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# TOTAL PRESSURE CORRECTION OF A SUB-MINIATURE FIVE-HOLE PROBE IN AREAS OF PRESSURE GRADIENTS

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## ABSTRACT

*Five-hole probes, being a dependable and accurate aerodynamic tools, are excellent choices for measuring complex flow fields. However, total pressure gradients can induce measurement errors. The combined effect of the different flow conditions on the ports causes the measured total pressure to be prone to a greater error. This paper proposes a way to correct the total pressure measurement.*

*The correction is based on the difference between the measured total pressure data of a Kiel probe and a sub-miniature prism-type five-hole probe. By comparing them in a ducted fan related flow field, a line of best fit was constructed. The line of best fit is dependent on the slope of the line in a total pressure versus span and difference in total pressure between the probes at the same location.*

*A computer program, performs the comparison and creates the correction equation. The equation is subsequently applied to the five-hole probe total pressure measurement, and the other dependent values are adjusted. The validity of the correction is then tested by placing the Kiel probe and the five-hole probe in ducted fans with a variety of different tip clearances.*

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## NOMENCLATURE

| | |
|---|---|
| $C_{PT}$ | Coefficient of total pressure |
| $K$ | Correction Slope |
| $Location$ | Current spanwise location that data is found |
| $Location+1$ | Next spanwise location that data is found |
| $P_T$ | Total pressure |
| $Slope$ | Slope of found between two data points |
| $Step$ | Rotor span movement size |
| $U_M$ | Speed of the motor at midspan |

### Greek

| | |
|---|---|
| $\delta P_T$ | Change in total pressure due to gradient |
| $\rho$ | Air density |

### Subscript

| | |
|---|---|
| $Corrected$ | Corrected value |
| $Correction$ | Correction value based on $Slope$ and $K$ |
| $Difference$ | Difference between probes |
| $exit$ | Denotes area downstream of rotor |
| $FHP$ | Denotes measurements taken by the five-hole probe |
| $in$ | Denotes area upstream of the rotor at the inlet |
| $Kiel$ | Denotes measurements taken by the Kiel probe |
| $Original$ | Original measured value, before correction |

## INTRODUCTION

The displacement effects of probes in pressure or velocity gradients have been known about and studied for a long time. Some of the earliest studies of these effects were related to a total pressure Pitot probe. The probes were simplified as a sphere with a total pressure tap and gradient effects of probe size and hole diameter were solved using small perturbation theory. This analysis showed that most of the probe displacement effects were due to the vorticity of the flow, not the velocity gradient itself [1]. Hall's approach, however, uses an approximation for the stretching of the vorticity. A similar problem was tested without this approximation and concluded that the shape of the probe behind the head had little effect on the probe measurement. The shape of the head, being the main cause of image vorticity, was found to be the largest contributing factor in the Pitot tube displacement [2].

While the previous experiments gave an insight about the cause of the displacement, they did not put forth an exact method of correcting this error. One method for correcting this error is to use a correction factor that is based on the shape of the probe and the probe hole geometry [3]. This theory is best for larger probes (more than 3mm in diameter). Other corrections have been made over the years, and a summary has been made by Wysocki [4]. This summary divides the corrections into two camps. The first is correction due to the inner tube diameter and the second is correction due to the probe shape and the local velocity gradient. This study finds that correction in the second camp measures the displacement more accurately than that in the first camp [4].

Based on these experiments and theories, various types of multi-port probe designs have been tested. Huffman [5] dedicates a paper to the non-nulled cone type of probes. His study works out a theory to find the ideal calibration through CFD calculations. While this does not take into account manufacturing imperfections, it helps determine which cone designs should work most effectively in areas of velocity gradient [5]. An examination into the probe design and Reynolds number effects has confirmed the existence of two different phenomena [6]. The first concerns the incidence angle causing a flow separation at the head of the probe. The second is the influence of Reynolds number on the dynamic pressure coefficient. An optimization must be found with the cone angle, as larger cone angles will make the probe less sensitive to angle effects, but increase the variation in dynamic pressure measurements [6].

