors reported that single points which usually appear in the calibration coefficients are prevented from occurring with the normalization factor. In addition, the authors stated that the new method can attain an angular range of 70°, which is greater than the typical traditional angular range of 30°. Barkter *et al.* (2001) presented the calibration characteristics of a three- Hole Probe and a static tube in a superheated wet steam.

Munivenkatareddy and Sitaram (2016) conducted the calibration of cantilever type four-hole probe by extending the range to ±60 degrees in the yaw plane and −50 to +30 degrees in the pitch plane. It was reported that the space zones were divided into center, left, and right zones. In addition, the authors stated that no point in calibration space was left without calibration coefficients since they were overlapping, and the calibration coefficients were defined differently for each zone. Babu *et al.* (1997) presented a non-nulling calibration method using a seven-hole probe. The calibration zones were divided into seven zones (one central and six side zones) to enable maximum probe pressure readings to be obtained. A localized two-variable polynomial was used at each point with the calibration data surrounding it for interpolation. The authors reported that the interpolation errors in flow angles were found to be within ±1◦ and the errors in total and static pressures were within 0.5% and 1% of the dynamic pressure respectively. Yao *et al.* (2022b) designed a three coordinate, and multi-directional rotatable testing system, which can measure both the flow field at any position and angle. A hemispherical seven-hole probe was calibrated with this test system, and the flow field around cylinders of different diameters was measured to obtain the pressure distribution and vortex shedding frequency. Calibration was conducted on a hemispherical seven-hole probe while implementing the test system. Measurements of the flow field around the cylinders of different diameters were carried out to obtain the pressure distribution and shedding frequency of the system. The authors verified that the designed test system could perform multi-angle testing during the calibration of the multi-hole probe.

Dominy and Hodson (1993) investigated the effects of different operating parameters such as Reynolds number, Mach number, and turbulence on the calibrations of commonly used types of five-hole probe. The authors observed two distinct effect of Reynolds number on the calibration of five-hole probes. It was reported that the probe calibrations which were conducted at relatively low Reynolds numbers were mainly affected by flow separation around the probe head. Changes in structure of the flow around the sensing holes was also reported as one the factors that affected the calibrations even when the probe was nulled. Gundogdu and Goksel (1998) presented a novel orientation mechanism designed to achieve the calibration of a five-tube probe. According to the authors the mechanism enables the probe to rotate about its tip in two planes perpendicular to each other with precision.

From literature search, it is obvious that a lot of study has been conducted using multi-hole probes. However, there are few studies available which have covered calibration of three-hole probes on the transonic wind tunnels such as the facility under investigation. This study presents the calibration of a three-hole probe in a transonic wind tunnel.

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2.0 MATERIALS AND METHODS

The transonic wind tunnel shown in Figure 1 is a suction tunnel which has a diameter of 203 mm and is located in the Cranfield University Laboratory Test area, UK. The tunnel also has a calibrated intake nozzle and four static tappings averaging into blockings for the measurement of pressures. In addition, a filter is incorporated at the intake which causes a pressure drop hence necessitating the stabilization of the flow for it to be smooth. The tunnel's pitching facility has been used to calibrate both 3 and 5 hole-probes used for investigating 2 and 3 dimensional flows within rotating machines. The tunnel can take probes up to 13 mm diameter. As can be seen in Figure 1, the following equipment namely pitot static tube, five micromanometer transducers, barometer, thermometer and suction wind tunnel were employed during the calibration of the three-hole probe, while Figure 2 shows the positions of the pitot static probe and three-hole probe. The three-hole probe was positioned at the center of the tunnel, while the pitot static tube was placed at a distance of 50mm from the middle of the tunnel. Figures 3 and 4 show the three-hole probe and its geometrical notation respectively.

