1 Introduction

The detailed understanding of flow phenomena in turbomachinery remains an ongoing challenge. Probes with high spatial resolution are required to accurately resolve the flow within modern high-speed compressors or turbines. Pneumatic multi-hole probes are widely used to measure pressures, angles, and – in combination with temperatures – velocity components in turbomachinery. These probes are usually calibrated in wind tunnels at different Mach numbers, but typically under uniform, steady flow conditions with low-turbulence levels and ambient pressures. However, in high-speed turbomachinery applications, the probes are subject to high unsteady flows with strong shear gradients, high turbulence levels, and quite often also to significantly different Reynolds numbers due to operating pressures greater than the ambient pressure. All of these can have non-negligible influences on the calibration characteristics of the probes, and thus on the measured flow properties.

In this study, a numerical model is developed for a commercially supplied five-hole probe in order to carry out systematic investigations under controlled conditions on the effects of Reynolds number variations on the calibration characteristic of the probe.

A detailed 3D-flow analysis for a multi-hole pressure probe was conducted by de Guzman et al. [1] in incompressible flows at low Reynolds numbers ($Re = 2 \cdot 10^3$) using Reynolds averaged Navier–Stokes Solver for Aerodynamic Design (RANS) with the k-epsilon turbulence model. The numerical calibration showed good quantitative agreement with the experimental results.

Coldrick et al. [2] carried out a general investigation of the measurement uncertainties of five-hole probes in compressor flows by means of steady and unsteady flow simulations. For this purpose, a numerical calibration map was generated to investigate the blockage effect of multi-hole probes in compressor applications. One main finding was that a steady-state disturbance can cause errors in the probe measurements while effects from the unsteadiness produced by a compressor have a negligible effect on the probe characteristics.

A numerical calibration map for a five-hole probe was generated by Aschenbruck et al. [3] using the shear stress transport (SST) turbulence model of ANSYS CFX. A comparison between the experimental and numerical calibration identified good agreement for the total pressure and yaw coefficient for different yaw angles. In contrast, the static pressure and pitch coefficients exhibited a significant deviation. Aschenbruck et al. [3] hypothesized that the source of the error, especially for high yaw incidence, might originate from the difference in shape between the actual geometry of the probe head and the geometry used for the numerical calibration.

Passmann and Joos [4] introduced a procedure for calibrating additively manufactured multi-hole probes based on 3D scanning followed by a numerical calibration with the actual scanned geometry. Therefore, a compressible, steady-state Reynolds-averaged Navier–Stokes (RANS) solver was utilized which provided predictions for a numerical calibration map in subsonic flows within a yaw and pitch angle error of 2.5 deg and a total pressure deviation of less than 1.5%.

Keywords: five-hole probe, numerical calibration
However, the most recent investigations from Coldrick et al. [2], Aschenbruck et al. [3], Passmann and Joos [4], Sanders et al. [5], and Arguelles Diáz et al. [6] did not consider the geometry of the probe holes and modeled only the probe surface in their investigations. In contrast, Li and Bohn [7] stated that modeling of the actual probe hole geometry is significant if accurate numerical results are to be achieved.

Dominy and Hodson [8] considered the effect of Reynolds number variation on the calibration of five-hole probes, identifying a major effect at low Reynolds numbers. The flow separation at the probe head under incidence results in sensitivity changes in the yaw measurement.

Arguelles Diáz et al. [6] investigated the effect of small Reynolds number changes in the range $Re = 1 \cdot 10^5$ to $Re = 2.4 \cdot 10^4$ using a one-equation turbulence model. The numerical and experimental calibration generally agree well; however, at large yaw angles, the numerical model did not accurately reproduce the effect of Reynolds number changes when compared to the experimental calibration.

A numerical study of the influence of Reynolds number on calibration maps was also carried out by Li and Bohn [7]. Effects due to modeling of the probe holes are presented and stated to be significant for numerical investigations of multi-hole probes. The study was conducted for $Ma = 0.35$ at $5.25 \cdot 10^5 < Re < 2.63 \cdot 10^6$ and reference pressures below ambient of 0.0709 MPa and 0.5065 MPa while varying the yaw angle up to 20 deg. The results show a significant deviation in the pressure coefficients if the Reynolds number of the calibration differs significantly from that of the measurement.

