MEASURING UNSTEADY 3D FLOW WITH A SINGLE PRESSURE TRANSDUCER

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ABSTRACT

This paper presents a new method to measure unsteady 3D flow using a single pressure transducer mounted on a miniature probe shaft of 1.8 mm diameter. The probe consists of a semi-hemispherical probe tip attached to the cylindrical shaft. A pressure tap on the surface of the hemisphere connects the transducer to the instantaneous pressure of the measurement volume. The unsteady 3D flow data is derived from five consecutive pressure measurements at five predefined angular positions relative to the probe axis for a given geometric grid point in the flow field. Due to the three dimensionality of the flow at the probe tip, the measured pressure characteristics depend on yaw and pitch angle. The proposed calibration model to derive the flow parameters from the measured pressures is described in detail. The concept is validated in the unsteady flow field after a stator blade row of a 2-stage axial research turbine. The results are compared to measurements derived from other probe techniques. The presented technique leads to accurate time resolved total pressure measurements that are comparable with results from equivalent 3D probe techniques.

INTRODUCTION

The flow in any turbomachine is three dimensional due to radial pressure gradients or unsteady effects such as rotor-stator interactions. In low aspect ratio airfoils the three dimensionality of the flow affects the entire flow path. In this environment, a measurement technique is required for tracking the unsteady flow field and capturing the complete 3D velocity vector in order to get a realistic picture of the flow parameters. In general, the total pressure distribution in the flow path is of prime interest to the airfoil designer. An innovative way to measure this parameter is provided by fast response probe technology with single or multiple sensors in a single probe [1]. A miniature silicon chip is mounted within the head of a cylindrical probe shaft. The sensor is glued beneath the hole of the pressure tap to reduce the cavity size and therefore dynamic effect such as resonance of the cavity volume. The measurement of any 3D flow with a single probe requires at least two different sensors within one probe. The first sensor measures three consecutive pressures at three different probe yaw angles relative to the probe axis (middle, left and right) and define a coefficient for flow yaw angle. The second sensor gets the fourth local pressure at the middle probe yaw angle through a second pressure tap, drilled in the probe head and ideally on a curved or slanted surface [1]. Since both sensors register two different middle pressures, a coefficient for the pitch sensitivity of the probe is defined and used to derive the 3D flow vector. This technique is referred in this paper as virtual 4 sensor mode. Without the second sensor such a probe could only be used in virtual 3-sensor mode for pure 2D flow measurements. Being able to measure any 3D flow with one single sensor probe would be ideal. In [2] a study of pitch sensitive probes is presented and evaluated for ideal pitch and yaw sensitivity within a given calibration range. In this study the pitch sensitivities for different probe head geometries were reported.

A new concept is presented that can be used to derive the unsteady 3D flow vector from five consecutive pressure measurements with a single sensor probe in virtual 5-sensor mode [3]. The required second sensor is replaced by a novel pitch angle coefficient that is defined by a combination of the five tap pressures obtained at five different probe yaw angles of the single sensor probe.

The first part of the paper is addressing the pitch sensitivity of this novel probe in a flow visualisation experiment followed by a description of the probe design. Furthermore, the calibration model and accuracy as well as typical error bandwidth for the different flow parameters and probes are listed. In the last chapter the concept is validated in a two stage axial turbine [4], comparing the time resolved results for this type of probe to measurements using other fast response probe techniques [5] and [6]. Finally, the unsteady measurements are time- and mass-averaged in pitch wise direction and compared to equivalent pneumatically averaged 5-hole probe results for one blade pitch after the 2nd stator of the axial turbine.

FLOW VISUALISATION AROUND A SHAPED PROBE HEAD

The 3D flow around the tip of a shaped probe tip is visualised in a water channel as shown in Figure (1a) and (1b). The streamlines around the probe head are coloured by ink injection upstream of the enlarged probe. The diameter of the body is 20 mm and the ellipse on the probe tip has an aspect ratio of 2:1. The experiment is performed at a subcritical Reynolds number (Re) of $1.2 \cdot 10^4$, which is identical to the Re at the measurement area in the research turbine. Figure (1a) shows the deflected streamlines as they convect along the probe in function of the surrounding potential field. A variation of pitch angle changes the potential field, deflect the streamlines and affect the surface pressure on the probe body.