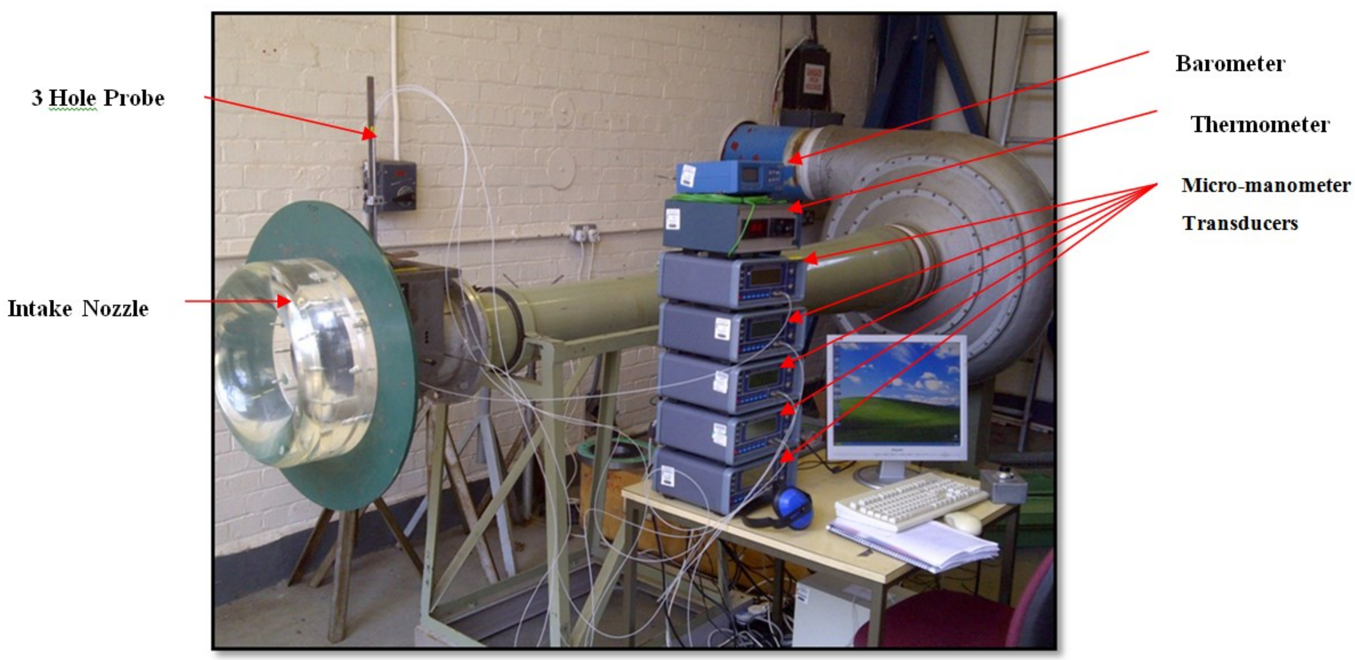

Figure 1: Transonic wind tunnel experimental setup for three-hole probe calibration

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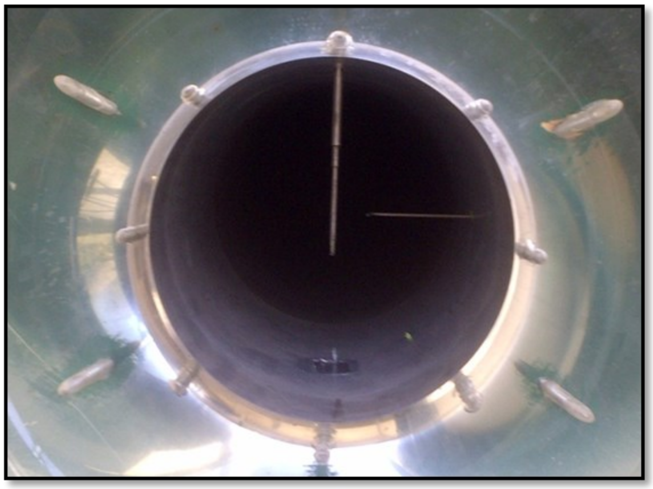