General form corrections of flow angle for multi-hole probes of all designs have been attempted. It is suggested that probes of all designs can be corrected when the probe is used in the null method. With calibration and previously known characteristics, it is possible to develop a method that is applicable to a non-nulled probe, but only in small gradients [7]. The previous paper written by Hall [1] describes the correction of spherical multi-hole probes, while Ikui attempts to create a correction factor applicable to all probes [7]. These theories are tested using a few inventive testing techniques. Foremost, a shear free flow with a velocity gradient is obtained using unequally spaced wires [8]. This technique is used to test the correction theories set forth by Hall and Ikui, and finds that Hall's theory falls when the ports are at 80° or more due to the lack of consideration of the viscous flow effects. Ikui's theory worked better for some probe designs and worse for others [8], but would not work with large velocity gradients [7]. Finally, a tactic using streamline projection and the probe head geometry in order to create a correction angle for the flow itself. It achieved an improvement in flow angle measurements [9].

Applications of a sub-miniature five-hole probe in turbomachinery and the associated problems were discussed in detail by Sitaram et. al [10]. This experimentation went through a variety of errors encountered by the probe within a turbomachine, and obtained a pressure correction due to the gradients within the machine [10]. This correction was based on the measured pressures in each port and a constant which was dependent on the pressure gradient, orientation, and geometry of the probe. This constant must be found with experimental or theoretical data [10]. A more general approach, proposed by Ligrani et. al., was taken to correct the pressure measurements and the velocity components in pitch and yaw [11]. The corrections were broken into two parts. The first part was related to the fact that the pressure gradient can cause the ports to measure different flow conditions relative to each other. A curve was fitted to data from the ports and interpolation was conducted in order to make all measurements act as if they were being taken from a single location [11]. Secondly, pitch and yaw velocities were corrected with the induced downwash velocities in their respective directions and a delta correction factor [11]. The corrections of pitch and yaw are not within the scope of this paper, and comparison of the methods would not be compatible. Any corrections of this nature should be done as described by Ligrani et. al. [11]. This has further been simplified by changing the delta correction factor to include spatial location correction [12].

## EXPERIMENTAL SETUP

### Equipment

All tests are performed in the wake of a 55.88 *cm* (22 *inch*) diameter ducted fan that has been set up previously by Akturk and Camcı [13]. The system consists of multiple components. The main structure is made of thermoplastic, with an inner diameter of 56.64 *cm* (22.3 *inch*) and it is topped with a replaceable inlet lip, and a six degree half angle exit diffuser. The system is driven directly by a 20 *HP* brushless electric motor from Hacker. Four deep cycle batteries connected in series supply the power to the motor. The high torque motor is monitored by a K-type thermocouple and a current shunt meter to monitor its operating conditions. Multiple eight-bladed fan rotors are available for testing, which are made of glass reinforced Polyamide with a va-

**TABLE 1**. ROTOR BLADE DATA

| Rotor radius (m) | Tip gap height (m) | Tip clearance (%) |
|---|---|---|
| 0.2794 | 0.0038 | 1.71 |
| 0.2766 | 0.0064 | 3.04 |
| 0.2728 | 0.0104 | 5.17 |
| 0.2685 | 0.0145 | 7.13 |

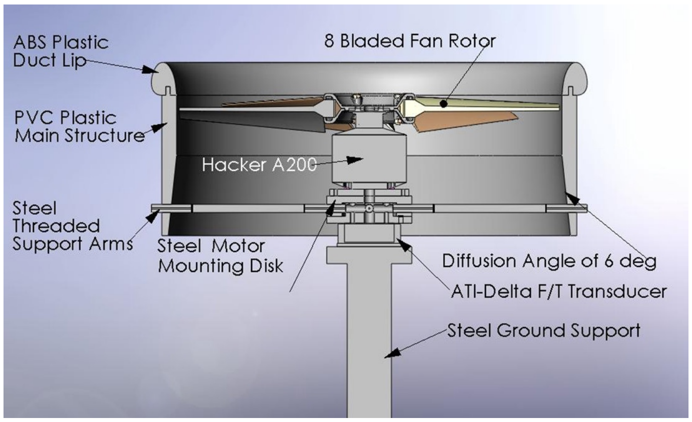


**FIGURE 1**. DUCTED FAN TEST SETUP

riety of tip clearances and designs. The general characteristics of these rotors are listed in Tab. 1. The general design of the setup can be found in Fig. 1.