Aschenbruck et al. [3], Passmann and Joos [4], Sanders et al. [5], Passmann et al. [10] also carried out an experimental investigation of the Reynolds number effect on five-hole probe performance. Their study gives a deeper insight into the Re sensitivity mechanisms with the help of particle image velocimetry (PIV) techniques and oil flow visualizations.

The present study focuses on setting up a numerical model that is able to reproduce the experimental calibration data in a reasonable manner, while taking into account the effect of modeling the probe holes. To do so, four actual five-hole probe calibrations of probes with the same nominal geometry are analyzed and compared to the results of a numerical calibration. Since five-hole probes are often used in areas with higher pressure levels but calibrated at ambient pressure, this investigation also concentrates on measurement uncertainties in flow conditions with higher density at constant Mach number, hence for higher Reynolds numbers.

The five-hole probes considered in this study are eccentric ferrule probes. This is a drilled elbow probe made from stainless steel with a cone angle of 60 deg. Figure 1 shows the arrangement of the probe heads and the nominal dimensions of the probe head.

The probes are used in the high-speed research compressor at Technical University of Munich. As the compressor has 3.5 stages with three circumferentially distributed slots behind each rotor and stator, use of three of the available probes allows measuring downstream of all rotors or stators at the same time. An additional fourth probe functions as spare. All four probes are considered in the following investigations. The experimental calibration describes the characteristics of the four real probes, while the numerical calibration represents the actual numerical results of the ideal probe.

### Calibration Procedure

The probes are rotated in yaw direction $\alpha$ (cf. Fig. 2) during traversing in the test rig to maintain relative flow angles close to 0 deg. The real probes are calibrated over a yaw angle range of $-30 \deg < \alpha < 30 \deg$. The expected pitch angle tends also to be within $-30 \deg < \beta < 30 \deg$. Probe calibration was carried out in a low-turbulence calibration channel over a Mach number range of $0.1 < Ma < 0.64$. This results in four different non-dimensional calibration coefficients for each Mach number, each over a two-dimensional grid with yaw ($\alpha$) and pitch ($\beta$) angles as the coordinates (cf. Fig. 3). A familiar definition of the calibration coefficients is given by Treaster and Yocum [11]. However, in the present study, the coefficients are defined as follows:

\[
C_{\text{yaw}} = \frac{P_{\text{PH5}} - P_{\text{PH4}}}{P_{\text{PH3}} - P_{\text{PH2}}} \tag{1}
\]

\[
C_{\text{pitch}} = \frac{P_{\text{PH4}} - P_{\text{PH2}}}{P_{\text{PH1}} - P_{\text{PH2}}} \tag{2}
\]

\[
C_P = \frac{P_t - P_{\text{PH1}}}{P_{\text{PH3}} - P_{\text{PH2}}} \tag{3}
\]

\[
C_{Pr} = \frac{P_t}{P_{\text{PH3}} - P_{\text{PH1}}} \tag{4}
\]
\[ P_{\text{max}} = \frac{P_{\text{PH1}} + \max(P_{\text{PH1}} - P_{\text{PH5}})}{2} \]  
(5)

\[ P_{\text{avg}} = \frac{P_{\text{PH2}} + P_{\text{PH3}} + P_{\text{PH4}} + P_{\text{PH5}}}{4} \]  
(6)

The total pressure \( P_t \) represents the pressure in the settling chamber of the calibration channel. In the subsequent numerical study, the probe was numerically calibrated over a yaw angle range of \(-10 \, \text{deg} < \alpha < 30 \, \text{deg}\), a pitch angle range of \(-5 \, \text{deg} < \beta < 5 \, \text{deg}\), and at a Mach number of \( \text{Ma} = 0.3 \), as the main focus of interest was the behavior at different yaw angles. The accuracy of the used 5 psi-module lies in the range of \( \pm 0.05\% \) of full scale, which corresponds to an error of \( \epsilon = \pm 17.5 \, \text{Pa} \). An error propagation analysis with the maximum possible error of \( \Delta Z \) resulting from the measurement accuracy of the pressure modules is considered in the representation of the calibration coefficients and marked with error bars in the following figures. The expected value \( Z \) is calculated from the measured probe hole pressures and total pressure depending on the calibration coefficient (cf. Eqs. (1)–(4)):

\[ Z = f(P_{\text{H}}, P_{t}) \]  
(7)

