Fast Traveling Pneumatic Probes for Turbomachinery Applications

Christoph Brüggemann\textsuperscript{1}, Lukas Badum\textsuperscript{2}, Maximilian Bauer\textsuperscript{1}, Markus Schatz\textsuperscript{1} and Damian M. Vogt\textsuperscript{1}

\textsuperscript{1}Institute of Thermal Turbomachinery and Machinery Laboratory (ITSM), University of Stuttgart
Pfaffenwaldring 6, 70569 Stuttgart, Germany
\textsuperscript{2}Turbomachinery and Heat Transfer Laboratory, Technion, Israel Institute of Technology

ABSTRACT

Pneumatic probes are commonly used to determine the flow vector as well as the thermodynamic state of the fluid in turbomachinery applications. The conventional method to measure a flow passage velocity or pressure field is to move the probe to discrete positions and to hold a certain settling time before valid data can be recorded.

This study presents a measurement methodology leading to a reduction in the required measurement duration of up to 70-90\%, depending on the level of flow field resolution. The approach is based on the concept of continuously traversing probes as introduced by Gomes et al. \cite{1}. However, the system model is changed by reducing the transfer function to a single PT1-behavior. While the experiments conducted by Gomes et al. \cite{1} were limited to only linear cascade measurements, the method used here is extended to turbomachinery applications with highly complex flow structures. The continuous traverse measurements are validated through a comparison with conventional discrete measurements that include characteristic settling time. For this purpose, tests have been performed in an axial diffuser test rig operated with air and a low pressure steam turbine. The results obtained with the new approach show a good match, thus proving the viability of the proposed method for turbomachinery applications. For future tests, a significant reduction in measurement time and cost can be achieved.

NOMENCLATURE

- \(a, b\) Transfer function coefficients
- \(f\) Sampling frequency
- ITSM Institute for Thermal Turbomachinery and Machine Laboratory
- \(K\) Gain factor of transfer function
- \(m\) Order of transfer function
- \(Ma\) Mach number
- \(p, t\) Pressure, Time
- \(u\) Actual pressure
- \(v\) Traversing speed
- \(y\) Measured pressure
- \(\alpha\) Flow angle in yaw direction
- \(\gamma\) Flow angle in pitch direction
- \(\xi\) Error function
- \(\tau\) Time constant

Subscripts

- \(\text{con}\) Condenser
- \(\text{in, out}\) In or out going trip of traverse
- \(i\) Natural number
- \(j\) Time instance
- \(R\) Response
- \(\text{stat}\) Static state
- \(\text{tot}\) Total state

INTRODUCTION

The aim of all types of measurements in turbomachinery is to record the flow characteristics with the highest possible accuracy in order to validate design tools such as 3D CFD flow simulations and to develop more efficient machines in the future. In order to keep the test duration on the test-rigs and thus the costs for measurement campaigns low, the goal of high accuracy is followed by the desire to minimize the measurement time. For the measurement of pressures along the flow path of turbomachinery, pneumatic measuring points are usually used, e.g. to record wall pressures, as well as pressures along the height of the flow passage. Pneumatic multi-hole probes are often used for the latter, which, in addition to recording the pressures, also allow the determination of the local flow vector.

With pneumatic pressure measuring probes, however, the high accuracy is affected by a high expenditure of time, which is essen-

![Fig. 1 Schematic view of the traversing system (1) probe head, (2) probe stem, (3) measuring tube and (4) pressure transducer) and the typical response behavior of such a pneumatic probe system to a pressure change](image)
tially determined by the response time of the system used for pressure measurement. The response time \( t_R \) describes the time required for a pressure change at the measuring point \( j \) to be detected by the pressure transducer \( 4 \), cf. Fig. 1 (right). A change in pressure at the measurement location can occur either by changing the operating point of the machine or by varying the measurement location, e.g. by moving the probe. A recording of the pressure without falsification of the measurement result can therefore only take place if the pressure at the measurement location and at the pressure transducer match. Therefore, at the least the duration corresponding to the response time of the system must be waited for before the recording of pressures.