Figure 2: Wind tunnel intake

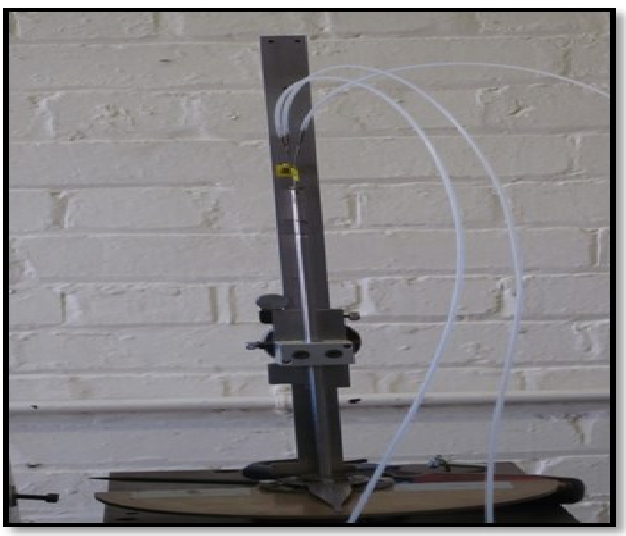

Figure 3: Three-hole Probe

A speed transmission control which actuates an 86kW DC motor was used manually to adjust the flow field velocity. A centrifugal fan blower which supplies an airflow of $6.6m^3/s$ was driven by a motor that runs at 4000rpm. The presence of the four static ports inside the tunnel enables the readings of the static pressure to be obtained while the pitot static tube was employed in acquiring the total pressure.

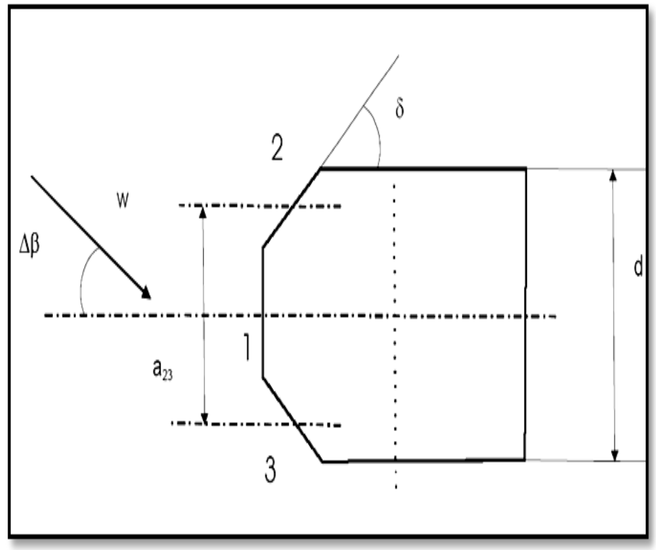

Figure 4: Three-hole Probe Geometric Notation

The static pressure associated with both the pitot tube and tunnel static ports were averaged together. The temperature and pressure measurements were obtained from an externally positioned thermometer and barometer from the suction wind tunnel. The measured pressures from the three-hole probe were converted to an electric signal with the aid of the five micromanometer transducers.

The micromanometers 1 and 2 were used to obtain the values of the wall static and total pressures from the pitot tube while 3, 4 and 5 produced the total, static 1 and 2 pressures from the three-hole probe. The nulling of the probe was done to ensure that the tip of the probe is aerodynamically facing in the direction of the airflow, and this can be obtained when the static pressure for holes 2 and 3 are equal. The calibration of the probe was carried out by increasing the angular setting at various positions with low turbulence intensity and constant free air jet velocity. In addition, for zero pitch angles, the yaw angle of the probe was varied from -400 to +400. An increasing order of 50 was applied when varying the yawing angle between -40 to -200 and 20 to +400 while between -20 to +200 an increasing order 20 was used. This

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was done in a bid to achieve a more reasonable calibration coefficient plots as well as accuracy.
The three-hole probe is usually employed in two-dimensional flow analyses of compressor cascade blades, to obtain velocity vectors in the regions around the trailing edge, where there are vortices and wakes due to boundary layer separation. Figures 3 and 4 show the three-hole probe and its geometrical notation respectively.
The four calibration coefficients are defined as follows (Diaz, 2003):

$$k_\beta = {(P_2 - P_2)}/{(P_1 - \bar{P})} \quad (1)$$

$$k_\gamma = {(P_4 - P_5)}/{(P_1 - \bar{P})} \quad (2)$$

$$k_t = {(P_1 - P_t)}/{(P_1 - \bar{P})} \quad (3)$$

$$k_s = {(P - P)}/{(P_1 - \bar{P})} \quad (4)$$

$$\bar{P} = {(P_2 + P_3 + P_4 + P_5)}/{4} \quad (5)$$

3.0 RESULTS AND DISCUSSION

Figure 5 shows the plot of total pressure coefficient against yaw angle. As can be seen in the figure, the total pressure coefficient at stagnation point around yaw angle is zero, and this value decreases at lower and higher yaw angles. Also, as can be seen from the figure, is not perfectly centered which can be attributed to machine asymmetric. For the plot of static pressure coefficient ks as shown in Figure 6, it is observed that the static pressure coefficient is nearly independent of the flow angle Δβ. However, at higher flow angles, it was observed that some points in the plot of static pressure coefficient fluctuated significantly for different Mach numbers 0.3, 0.35 and 0.4 investigated. These trends follow similar patterns of plots obtained in Diaz (2003), and Bereznai and Mlynár (2016).