Vector \( Z \) contains the different combinations of the expected values with the error \( \epsilon \) due to the error propagation over the calibration coefficients:

\[ Z = f(P_{\text{H}} \pm \epsilon, P_{t} \pm \epsilon) \]  
(8)

Finally, the error bar represents the maximum difference between the error containing value and the expected value:

\[ \Delta Z = \max (Z - Z) \]  
(9)

3 Numerical Setup

The numerical model was developed using Fluent Meshing and computed with ANSYS FLUENT 2020 R1. The simulations were conducted on a workstation equipped with 16 physical cores. As remeshing is necessary for every new angle, the computational time was around 2 h per angle including meshing. In order to reproduce the probe’s behavior in the best possible manner, a full 3D model of the probe was developed based on the nominal shape and dimensions of the probe. This includes the stem and the head with five holes, at the bottom of which the pressures are extracted (cf. Fig. 2, “Measurement plane”) based on the area-weighted average of the total pressure.

3.1 Domain. The computational domain is illustrated in Fig. 4. The domain is represented by a 200 mm cube which corresponds to 126 times the head diameter. Based on recommendations from ANSYS and in order to minimize interaction with the domain boundaries, the domain was greatly enlarged compared to Willinger et al. [12].

The upstream effect of the probe was estimated using potential theory and verified by CFD in order to minimize any upstream influence of the probe on the boundary conditions at the inlet. To model the flow around a cylinder, the cylindrical stem can be considered as a dipole comprising a source and a sink. Figure 5 shows the change in velocity along the \( x \)-axis near the probe for \( \text{Ma} = 0.3 \) and \( R = 0.795 \, \text{mm} \). Since potential theory does not consider friction forces, the upstream effect is somewhat smaller than that computed using CFD. Based on these results, it can be concluded that the influence of the probe on the domain inlet is negligible because the velocity falls below \( \text{Ma}/\text{Ma}_{\infty} < 99.9\% \) only 25.14 mm upstream of the centerline of the cylinder.

The different yaw and pitch angles were simulated by rotating the probe in an otherwise fixed domain with constant boundary conditions. This approach, which was deemed more practical for the present purpose which includes rather large angle variations and possibly also controlled shear flow and turbulence variations, requires a unique mesh for every angle setting. Finally, the probe tip was positioned in the center of the cube and the probe was rotated around this central point. Table 1 summarizes the domain planes with the respective boundary conditions.

3.2 Probe Geometry. The original computer aided design (CAD) geometry represents the nominal shape of the real probes.
Figure 6 illustrates the deceleration of the velocity along the centerline of every probe hole PH1–PH5 at $\alpha = 0$ deg. Since the probe tip is located at 0 mm, deceleration occurs first at PH1. The side holes PH4 and PH5 are laying on top of each other due to the symmetry of the probe in the $x$–$y$ plane. The influence of the stem is visible for the top hole PH3 over the first 0.5 mm. Due to a recirculation area at the side holes, a velocity of small magnitude is still present after the “Outer edge of PH2-5” but disappears before reaching the measurement plane at 2 mm. This is valid for all tested yaw angles $\alpha$. At the bottom of every probe hole, at the 2 mm location, the kinematic part is completely converted, which means the static pressure equals the total pressure. At this point, the numerical pressure is acquired and averaged over the surface. In the real probes, the pressure sensor is actually much further away, namely outside the probe after approximately 10 m of tubing. However, according to Fig. 6, a minimum hole depth to diameter ratio of $d_{PH2-5}/\phi_{PH1} = 4.1$ for the probe holes proved adequate for the numerical model.

Since the probe head has a relatively small overhang of $s_{tip-stem} = 1.59$ mm, the influence of the stem is visible in the measurement of PH3 and under certain yaw angles also at PH4 or PH5. Figure 7 illustrates the total pressure distribution over the surface of the probe head at a yaw angle of $\alpha = 20$ deg and a pitch angle of $\beta = 0$ deg. The potential effect of the stem is clearly visible in the non-symmetrical pressure distribution over the probe head.

3.3 Mesh. Due to the complex geometry, mosaic meshing technology with the poly-hexcore feature provides a suitable solution for matching different types of meshes [13]. This meshing technology offers a number of advantages, especially where modeling of the probe holes is concerned. A layered polyprism mesh in the boundary layer is connected with general polyhedral elements to the octree hexes in the bulk region (cf. Figs. 8 and 9). The 10 prism-layers on the probe’s surface yielded a $y^+ < 1$ for all presently performed calculations.