The response time depends mainly on the following factors: Distance between measuring point and pressure transducer, diameter of pressure tubes, pressure level at measuring location, magnitude of pressure change at measuring location. In the past, much research has therefore been devoted to reduce the response time of the pressure measurement system by reducing the duration of measurement campaigns and ultimately saving costs. For example, by positioning the pressure transducer as closely as possible to the measurement location, the response time can be reduced so much that high frequency pressure changes can be recorded. However, the disadvantage of this method is that the probe head has to be relatively large to accommodate the pressure transducers and the sensors are expensive and susceptible to damage due to their proximity to the measurement location. A different method to reduce the response time is by placing the pressure transducer outside the actual probe and then optimizing the length and diameter of the pressure measuring tubes. This way the probe is usually not capable of measuring details of the highly unsteady flow of a rotating turbomachine. Instead only the steady component can be captured. For optimizing the size of the measuring tubes with regard to the response time two model groupings can be found that are based on differential equations in the literature besides analytical (e.g. \[2\]) and numerical definitions: the distributed parameter models and the lumped parameter models. For an overview of the models reference is made here to \([3–6]\). For example, by applying a lumped parameter model Grinshaw and Taylor \([7]\) were able to develop a miniaturized pneumatic probe with short response time.

In contrast to the presented methods with the aim to reduce the response time, Gomes et al. \([1]\) recently presented another possibility to decrease the duration of measurement campaigns utilizing pneumatic probes. The authors’ approach is based on the method first introduced by Bartsch et al. \([8]\) for an adaptive determination of the necessary spatial resolution of measuring points. In the experiments conducted by Gomes et al. \([1]\), a pneumatic probe is traversed into and out of the flow path. For both directions, the probe passes the same wake of a blade’s trailing edge and measures a pressure peak. However, the position of this peak is shifted locally due to the delay time of the measurement system, resulting in a spatial offset of the recorded pressures between the in and out going traverse, cf. Fig. 2.

By using a transfer function, the actual pressure \( u \) can be determined from the two measured curves. For the transfer function the authors use an approach originally presented by Panigagua and Denos \([9]\). This is based on an one step ahead prediction that recursively calculates the measured pressure from the actual pressures at the measurement location and the measured pressures at the pressure transducer. Neglecting the response time yields:

\[
y_j = \sum_{i=0}^{m} b_i \cdot u_{j-i} - \sum_{i=0}^{m} a_i \cdot y_{j-i}
\]  

(1)

Based on the assumption that the first recorded pressure of each trip corresponds to the actual pressure, the coefficients \( a_i \) and \( b_i \) and thus the actual pressures \( u_i \) at a time instance \( j \) can be determined for both the in- and out-going trip of the traverse unit. Since both measurements are based on the same actual pressure, the determined pressure curves of both trips \( u_{in} \) and \( u_{out} \) must yield the same result. Therefore the transfer function coefficients \( a_i \) and \( b_i \) can be determined iteratively in such a way that the difference \( \xi \) of both curves \( u_{in} \) and \( u_{out} \) is minimized:

\[
\min(\xi) = \min(u_{in} - u_{out})
\]  

(2)

In this way, the pressure curve can be recorded at a significantly increased speed. The authors achieved with the continuous measurement method a comparably high accuracy as with a discrete measurement and a time reduction of up to 80%. In addition, this method offers the advantage that not only discrete measuring points can be captured, but an almost continuous curve along the traversed passage is recorded. Furthermore, this approach is based on the assumption that the response behavior of the measurement system does not change along the traversing path. It is known, however, that the response time varies with the level of pressure it is exposed to. The method therefore tries to find a transfer function that on average has the least error over the entire pressure curve observed. If the pressure fluctuations are too large, this can lead to errors in the measurement.

**Objective**

The approach presented by Gomes et al. \([1]\) offers a large potential to reduce the measuring time with pneumatic probes considerably. For this purpose, it is neither necessary to know the real response time of the measuring system nor to develop new pneumatic probes which are optimized with regard to their response time. However, the disadvantage of this method is that its effectiveness has so far only been demonstrated by measuring the trailing edge of a compressor in a linear cascade and thus in a relatively idealized case. Therefore, the aim of this work is to extend the existing process in order to enable it to be employed for general turbomachinery applications. Accordingly, a rotational component for tracking the flow direction is added to the existing method and validated by measurements in an axial diffuser test rig operated with air and a low pressure steam turbine.