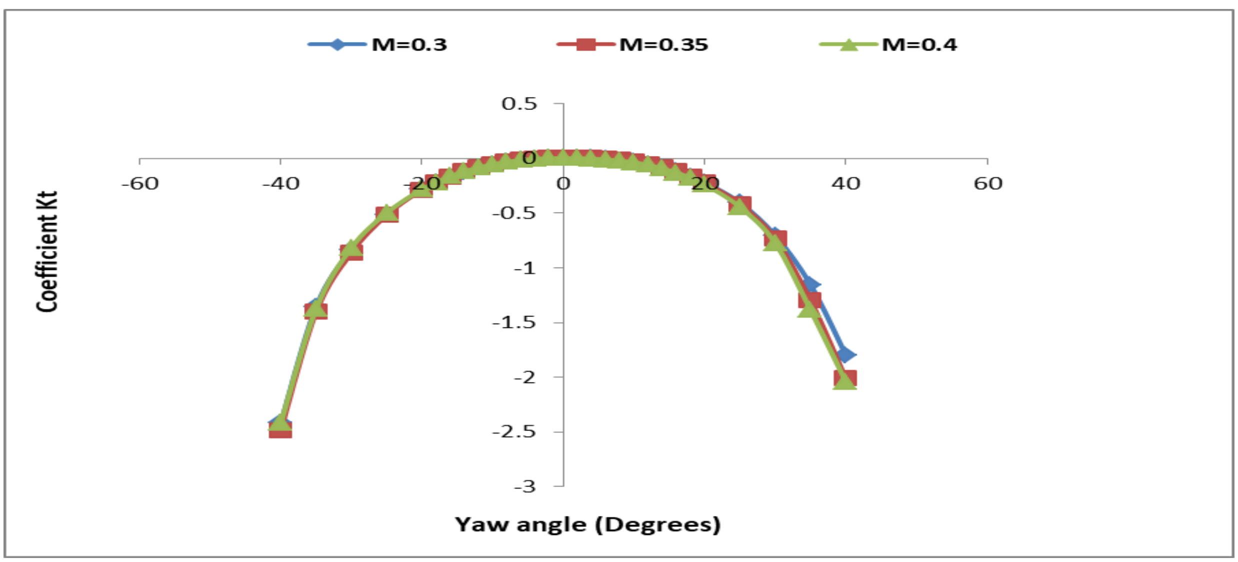

Figure 5: Total pressure coefficient Kt vs yaw angle

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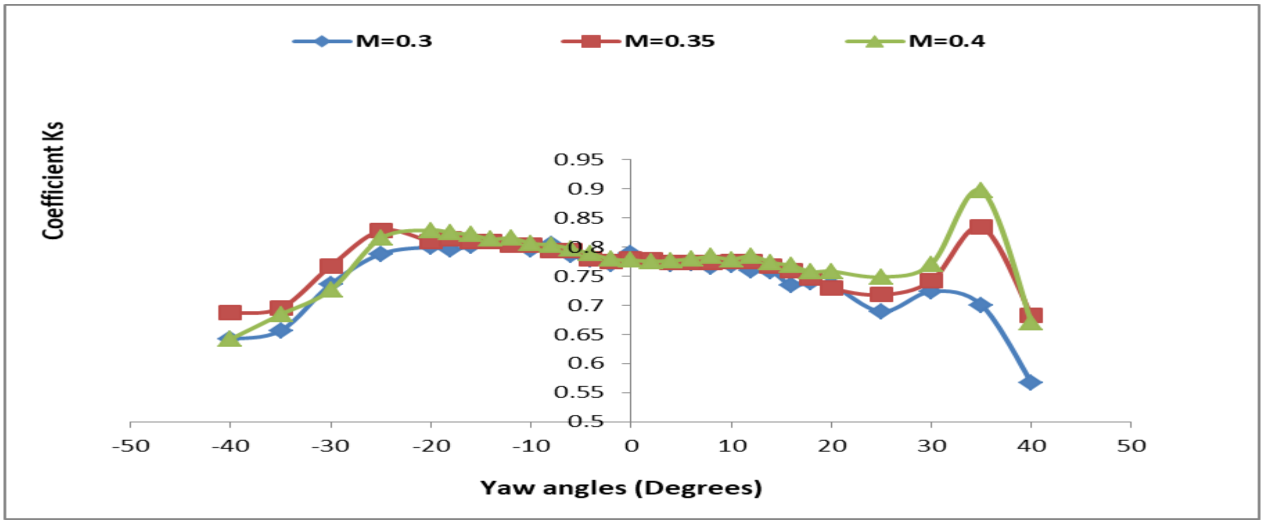