A mesh study was conducted to analyze the appropriate mesh density. Three different grids were tested in this investigation. For each case, the local mesh density within the domain is increased progressively towards the probe surface. This yields a coarse grid in the outer region near the domain boundaries and an increasingly finer mesh towards the probe. Table 2 summarizes the main parameters.

Since the probe is symmetric in the $x$–$y$ plane (cf. Fig. 2), the mesh study was mainly conducted in the positive yaw direction $0 \deg < \alpha < 20 \deg$ at a Mach number of $Ma = 0.30$. A few points were also calculated at negative yaw angles to verify the symmetry of the grids. At PH1 (cf. Fig. 10, top), the sensitivity to grid resolution is mainly visible at yaw angles $-12 \deg > \alpha > 12 \deg$. For the fine mesh, a few additional points were taken in the vicinity of 0 deg. The differences for this mesh across the symmetry plane are

| Plane | Boundary condition |
|-------|--------------------|
| 1     | Velocity inlet $v = 104 \text{ m/s}, T_t = 300 \text{ K}$ Flow direction: normal to inlet Fluid: air Density: compressible, ideal gas Turbulent intensity: 1% Turbulent viscosity ratio: 10 kg/ms |
| 2     | Pressure outlet $P_s = 99432 \text{ Pa}, T_t = 300 \text{ K}$ |
| 3, 4, 5, 6 | Free slip wall No slip wall |

| Mesh | No. cells | $y^+$ | No. layers |
|------|-----------|-------|------------|
| Coarse | 0.4 Mio. | $<1$ | 10 |
| Medium | 3.0 Mio. | $<1$ | 10 |
| Fine | 9.4 Mio. | $<1$ | 10 |
around $\Delta P = 20$ Pa. Figure 10 (bottom) shows the pressure at PH3. The variation of the pressures between the grids is significantly larger and the symmetrical variation also increases to around $\Delta P = 60$ Pa for PH2 and PH3. Overall, the coarse mesh exhibits significant differences in comparison with the medium and fine mesh while the medium and fine mesh are in close agreement. However, the fine mesh was chosen for the following investigations, even though the medium mesh tends to achieve reasonable results and does not differ much from the fine mesh. The choice was made to allow for future studies with significant shear flows and turbulence which are expected to require a finer mesh.

3.4 Turbulence Model. The generalized k-omega (GEKO) two-equation turbulence model was used to simulate the probe calibration and to investigate its behavior under different Reynolds number conditions [14]. Arguelles Diáz et al. [6] also applied the one-equation Spalat Almaras model and achieved better results but only for high angles of attack compared to the k-omega model. The GEKO model was chosen because of the planned follow-up studies, which will require a higher-order model.

3.5 Convergence. At higher Reynolds numbers, the total pressure inside PH3 tended to oscillate around a constant value over the last iterations. It is likely that these oscillations are provoked by the inherently unsteady flow conditions associated with vortex shedding from the stem of the probe. This fact questions the validity of the steady-state computation because the situation favors an unsteady simulation. To assess this factor, an unsteady reference simulation was conducted to quantify the effect of unsteadiness. It was found that the average of the last iterations of the steady simulations agreed well with the unsteady solution. Since the frequency of the oscillation varies for every incidence, a moving average was used to flatten the pressure oscillations. The convergence and averaging criteria were set such that each of the five pressures had to be converged to within the target accuracy corresponding to the experimental measurement system of $\pm 17.5$ Pa.

4 Results

First, a comparison between the initial experimental calibration of all four real probes – calibrated before their extensive use – and the numerical calibration is made in order to investigate the influence of the geometry on the calibration coefficients and to validate the numerical model. Second, the influence of modeling the probe holes is shown. Third, a wide-area 3D measurement system from Keyence with an accuracy of $\pm 2 \mu m$ was used to compare the actual probe head geometries with their nominal shape and the results are shown here. Finally, the effect of Reynolds number on the numerical measurement data is assessed.