**METHODOLOGY**

The methods used in this study are essentially based on the investigations by Gomes et al. \([1]\). For this purpose, a forward and a backward traveling trip of the probe are required for each measured pressure curve. The probe is moved with a constant speed and a constant yaw angle from the start to the end position and vice versa. Since the approach is a one step ahead prediction, the first recorded data points must correspond to the actual pressure. This requires a waiting time of the probe corresponding to the response time at the beginning of each trip, so that the pressures at the pressure transducer for the first measuring point match the actual pressures. The traverse is controlled via an Arduino-based platform capable of interpreting commands in GCode. In this way, the probe can be positioned precisely. For recording of the pressures a stan-
standard multi-channel pressure transducer is used, which records data with a sampling frequency of \( f = 10 \, Hz \).

After measuring the pressures, the actual pressure curve can be calculated using a transfer function and an error minimization described in Eq. 2. Gomes et al. [1] use the approach presented by Paniagua and Denos [9] as a transfer function, see Eq. 1.

Subsequently, the recorded pressures at the holes of the multi-hole probe can be evaluated by means of a calibration field and thus the flow field along the traveled positions can be determined. By setting the probe to a constant angle before the measurement run, any change in the flow direction must be compensated via the calibration field. Therefore it must be ensured that the probe is sufficiently calibrated for the expected flow characteristic. However, in turbomachinery applications, the selected design strategy for blade profiles can lead to large changes in the flow direction, so that an evaluation exclusively via the calibration field can reach its limits. This is illustrated schematically in Fig. 3 (left).

Therefore, the general strategy for discrete probe measurements here is to align the probe according to the local flow direction via rotation in the yaw axis as soon as the measured flow angle reaches the border of the calibration field, cf. Fig. 3 (right). This ensures that the working point of the probe stays within the calibration field at all times. Experience has shown, however, that the measurement error for a 5-hole cone probe, for example, increases with increasing inclined flow relative to the probe even when the working point of the probe is still within the calibration field. For conventional measuring methods, this error can be reduced by correcting the probe yaw angle not only when reaching the border of the calibration field, but with every new position in traversing direction. Disadvantages compared to the usual measuring routine is, however, that the pressure field at the probe head changes with each rotation, inducing every time a pressure change between probe head and pressure transducer and therefore a corresponding response time must be accounted for after each rotation.

In order to derive a procedure generally valid for turbomachinery applications from the method of Gomes et al. [1], the continuous traveling concept must be extended by allowing a continuous adaptation of the probe yaw angle according to the flow direction.

Model Extension and Simplification

The basis for the method presented is that the probe moves at constant speed through the flow passage. The probe thus passes through a changing pressure field and, in simplified terms, is continuously exposed to infinitesimal small pressure steps. This changing pressure field is crucial for the functioning of the method. A continuous traversing speed, on the other hand, is not a requirement for the methodology. The only decisive factor for the correct function is the fact that there are pressure changes at the probe head of the same magnitude at the same flow passage location for both the in- and out-going trip. In order to ensure the same pressure change for both trips, the same location has to be traveled with the same local speed. Other than that, the probe can be moved independently in its speed, linear axis and rotational axis.

Gomes et al. [1] model the response time using a transfer function that represents a third order system, which, in the overdamped case, can be described as a series of three PT1 elements. Since this approach is relatively complex to implement and to automate due to the necessity of specifying additional boundary conditions, a simplification of the system behavior is presented in the following. Clark and Atkinson [10] point out that an overdamped system is to be modeled sufficiently in second order and even as a 1st order model shows only minor errors. However, it is irrelevant for the method how the response behavior is represented exactly, instead only the time constant of the system is of specific interest. In other words, the magnitude of pressure change that is perceived by the transducer after a given time is the crucial factor of this method. In principle, the transfer behavior could therefore also be simplified by reducing the transfer function to a black box behavior that maps only a weight function from 0 to 1. However, due to the relevance to reality and its simplicity in modeling, the approach utilizing a single PT1 behavior is further pursued here, which is as follows in the time domain:

\[
\frac{u(t)}{u_0(t)} = 1 + \frac{1}{\tau} e^{-\frac{t}{\tau}}
\]

Here \( K \) corresponds to the gain factor and \( \tau \) to the time constant of the system. Assuming that the gain factor is \( K = 1 \), the dependence is only given by one variable, the time constant \( \tau \). Compared to the transfer function in Eq. 1 with 7 degrees of freedom, this function has become considerably simplified. The time constant can be determined by minimizing the error between the in and out going trip and thus the actual pressure curve can be determined.