## Instrumentation

The probes are held approximately 45 *mm* downstream of the fan rotor, and are rotated in order to keep the flow angle within the probes respective range. The first probe is a Kiel probe type KB manufactured by United Sensor Corporation. It has a large range of angle insensitivity around $\pm 52^\circ$ and an outer diameter of 3.175 *mm*. The second probe is a five-hole probe with a maximum head diameter of 1.62 *mm*. Its calibration method and additional information can be found in a previous paper [14]. This probe is much more sensitive to flow angle than the Kiel probe and must be rotated throughout the run. Five transducers are employed, each of which are open to the atmosphere. They are amplified by a Techkor Instrumentation MEPTS-9000. An optical sensor using a Hamamatsu p5587 photoreflector IC measures the rotational speed of the rotor. A high precision linear transverse from Velmex moves the probes in the radial direction. Two 12-bit data acquisition devices (MCC 1208FS) take the measurements from all five ports simultaneously and control

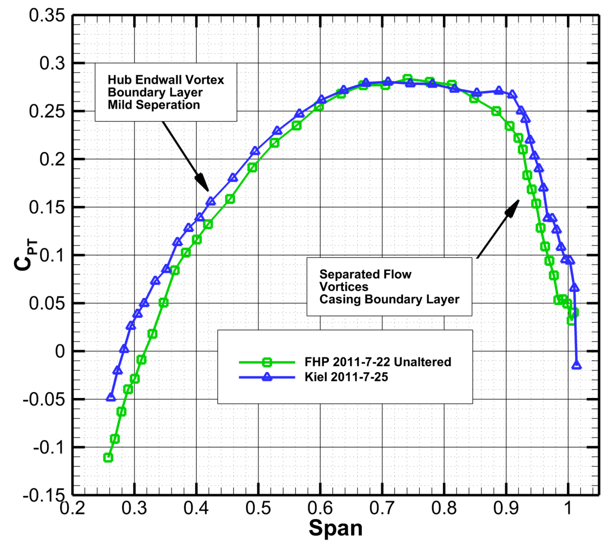


**FIGURE 2**. UNCORRECTED NON-DIMENSIONALIZED TOTAL PRESSURE DATA

the instrumentation. The experiment is run via a LabVIEW interface and MATLAB performs the data analysis.

## PROBLEM

The ducted fan has been run before, and the data gathered by the Kiel probe has been found to have a good agreement with a CFD code [13]. Thus, it is expected that the data gathered by the five-hole probe should also be in agreement. This was hardly the case, and in Fig. 2 it is seen that the five-hole probe will underestimate the coefficient of total pressure in most cases. The underlying cause of this underestimate is due to differing aerodynamic effects within the rotor. Near the hub, the pressure gradient is caused by the hub endwall vortex, the hub boundary layer, and a mild separation. Near the rotor tip, the pressure gradient is caused by flow separation, tip vortices, and the casing boundary layer.

Previous literature has suggested that this is due to a pressure or velocity gradient causing each port of the five-hole probe to measure a slightly different flow condition. Such flow conditions are illustrated in Fig. 3. The flow is assumed to have total pressure $P_T$ at the center. Away from the center there will be an increase and decrease of $\delta P_T$. Since the probe itself has been calibrated in a gradient free environment, the unaccounted gradient effects will cause error in the total pressure measurements. In the Kiel probe, the presence of a settling chamber around pressure inlet reduces the effect of the pressure gradient. This paper proposes that error in total pressure measurements of the five-hole

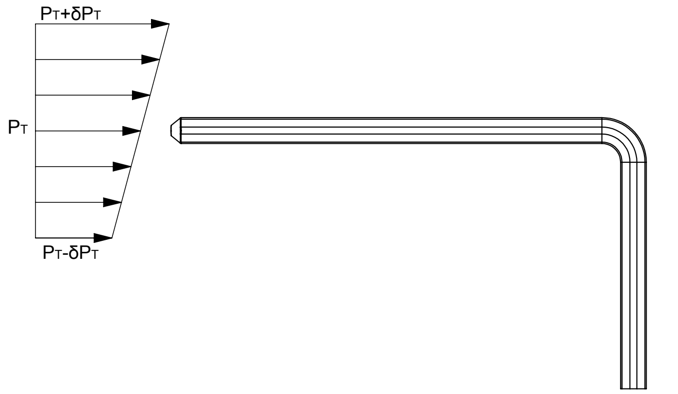


**FIGURE 3**. VELOCITY GRADIENT ON A PYRAMID TYPE FIVE-HOLE PROBE

probe can be corrected with a linear correction method.