For negative flow pitch angles (Figure 1a) a distinct stagnation point is noticed at the tip of the probe. The surface pressure in front of the probe head reaches a maximum total pressure. Pitching the probe to positive angles will remove the stagnation point at the probe tip, resulting in a stagnation line along the stem axis. The surface pressure will be reduced due to the down wash of the flow as seen in Figure (1b) and leading to a pitch sensitive behaviour of the pressure field at the probe tip.

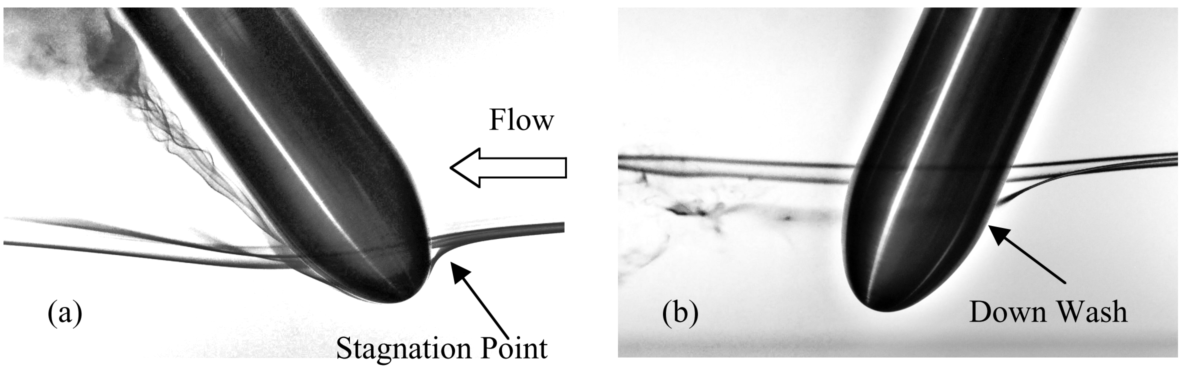

Figure 1: Streamlines around the Probe Head
(a) Negative Pitch Angle, (b) Positive Pitch Angle (Down Wash)

A pressure tap could be drilled at a given point on the surface of the ellipse to actually measure the local pressure in function of pitch and yaw angle. This probe would face the 3D-flow vector and measure the pressure characteristics of the surface pressure in function of both flow angles. The probe needs to be turned to e.g. five angles relative to the probe axis in order to get a cut through the meridian of the pressure contours for an unknown 3D flow vector. The measured set of five pressures contains the full information of the 3D flow vector and is used to derive yaw and pitch angle (α , β), the total and static pressure (P°, P_s) as well as the Mach number (Ma).

DESIGN OF MINIATURE FAST RESPONSE PROBE

Through systematic parametric studies of different head geometries a suitable probe with ideal position of the pressure tap was found as described in [3]. This parametric study resulted in a fast response probe with hemispherical probe tip and a tap angle γ of 0°. To simplify the manufacturing of the probe and to validate the proposed concept, a miniature commercial pressure transducer is mounted into a cylindrical probe shaft of 1.8 mm outer diameter (See Figure 2).

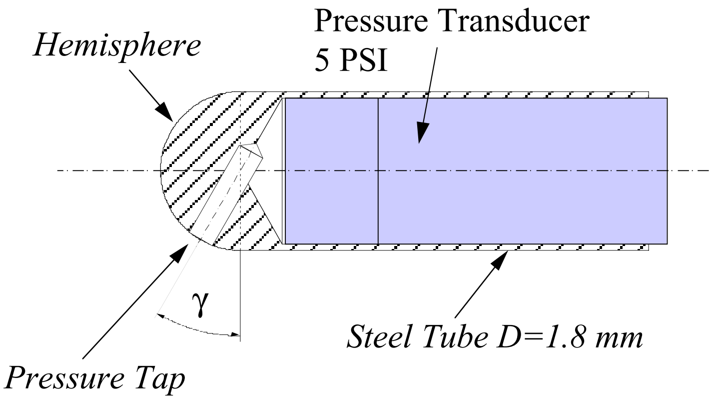

Figure 2: Miniature Fast Response Hemispherical Probe

The inner diameter of the pressure tap is 0.3 mm. This robust miniature fast response probe was calibrated at a Ma of 0.3 in the freejet probe calibration facility of the Turbomachinery Laboratory at the ETH Zurich. The selected calibration Ma of 0.3 corresponds to the average velocity after the 2nd stator of the axial turbine for the probe validation measurements.