Validation and General Test Procedure

In order to validate the method adapted here (PT1 element and implementation of the rotational component), a comparison with the procedure according to Gomes et al. [1] on a low velocity wind tunnel is presented, see Fig. 4. At the outlet of the wind tunnel a series of arbitrary blade profiles is mounted in order to provide sufficient wake profiles and flow direction changes to be measured with a standard 5-hole probe. Here four methods are compared with each other:

1. The normal measuring routine, in which the probe is positioned according to the flow direction and sufficient waiting time is given for the recording of a measuring point. This is used as a reference measurement and in the following referred to as a discrete measurement.
2. The continuous measuring routine according to Gomes et al. [1].
3. The continuous measuring routine with the simplified transfer function (PT1 element)
4. The continuous measuring routine with both the simplified transfer function (PT1) and an additional rotational component.

Fig. 4 shows the comparison of the four different methods. The employed standard 5-hole cone probe (see Fig. 6) is calibrated to a yaw angle range of \(\pm 10^\circ\).

In general there is a good agreement of the four methods, but some relatively large differences of both continuously moving methods without rotational component in the range of 35 – 55% relative height (marked by the colored area) and at the borders can be observed compared to the reference measurement. Here, the probe moves for the case without adjustment of its yaw angle close to and beyond the boundary region of its calibration range, which leads to
an increased error. While the evaluation routine for the flow angles $\alpha$ and $\gamma$ used here extrapolates the flow values beyond the limits of the calibration field, this does not happen for the total pressure. Thus no meaningful values for the total pressure result in the marked area and are therefore not displayed. Comparing both continuously moving methods without an adjustment of the probe angle, a good agreement can be observed for the displayed flow values. In the marked area a larger difference for the flow angle $\alpha$ between the two methods can be seen with the original routine being slightly closer to the reference measurement points. Within the calibration field, however, both methods hardly differ from each other, thus it can be concluded that the simplification with the adjusted transfer function using a PT1 behaviour is valid. The continuous traverse including rotation, on the other hand, reproduces the discrete measurement with minimal error. This case clearly shows the necessity of an adjustment of the yaw angle of the probe with a large inclined flow. The probe was traversed at a speed of $v = 100 \text{ mm/min}$. This way a reduction of the measuring duration from 7 to 1.5 minutes could be achieved for this case in comparison with the discrete measurement. Since this test setup shows a very fast response behavior and only a small number of discrete measuring points have been recorded, systems with higher response times and finer spatial resolution are expected to yield greater time savings.

For this idealized test case, the superiority of the adapted method of the continuous traverse with rotational component over the ones without adjustment to the local flow direction in terms of accuracy and duration is demonstrated. However, the disadvantage is that a knowledge of the flow direction along the traversing path must be given in order to complete it accurately. If the flow direction is unknown before the start of measurement, an adapted strategy must be pursued, which is shown in figure 5. If the flow direction is completely unknown, a continuous probe measurement with a constant yaw angle is carried out (1). If the flow direction is unknown before the start of measurement, an adapted strategy must be pursued, which is shown in figure 5. If the flow direction is completely unknown, a continuous probe measurement with a constant yaw angle is carried out (1). If the flow direction is unknown before the start of measurement, an adapted strategy must be pursued, which is shown in figure 5. If the flow direction is completely unknown, a continuous probe measurement with a constant yaw angle is carried out (1). If the flow direction is unknown before the start of measurement, an adapted strategy must be pursued, which is shown in figure 5. If the flow direction is completely unknown, a continuous probe measurement with a constant yaw angle is carried out (1). If the flow direction is unknown before the start of measurement, an adapted strategy must be pursued, which is shown in figure 5. If the flow direction is completely unknown, a continuous probe measurement with a constant yaw angle is carried out (1). If the flow direction is unknown before the start of measurement, an adapted strategy must be pursued, which is shown in figure 5. If the flow direction is completely unknown, a continuous probe measurement with a constant yaw angle is carried out (1). If the flow direction is unknown before the start of measurement, an adapted strategy must be pursued, which is shown in figure 5. If the flow direction is completely unknown, a continuous probe measurement with a constant yaw angle is carried out (1). If the flow direction is unknown before the start of measurement, an adapted strategy must be pursued, which is shown in figure 5. If the flow direction is completely unknown, a continuous probe measurement with a constant yaw angle is carried out (1). If the flow direction is unknown before the start of measurement, an adapted strategy must be pursued, which is shown in figure 5. If the flow direction is completely unknown, a continuous probe measurement with a constant yaw angle is carried out (1).