## CORRECTION METHOD

### Correction Creation

The correction is made by first taking the total pressures and non-dimensionalizing as shown in Eqn. (1).

$$C_{PT} = \frac{P_{T_{exit}} - P_{T_{in}}}{\frac{1}{2}\rho U_M^2} \tag{1}$$

This non-dimensionalization is necessary to negate the effects of rotor speed and density changes from run to run, and even point to point. Total pressure at the inlet is found to be equal to to the ambient pressure. Thus, the numerator of this term is simply equal to the gauge pressure measured by a probe located at the exit. Total pressure of the Kiel probe is found by reading the connected transducer. The total pressure of the five-hole probe is calculated by a calibration look up table based on a previously determined $C_{P_{total}}$ value and $\bar{P}$ shown in Eqn. (2). The five-hole probe uses the measurements of all the ports surrounding the center and is calculated in Eqn. (3). Additional information on the calibration and design of this five-hole probe can be found in Town and Camcı [14]

$$P_T = P_1 - C_{P_{total}}(P_1 - \bar{P}) \tag{2}$$

$$\bar{P} = \frac{P_2 + P_3 + P_4 + P_5}{4} \tag{3}$$

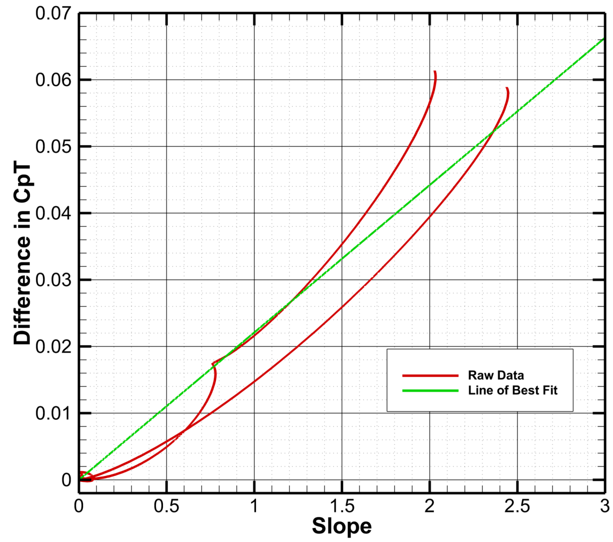


**FIGURE 4**. CORRECTION DATA AND FIT

The next step is the application of a curve fit to both the Kiel and the five-hole probe data. This is necessary for increasing the amount of sampling done on the data. The ultimate goal is to find the difference between the total pressure coefficient of each probe and the slope at which the five-hole probe is rising or falling. The entire range is split into many small steps (in this case a step size of 0.1% of the span is used). The difference is calculated in Eqn. (4). The calculation for slope is shown in Eqn. (5).

$$C_{PT_{Difference}} = C_{PT_{Kiel}} - C_{PT_{FHP}} \tag{4}$$

$$Slope = \frac{C_{PT_{FHP}}[Location+1] - C_{PT_{FHP}}[Location]}{Step} \tag{5}$$

As seen in Fig. 2, all of the total pressure measurements of the five-hole probe are less than the total pressure measurements of the Kiel probe. Thus, it has been assumed that the five-hole probe will always measure less pressure, and the correction factor will always be positive. As such, the absolute value of the slope is taken, explaining the occurrence of two lines in the raw data in Fig. 4. One is simply the mirror of the negative slope values.

A line of best fit is drawn and has a condition set so that it must go though the zero point. As per the previous argument;