4.1 Numerical and Experimental Calibration. The comparison between the experimental and the numerical calibration for $Ma \approx 0.3$ and $Re \approx 1.1 \cdot 10^4$ reveals significant deviations in certain areas of the calibration. It is clearly apparent that even amongst the four probes themselves, there is a significant difference in the experimental calibration coefficients. Figure 11 illustrates the deviations of the location and diameter of the probe holes and the probe head itself relative to the nominal geometry. The measurements revealed that the shape of probe 4 (spare probe) comes closest to the nominal geometry. Therefore, this probe is highlighted separately in the following figures. The already mentioned error propagation for the experimental calibration is indicated by error bars. The probe spread covers the complete area over which the four probes are extended to emphasize the variation of the real probes that are supposed to have the same nominal geometry. The numerical simulations were performed for this nominal geometry.

Figure 12 presents the total pressure coefficient $C_p$ over the yaw angle calibration. Within a range of $\alpha = -4$ deg to 4 deg, PH1 is quite insensitive to yaw angle changes. However, the further the probe is rotated away from the center, the larger is the spread in the experimental calibration coefficients of the real probes. The numerical $C_p$ falls fully within the range of the experimental coefficients and is well aligned with the spare probe.
The experimental yaw angle coefficient $C_{\text{yaw}}$ also indicates a progressively larger deviation from the mean value at higher angles (cf. Fig. 13). The numerical calibration points are in good agreement with the experimental points for angles $-10 \, \text{deg} < \alpha < 10 \, \text{deg}$. They are slightly outside the range at large angles, as was also observed by Arguelles Diáz et al. [6].

The experimental pitch angle coefficient $C_{\text{pitch}}$ is found to vary significantly between the four real probes (cf. Fig. 14). The numerical calibration largely falls within the range.

The spread of the experimental dynamic pressure coefficient $C_{\text{pd}}$ behaves similarly to the total pressure coefficient $C_{\text{pt}}$ for probes 1, 2, and 3 (cf. Fig. 15). At small angles, the variation across the three probes is approximately $\Delta C_{\text{pd}} = 0.05$. However, the numerical calibration shows a general offset of around $(C_{\text{pd,exp}} - C_{\text{pd,num}})/C_{\text{pd,exp}} = 9\%$. Aschenbruck et al. [3] also observed a significant error in the dynamic pressure coefficient. This deviation might be related to the exact position, size, and shape of the pressure holes because the coefficients and the geometrical shape of the spare probe lie significantly closer to the numerical points and nominal geometry. Therefore, the real probe geometries were found to have some non-negligible deviations from the nominal shape, which was the basis used for the numerical model. This will be discussed later on in the section about real probe geometries. But this issue is also related to the topic of modeling the probe holes.

### 4.2 Modeling Probe Holes

The need for modeling of the probe holes is clearly apparent from Fig. 16, which compares the numerically measured pressures at PH1 and PH4 with and without modeling of the holes. Without the holes modeled, the measured total pressure does indeed behave in a way that is qualitatively similar to the results obtained with probe holes but is significantly lower for all probe holes. A further analysis of the pressure distribution on the surface where the pressure is measured reveals that without probe hole modeling, the stagnation point does not cover the entire surface (cf. Fig. 17). This is why the averaging tends to capture lower values. In contrast, modeling of the probe hole leads to streamlines to the measuring surface at the bottom of the

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**Fig. 13** Yaw angle coefficient of experimental and numerical calibration

**Fig. 14** Pitch angle coefficient of experimental and numerical calibration

**Fig. 15** Dynamic pressure coefficient of experimental and numerical calibration

**Fig. 16** Pressure measurement of probe holes with and without modeling the holes

**Fig. 17** Averaging surface of probe without modeled probe holes
hole where the total pressure is constant over the whole plane. The influence of modeling without probe holes on the calibration coefficient is found to be non-negligible. For yaw angles $\alpha > 10$ deg, the error in yaw angle measurement increases by up to 2.5 deg. The pitch angle error lies in the range of 1 deg without probe holes. The total and static pressure are underestimated by around 1%.

### 4.3 Real Probe Geometry

In order to verify how closely the real probe geometries, used in the present study, correspond to the nominal shape, used in the numerical model, a wide-area 3D measurement system from Keyence with an accuracy of $\pm 2 \mu m$ was utilized to scan the actual probe heads. It should be noted that the resultant deviations can be due either to original manufacturing deviations or aging associated with a few hundred hours of testing in a high-speed compressor environment.