![Fig. 4](image1.png)

**Fig. 4** Comparison of the adjusted continuously working method with discrete measurements and the method according to Gomes et al. [1]

![Fig. 5](image2.png)

**Fig. 5** Process chart of the usual approach with the continuous measuring method when an unknown flow field is given
Below the actual probe hole pressures in Fig. 8 the evaluated flow values from each traverse run are displayed and compared to a reference measurement (40 discrete measurement points) in terms of mass number Ma, static pressure $p_{stat}$ and the flow angles $\alpha$ and $\gamma$. No moving average filter is applied to the shown data set. Generally, the flow is governed by a large separation area towards the shroud (between 0.7 and 1 relative diffuser height). This is indicated by non-existent evaluated flow values at these positions, while recorded pressures can be seen from the images at the top for these locations. For the most part, the reference values can be matched very precisely with all set measurement parameters ($|\Delta \alpha| < 0.5^\circ$ and $|\Delta p_{stat}| \approx 1$ mbar). Moreover, the separation region is captured accurately and the Mach number Ma curves all agree well with the reference values. For the static pressure $p_{stat}$ and flow angle $\alpha$ scattering of the data seems to increase. This, however, is mostly due to smaller changes of these flow values along the measured traverse. Despite the general good agreement, on close inspection deviations from the reference especially for the case M3 with high speed and large response time ($v = 200$ mm/min) can be observed. M3 overestimates the Mach Number around 20% relative height and shows the largest differences for the resulting static pressure and flow angle $\alpha$ along the whole passage height. The results indicate that a large response time $t_R$ can be compensated by slower traversing speed (compare M2 to M3), however, the setup of M1 seems to yield the best results. At a traversing speed of $v = 200$ mm/min the recording of pressures takes about 1.2 minutes compared to roughly 18 minutes, resulting in a reduction of measurement duration of more than 90%. Thus, the continuous traversing method with its high accuracy compared to the reference measurement presents a valid alternative for measurements in turbomachinery test rigs operated with air. Especially if area traverses are to be measured, one can benefit of the scaling effect of reduced measurement duration.  

**Low Pressure Steam Turbine**

At the ITSM, investigations are carried out on the efficiency and stability of low-pressure steam turbines. The methodology for continuous probe measurement is used for flow measurements in a three-stage steam turbine, see Fig. 7. Challenges in the measurement with pneumatic probes in low-pressure steam turbines are high flow velocities, large flow angle changes of in some cases over $\Delta \alpha = 40^\circ$ from hub to shroud, ambient pressures near vacuum and the flow medium steam. The latter leads to the filling of the measuring tubes with steam so that condensation can occur within them. In addition to the potentially damaging effect of condensate on the
Fig. 8 Results of the continuous measuring method recorded with a set of three different measurement parameters compared to a reference measurement from an axial diffuser test rig.
pressure transducer, the response behavior also changes due to water droplets in the measuring tubes. Therefore, steam or condensate in the measuring tubes is generally undesirable. At the ITSM all pressure measuring tubes used in steam turbines are continuously purged in order to keep the tubes free of steam and thus to either ideally avoid condensate completely or to blow occurring condensate out of the tubes quickly. The continuous purging leads to an offset in the measured pressures which can be corrected by applying the purging correction according to Heneka [13].