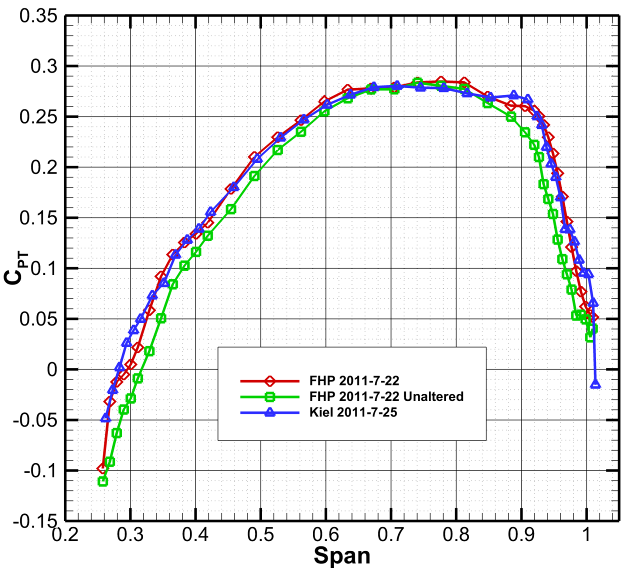


**FIGURE 5**. CORRECTED VALUES WITH 1.71% TIP CLEARANCE

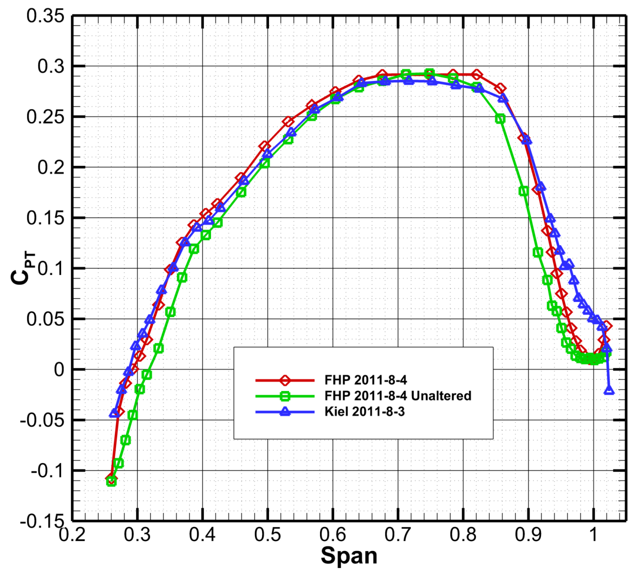


**FIGURE 6**. CORRECTED VALUES WITH 3.04% TIP CLEARANCE

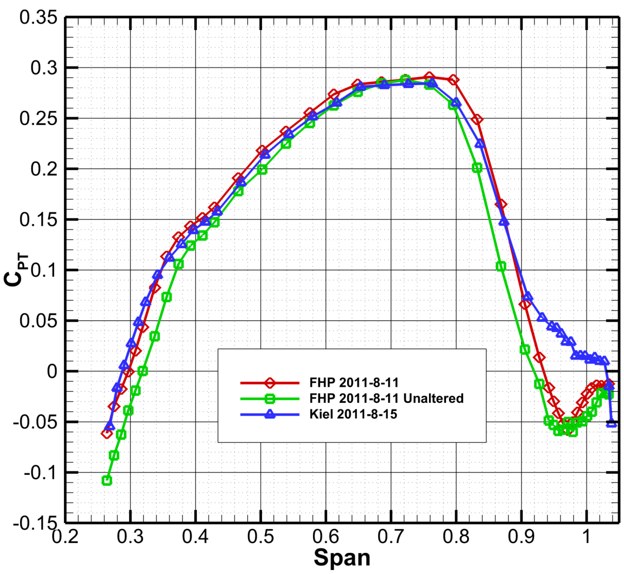


**FIGURE 7**. CORRECTED VALUES WITH 5.17% TIP CLEARANCE

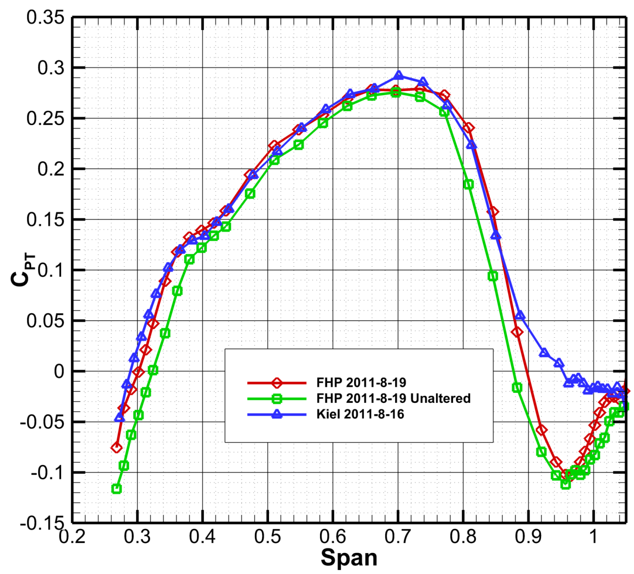


**FIGURE 8**. CORRECTED VALUES WITH 7.03% TIP CLEARANCE

there can be no negative correction. Thus, the correction factor is linear and comes in the form shown in Eqn. (6), where $K$ is calculated as the slope of the line of best fit shown in Fig. 4.