Figure 18 compares two probe heads: one corresponding to a new, unused spare probe and the other to one of the used probes (5HP-1) that has undergone around 300 h of testing. The center hole in particular exhibits clear signs of abrasion and deformation. The reflective surface around the center hole of the used probe is larger than that of the new one which suggests a flattening of the probe tip. Therefore, significant deviations in the calibration characteristics might be expected, especially at larger yaw angles.

The manufacturer’s error for the cone angle of the four probe tips varies in a range of $\Delta \theta = 0.3$ deg. The accuracy of the position of the side holes is also in a tight range of $\Delta s = \pm 10 \mu m$. Figure 19 shows the various measurement results for five-hole probe 1.

Figure 20 clearly shows the impact of particles in the flow on the surface of a five-hole probe even though a G2 filter was always installed at the inlet of the compressor rig. The increase in roughness and edge radii is clearly visible.

Figure 21 is a plot of the total pressure coefficient $C_{Pt}$ of 5HP-3 after around 300 test hours. A significant deviation is apparent, especially in the positive yaw angle direction. Hence, regular inspection, cleaning, and recalibration of the probes are mandatory.

### 4.4 Influence of Reynolds Number

The variation in the Reynolds number applicable for the following investigations was defined as a multiple of the Reynolds number $Re_1$ that was set for the numerical calibration.

The Reynolds number was defined as

$$Re_i = \frac{\rho_i \cdot v \cdot d_{Cyl}}{\eta}$$  \hspace{1cm} (10)

To increase the Reynolds number, the reference pressure $P_{ref}$ was multiplied by $i$:

$$\rho_i = \frac{i \cdot P_{ref}}{R_i \cdot T_i}$$  \hspace{1cm} (11)

Table 3 describes the constants, which were held steady during the investigations. Increasing or decreasing the reference pressure $P_{ref}$ resulted in the Reynolds numbers tabulated in Table 4.

The numerical pressures $P_{PH1-PH5}$ measured at the measurement plane of the five holes for different Reynolds numbers $Re_i$ and yaw angles $\alpha_k$ went through a standard data reduction routine using the original numerical calibration map, and the reduced yaw and pitch angles as well as total and static pressures were then compared to the actual angle setting of the probe within the domain and the pressure settings at the inlet, respectively.
To estimate the angle error (α, β)\text{error,i,k}, the actual set angle (α, β)\text{true,i,k} of the probe is subtracted from the measured angle (α, β)\text{meas,i,k}. The yaw angle error α\text{error} shows little dependency on Reynolds number across the incidence range α\text{true}, when the Reynolds number is increased to values greater than the reference value Re\text{i}. (cf. Fig. 22). It varies within a corridor of −0.4 deg < α\text{error} < 0 deg. However, for the Reynolds number Re\text{0.5}, which is less than the calibration Re\text{i}, the error in yaw angle increases somewhat linearly with incidence up to 0.6 deg. Dominy and Hodson [8] also investigated this behavior in their experimental studies. For higher positive yaw angles and lower Reynolds numbers, a separation bubble, triggered by the edge around PH1, was found to grow over PH4, thus reducing the measured pressure.

Figure 23 illustrates the error in the pitch angle β\text{error} with respect to the Reynolds number Re\text{i} from the calibration. In contrast to the yaw angle, the lower Re\text{0.5} has no significant influence on the pitch angle measurement. However, the pitch angle error increases gradually as the Reynolds number increases while remaining largely insensitive to the incident angle α. This results primarily from the decreasing pressure at PH3 for higher Reynolds numbers. The same effect of a decreasing pressure coefficient with increasing Re was also observed by Passmann et al. [10]. In this case, the influence of the stem might cause the imbalance in the effect of Re between PH2 and PH3. The maximum error of 1.2 deg at α = 20 deg occurs at Re\text{0.5}.

To estimate the total pressure error P\text{error}, the numerically measured pressure P\text{meas} is compared to the total pressure P\text{ref} prescribed
The maximum error at Re0.5 and maximum incidence angle $\alpha$ is about 0.06%, which is of the same order of magnitude as the accuracy of the pressure scanner used for the experiments.

Figure 25 is a plot of the error in the static pressure measurement $P_{s,\text{error}}$. The error is defined as

$$P_{s,\text{error},i,k} = \frac{P_{s,i,k,\text{meas}} - P_{s,i}}{P_{\text{ref}}}$$

The error in the static pressure is found to depend on the Reynolds number. With the maximum error approaching 0.2%, it is greater than the total pressure error by a factor of >3, a value that is no longer negligible.