CALIBRATION MODEL

For low aspect ratio blades, the measurement of the entire 3D flow vector is essential for capturing the real total pressure. Any 2D flow measurement technique could result in considerable errors of total pressure measurements due to the missing pitch wise flow component. Total pressure errors of 16 % are expected for flow pitch angles of 20°, typical for endwall or leakage flows. Those errors are considerably reduced by applying the following calibration model in combination with any single-sensor fast-response probe with a pitch sensitive probe head.

The calibration model for a virtual 5-sensor probe to assess the 3D flow vector is presented. The probe is turned to five predefined angular positions Θ_1 to Θ_5 with respect to the probe axis in order to measure the corresponding pressures as shown in Figure (3a). The angles Θ_1 to Θ_5 are found by an iteration and systematic study of the given values and denote the case for minimal standard deviations of the resulting flow parameters relative to the calibration set-up of the free jet facility.

The flow angles (α , β) are given in function of the pitch and yaw angle calibration coefficients K_α and K_β given in equation (1) and (2). The presented coefficients only consists of the measured five pressures and define a direct way to quantify the flow angle coefficients. The total and static pressure coefficients K_t and K_s are expressed as a function of the computed flow angles as well as a combination of the measured five probes pressures and the total and static pressure of the free jet calibration conditions (eq. 3 and 4).

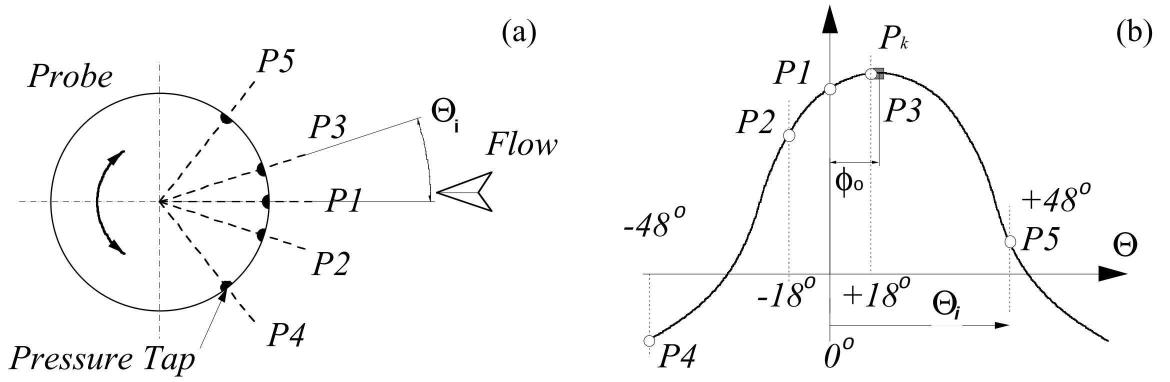

Figure 3: Virtual 5-Sensor Mode (a) and Peak Pressure Definition P_k (b)

The five measured pressures P_1 to P_5 are plotted in function of their probe angles Θ_i as seen in Figure (3b). An interpolation curve of 4th degree is fitted into the data set to find the peak pressure P_k. The obtained value represents the maximum surface pressure that the probe can register when exposed to an unknown flow vector at a certain yaw angle ϕ_o. The definition of the yaw angle calibration coefficient K_α is given in the literature e.g. [6] with the difference that the pressure P_1 at 0° probe angle is replaced by the computed peak pressure P_k [3].

$$K_\alpha = \frac{P_4 - P_5}{P_k - \frac{P_4 + P_5}{2}} \qquad (1)$$

$$K_\beta = \frac{P_k - \frac{P_4 + P_5}{2}}{P_k - \frac{P_2 + P_3}{2}} \qquad (2)$$