$$C_{PT_{Correction}} = K(Slope) \tag{6}$$

The value of $K$ is a function of $Slope$ and $C_{PT_{Correction}}$. This value should be found for each probe, as manufacturing defects may cause it to vary. The $K$ value is an estimation for how pressure measurements should be increased in the presence of a pressure gradient. As such, while $K$ is constant, if the measured pressure changes quickly, a larger correction appears, while if it changes slowly, the correction is approximately zero. For this experiment it is found that $K = 0.0221$.

### Correction Application

The correction is applied to the five-hole probe measurements. The total pressure measurements are first non-dimensionalized using Eqn. (1). Next, a curve fit based on Fourier series is done for $C_{PT}$ to keep a fit as near as possible to the data. The entire span is again broken into $step\ size = 0.1\%$, and the slope of the curve fit is found by Eqn. (5). With the known value of the slope, the correction value is found via Eqn. (6). The final step adds the correction to the curve fit using Eqn. (7).

$$C_{PT_{Corrected}} = C_{PT_{Original}} + C_{PT_{Correction}} \tag{7}$$

Since actual measurements were not taken at all the points, correction is interpolated back to the places where the original measurements were taken.

The corrected values of $C_{PT}$ are put into Eqn. (1) and $P_T$ is solved for. Using Bernoulli's incompressible total pressure equation, it is possible to find a corrected absolute velocity. The tested fan rotors are open to the atmosphere and the static pressure is not corrected for. The angles originally calculated by the five-hole probe are assumed to be correct, though corrections for angles can be found in Ligrani [11]. The calculations for the velocity components are carried out as outlined in a previous paper [14].

## RESULTS

Figures 5 through 8 show the data from the Kiel probe, the uncorrected data from the five-hole probe, and the corrected data from the five-hole probe. In Fig. 5, an improved agreement across the entire span of the 1.71% tip clearance rotor can be seen. The very low data point at the tip is not represented in the five-hole probe measurements. This is because the small size of the Kiel probe allowed the probe head to recede into the duct wall. The five-hole probe could not do this, and had to deal with boundary layer effects and flow acceleration between the probe and the wall. The unaltered data, however, is the base for the correction. As such, Fig. 5 is an ideal best check for the validity of the correction.

Good agreement for most of the span between the correction and the Kiel probe can be seen for the 3.04% rotor in Fig. 6. The correction diverges near the 94% span location. This is thought to be due to a region of low momentum vortex type flow that the five-hole probe had difficulty measuring. The structure of this flow is further elaborated on in Akturk's thesis [13]. Near the tip, the acceleration between the duct wall and probe can be seen, causing the measurements from the five-hole probe to rise.

In Fig. 7 a good correlation between the corrected values of the five-hole probe and the Kiel probe is observed. This correlation breaks down after the 90% span mark, again due to the vortical flow that has grown larger with the increased tip clearance. The acceleration near the wall is present as well. Finally, there is a small overshoot just as the value of $C_{PT}$ starts to drop. This is believed to be due to the curve fitting procedure that was used on the original data.

Figure 8 also shows a good relationship between the five-hole probe and the Kiel probe. This correlation again breaks down near the 88% mark, where,as before, the vorticies present in the flow make it very difficult to measure. Flow acceleration is present again, but deminishes off as the boundary layer accumulates.

## CONCLUSIONS

A Kiel probe was used to quantify the response of a five-hole probe in an environment where there is a realistic total pressure gradient. An experiment quantifying a five-hole probe pressure gradient response is very rare in literature. This is one of the few quantitative corrections that may provide reasonable correction of measurements in five-hole probes in pressure gradients caused by boundary layers, separated flow, and vortical flow. The tests are done behind the rotor of a previously tested ducted fan. This correction has been successfully implemented, and reduced the amount of measured error between the five-hole probe and the accepted measurements of a Kiel probe.


## ACKNOWLEDGMENT

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