## 5 Conclusion and Outlook

A numerical model was setup using ANSYS FLUENT for a five-hole probe with a tip diameter of 1.59 mm and a cone angle of 60 deg. After an initial mesh resolution study, the numerical model was used to reproduce conditions equivalent to those of a calibration tunnel with a uniform low-turbulence flow and typical ambient conditions, at a Mach number of Ma=0.3 and at varying yaw and pitch angles to obtain a numerical calibration map of the probe. The pressures inside the probe holes served as the convergence criteria. The results provide generally good agreement with the calibration data from the wind tunnel. Some differences are most probably caused by deviations between actual and nominal probe geometries, which could be observed under a microscope.

The analysis of the real probe geometry of a brand new probe in comparison to a significantly aged probe also reveals the impact of utilizing the probe in a compressor test rig with an inlet filter. The actual geometry changes significantly over time and therefore probes need to be periodically inspected, cleaned, and recalibrated. This aging effect is reflected in the calibration coefficients.

The positive effect of modeling the probe holes has been discussed in detail. Measuring the pressure only over the surface of the probe cone leads to significant differences, a finding similar to the results obtained by Li and Bohn [7]. Even though the meshing becomes more complicated, the benefit appears to outweigh the added complexity.

To investigate the effect of Reynolds number on the probe characteristics, the probe Reynolds number was decreased by halving and increased by factors of two, three, and six relative to the ambient conditions by decreasing or increasing the pressure at a given Mach number and simulations were then conducted while varying the yaw angle by up to 20 deg. The error in the total pressure measurement was found to be negligible with a maximum deviation of 0.06% relative to the actual total pressure. This insensitivity of the total pressure coefficient for small yaw angles was also observed during the experimental investigations conducted by Dominy and Hodson [8]. Passmann et al. [10] found the same behavior, although at even lower Re a noticeable change was discovered. The yaw angle error was also found to be generally small, only reaching 0.6 deg at maximum incidence for the smallest Reynolds number. A significant error could be observed for the pitch angle measurement which reaches 1.2 deg for the highest Reynolds number. The static pressure error was found to be small but not insignificant at up to 0.2%. Furthermore, the error with varying yaw angle tends to remain constant for most coefficients. Finally, the influence of the Reynolds number within the investigated range seems to be small but not completely negligible. How much the Reynolds number effect influences the measurement results also depends on the accuracy of the measurement equipment being used.

As it has been possible to demonstrate the accuracy of a numerical calibration, further investigations into pitch angle variations in combination with yaw angle variations at different Reynolds numbers are required. Also, surface scanning of actual probes using a computer tomograph is planned in order that the actual probe geometry can be numerically calibrated and the effect of geometry deviations on the numerical calibration and investigations can be minimized.

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### Conflict of Interest

There are no conflicts of interest.

### Nomenclature

- $d$ = diameter
- $s$ = distance
- $v$ = velocity
- $C$ = non-dimensional calibration coefficient
- $P$ = pressure
- $R$ = radius
- $T$ = temperature
- $Z$ = value considering errors
- $Z_e$ = expected value
- $R_s$ = specific gas constant
- $y^+$ = dimensionless wall distance
- 5HP = five-hole probe
- $Ma$ = Mach number
- PH = probe hole
- $Re$ = Reynolds number
- $x, y, z$ = Cartesian coordinates

### Greek Symbols

- $\alpha$ = yaw angle
- $\beta$ = pitch angle
- $\Delta$ = difference between two values
- $\epsilon$ = error
- $\eta$ = dynamic viscosity
- $\theta$ = cone angle of 5HP
\[ \rho = \text{density} \]

**Subscripts**
- \( \infty \) = initial value
- \( d \) = dynamic value
- \( i \) = factor
- \( k \) = yaw angle setting
- \( s \) = static value
- \( t \) = total value
- \( \text{avg} \) = average equivalent value
- \( \text{Cyl} \) = cylinder
- \( \text{exp} \) = experimental value
- \( \text{max} \) = maximum equivalent value
- \( \text{meas} \) = measured (calculated by pressures)
- \( \text{num} \) = numerical value
- \( \text{ref} \) = reference value

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