Figure 6: Static pressure coefficient Ks vs yaw angle

Figure 7 shows the plot of directional coefficient against yaw angle. As can be seen in the figure, the relation between the flow angle Δβ and the directional coefficient kβ is linear for small angles (–20° < Δβ < 20°) and follows from Taylor series expansion. At higher negative and positive flow angles, the sensitivity of the probe in the direction of the flow becomes greater. These trends follow similar patterns of plots obtained in Diaz (2003), and Bereznai and Mlynár (2016).

Also, in the figure, at zero yaw angle which is the stagnation point, the directional coefficient is zero. When Yaw angle was increased to 40^0 at Mach number 0.35, the directional coefficient decreased to approximately -6.1; while at -40^0, the directional coefficient increased to 7.0.

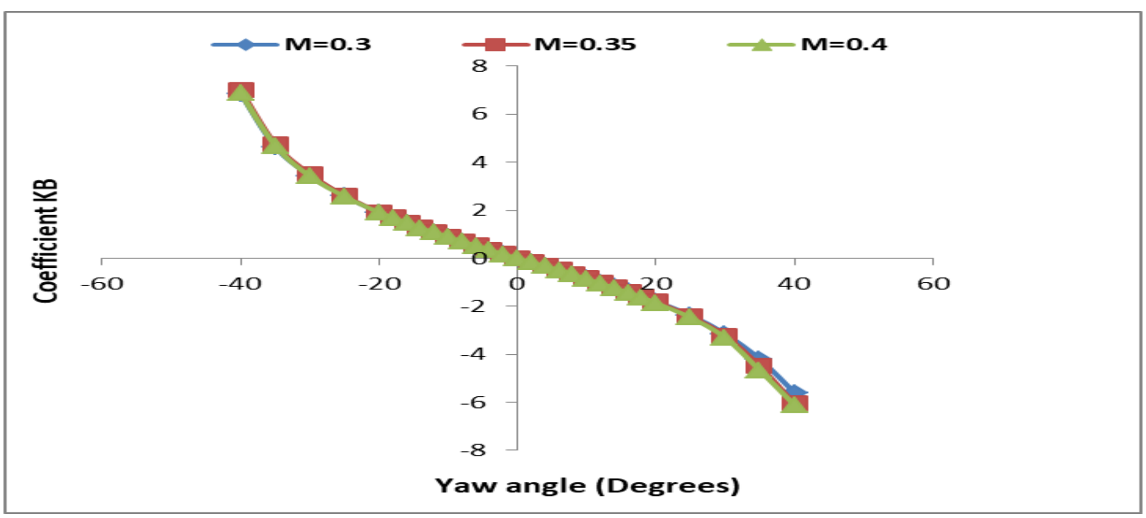

Figure 7: Directional coefficient Kβ vs yaw angle

4.0 CONCLUSION

The conclusions drawn from the research are:

i. That the total pressure coefficient at stagnation point around yaw angle is zero and this value decreases at lower and higher yaw angles
ii. At higher negative and positive flow angles, the sensitivity of the probe in the direction of the flow becomes greater.
iii. It is observed that the static pressure coefficient is nearly independent of the flow angle $\Delta\beta$. However, at higher flow angles, it was observed that some points in the plot of static pressure coefficient fluctuated significantly for the different Mach numbers.
iv. For small angles, the relation between the flow angle $\Delta\beta$ and the directional coefficient $k\beta$ is linear.

5.0 ACKNOWLEDGEMENTS

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