The introduction of a pitch angle calibration coefficient K_β as defined by equation (2) is the novel part in this calibration model. This coefficient relates the pressure differences or equivalent dynamic head between the peak pressure P_k and a combination of two pressures P_2 and P_3 taken close to maximum pressure (Θ_2 & Θ_3) and the dynamic head formed with two additional pressures P_4 and P_5 at larger probe angles (Θ_4 & Θ_5). The given relation in equation (2) registers the change of pitch angle and is therefore representative for a pitch angle coefficient. The coefficient is defined without the help of a tap pressure taken form a second pressure tap in the direction of the probe stem, unlike the normal practice for multi-hole probes.

$$K_t = \frac{P^o - P_1}{P_1 - \frac{P_4 + P_5}{2}} \qquad (3)$$

$$K_s = \frac{P^o - P_s}{P_1 - \frac{P_4 + P_5}{2}} \qquad (4)$$

The relations between the flow angles α and β and the coefficients K_α and K_β, total and static pressure coefficients K_t and K_s and the measured five pressures are taken from a direct parametric model proposed in [7].

PROBE CALIBRATION

Steady Probe Calibration

The presented calibration model is applied to a hemispherical fast response probe with a tap angle γ of 0°. The probe was calibrated at a Ma of 0.3 with a corresponding Re of $1.2 \cdot 10^4$ (identical to the flow visualisation experiment), neglecting any compressibility effects. The reference pressure of the probe was set to 15 kPa, preventing the sensor to operate at alternating membrane deflections. Any dynamic effects such as resonance of the cavity volume due to the large size of the cavity are neglected for the steady calibration. The free stream turbulence intensity of the freejet was below 1 % at the Ma number of 0.3.

The commercial pressure transducer of the miniature probe is temperature compensated and therefore primarily depending on pressure rather than temperature changes. The probe is calibrated for a flow angle range of ±16° in yaw angle and +18°/-12° in pitch angle, respectively. The accuracy of the calibration model depends on the selection of the probe angles Θ_i. A systematic variation of Θ_2 to Θ_5, while keeping Θ_1 at 0° is performed to minimise the interpolation or modelling errors of the calibration curves. The optimisation procedure resulted in the following probe angle setup (Hemisphere & γ=0° Tap Angle).

Probe Yaw Angles		
Θ_1	(P_1)	0 °
$\Theta_{2,3}$	(P_2 , P_3)	± 18 °
$\Theta_{4,5}$	(P_4 , P_5)	± 48 °

Table 1: Empirical Probe Angle Setup for Virtual 5-Sensor Probe

The calibration model error is quantified by the standard deviations σ of the computed flow angles α and β in [°] and pressures P^o and P_s relative to the dynamic head as a percentage. The derived Ma is given as a percentage of the calibration Ma.

Parameter		*Std. Deviation* σ	*Typical Coeff. Range*
Flow Angle α	[°]	0.07	K_α : 1.6/-1.6
Pitch Angle β	[°]	1.2	K_β : 3.1/9.3
Total Pressure P^o	[% Dyn. Head]	1.8	K_t : 0/0.6
Static Pressure P_s	[% Dyn. Head]	0.8	K_s : 0.7/1.4
Mach Number *Ma*	[%]	0.9	-

Table 2: Measured σ of Calibration Model and Range of Calibration Coefficients for a Probe Calibration Range of Yaw ±16° and Pitch +18°/-12°

Compared to multi-hole probes, the derived pitch angle and subsequent pressures are less accurate. Previous work [3] showed, that the pitch angle coefficient K_β depends on both yaw and pitch angle. The large range of K_{β}, as given in Table 2, is partly a result of yaw angle dependence and the chosen tap angles of Table 1. As a result, all subsequent values (e.g. pressure) are affected by the increased error bandwidth of the pitch angle computation. The position of the pressure tap at 0° is beneficial to the computation of total and static pressure, since the error of pitch angle is less affecting the accuracy of those parameters (as opposed to a tap angle at 30°). The pitch angle β is computed with an accuracy of 4% of the corresponding calibration range, whereas the yaw angle α reaches an accuracy of 0.2 % for the given calibration range.