In the three-stage steam turbine, measurements are possible with pressure probes in two planes, E30 and E32, before and after the last stage respectively, cf. Fig. 7. Both measuring planes are preceded by rows of rotor blades equipped with part-span connectors in order to reduce blade vibrations. Besides the usual strong change in the flow direction from hub to shroud in steam turbines, these connectors cause additional turbulence and strong local changes in the flow direction at around 75% span each. Thus, the test case shown here represents a highly complex flow field, which is particularly challenging for the measuring system. In this publication, results are shown only from measurements in plane E30.

Fig. 9 shows the results of the new measuring method in comparison with the conventional method of discrete measurement points for two operating points with little to no wetness occurring in the shown plane E30. OP1 describes an operating point at part-load and \( n = 50\% \) of design rotational speed, while the turbine for OP2 is operating at design speed and medium load. Both measurements for each operating point were made in direct succession, so that only minor deviations in the operating point occur and can therefore be virtually ruled out as the cause for differences.

The results show a good agreement between the two measuring methods for the flow parameters total pressure \( p_{\text{tot}} \), static pressure \( p_{\text{stat}} \) and flow angles \( \alpha \) and \( \gamma \). Especially for the total pressure and the flow angle the measured values of both methods are almost identical. Therefore, similar accuracy to the diffuser test can be achieved (\( |\Delta \alpha| \approx 0.5^\circ \) and \( |\Delta p_{\text{tot}}| < 1 \) mbar and < 2 mbar for OP1 and OP2 respectively). Slightly larger differences can be found in the measurement of the static pressure, which is recorded to be slightly less by the continuously moving traverse than with the discrete measurement. For operating point OP1 this is around 50% span and thus slightly below the direct wake of the PSC, while for OP2 the static pressure reduction is shown at 60–80% span which is in the direct wake of the PSC.

Generally it can be stated that for operating points without apparent wetness or sufficient distance to the two-phase area in the measuring plane, the continuous method achieves a high accuracy with a significantly shortened measuring duration. For the measurements at OP1, a speed of \( v = 100 \) mm/min was chosen, which resulted in a total measuring time of approx. 2.8 minutes, while the discrete measurement for 22 measuring points required about 16.2 minutes. Thus a time saving of about 80% could be achieved in this case. Usually the number of measuring points is with 40-50 points much larger and results in an even further increased measuring duration. However, the time needed for the continuous method does not scale accordingly, so that the expected time benefit is likely to be more than 90%. Thus, the continuous method is demonstrated to be an alternative for probe measurements in steam turbines as well.
CONCLUSION
In this publication, a new method for measuring the flow field in turbomachinery by means of traversing pneumatic multi-hole probes was presented, which enables shortening the measuring time by up to 70–90% depending on the spatial resolution of the discrete measurement points. The basis for this is the method of continuous probes according to Gomes et al. [1]. In order to make the methodology applicable for measurements in actual turbomachinery applications, an additional rotational component was implemented and the transfer behavior was simplified with the help of a transfer function that maps a PT1 behavior.

The modified continuous method was validated in a basic wind tunnel test and then successfully tested in both an axial diffuser and a low pressure industrial steam turbine test rig. The results at the diffuser test rig show a very good agreement with the usual measuring methods. Thus, the continuous measurement method is a reliable alternative to discrete measurements and allows in the presented case for a significant reduction of the measurement duration of up to 90% (comparing 40 discrete measuring points of the reference method with the continuous method at \( v = 200 \text{ mm/min} \), cf. Fig. 8). Further, the method can be very advantageous in the case of measuring area traverses, as the measurement durations scale in the same way.

The results of measurements in the steam turbine also yield good agreement with the reference measurement for the two operating points shown. The required measuring duration could be reduced by up to 80% compared to a conventional reference measurement. However, the measurement is highly challenging or may lead to unusable results when condensation in the measuring tubes occurs. This means that the continuous method is only recommended for measurements in substantially superheated steam in order to prevent condensate from penetrating the measuring tubes.

ACKNOWLEDGMENTS
The authors are grateful to the ITSM lab staff for their support in preparing the tests and operating the turbine and to Simon Lux for implementing the continuous traveling method. The support of Siemens Power and Gas and the permission to publish this work is kindly acknowledged.

REFERENCES