Probe Technique		*5-Hole* [8]	*V4S* [5]	*V5S*
Flow Angle α	[°]	± 0.22	± 0.35	± 0.4
Pitch Angle β	[°]	± 0.18	± 0.7	± 2.5
Total Pressure P^o	[Pa]	± 62	± 120	± 190
Static Pressure P_s	[Pa]	± 130	± 85	± 90
Mach Number *Ma*	[%]	± 0.8	± 0.8	± 1.2

Table 3: Typical Error Bandwidth for different 3D Probes

Apart from the calibration model accuracy, the uncertainty analysis for any measurements in a typical turbomachinery flow (e.g. axial turbine) is summarised in Table 3.

Dynamic Response of Sensor Cavity

A difficulty of the simple probe design is the large cavity volume within the head of the probe. The measured unsteady pressure is affected by the resonating cavity volume, which acts as a Helmholtz resonator. An additional frequency, the eigenfrequency of the cavity volume, is added to the spectrum of the signal. The blade passing frequency f_b of the turbine is 1.8 kHz, the measured eigenfrequency of the cavity reaches 13 kHz, respectively. The spectrum of the signal around 13 kHz is overestimated by approximately 10 dB. This error is corrected by applying a 7th order Butterworth filter to the signal post processing routines and choosing the cutoff frequency at 11 kHz. The signal is filtered in the time-domain, which is accepted for a high sampling frequency of 200 kHz.

Previous measurements, using a FRAP (Fast Response Aerodynamic Probe) probe with a cavity eigenfrequency of approximately 40 kHz, were performed to analyse the spectrum of the time varying pressure field at an arbitrary point within the flow. A Fast-Fourier-Transform (FFT) of the pressure signal showed that only the first 6 harmonics of f_b contribute with significant amplitudes to the actual signal. The simple probe of Fig. 2 (large sensor cavity) should resolve frequencies of up to 10.8 kHz. The selected cutoff frequency of the filter hardly affects this condition. The transfer function of the Butterworth filter reduces the overestimated amplitude spectrum of the pressure signal close to the sensor eigenfrequency. It is believed that this simple probe technique is applicable to most research facilities with f_b lower than 2 kHz to 3 kHz blade passing frequency. This technique is not needed for a probe with a small sensor cavity (e.g. V3S FRAP probe).

3D FLOW MEASUREMENTS IN A TWO STAGE AXIAL TURBINE

Experimental Method

The probe concept is validated with steady and unsteady main flow area measurements after the second stator of the axial turbine [4]. A peak Ma number of 0.35 is reached after the 2nd stator leading to a dynamic head of approx. 10 kPa, which is ideal for most pneumatic probe devices. In total, four different techniques of pneumatic probes were used and compared to each other in order to validate the presented virtual 5-sensor probe (V5S). For the steady flow measurements, a miniature 0.9 mm 5-hole pyramid cobra probe provided the pneumatically averaged flow field. A 1.8 mm fast response FRAP probe (small sensor cavity) is used to measure the time resolved flow field in virtual 3 sensor mode (V3S) leading to a 2D data set (no information on pitch angle). The third concept, as referred in [5], captures the unsteady 3D flow, using a set of two geometrically identical but independent fast-response single sensor probes. The dual probe technique superimposes the pressure signals obtained from one probe in V3S-mode to a fourth measurement done with the second probe that uses a pressure tap at a different location on the probe head. This technique is referred to as virtual 4-sensor mode (V4S). The fourth technique is the presented single sensor probe that measures the unsteady 3D flow in virtual 5-sensor mode (V5S). The V4S and V5S fast response probes uses the probe design as given in Fig. 2.

The reference measurement area after the 2nd stator of the axial research turbine is drawn in Fig. 4. The blade span is 90 mm with a tip diameter of 800 mm. The measurement grid consist of 23 radial immersions in the pitchwise direction covering 110 % of a blade pitch and 31 grid points along each radial traverse. The low blade aspect ratio of 1.5 combined with the labyrinth leakage flow, leads to strong secondary flow features and large flow pitch angles (up to 20°).

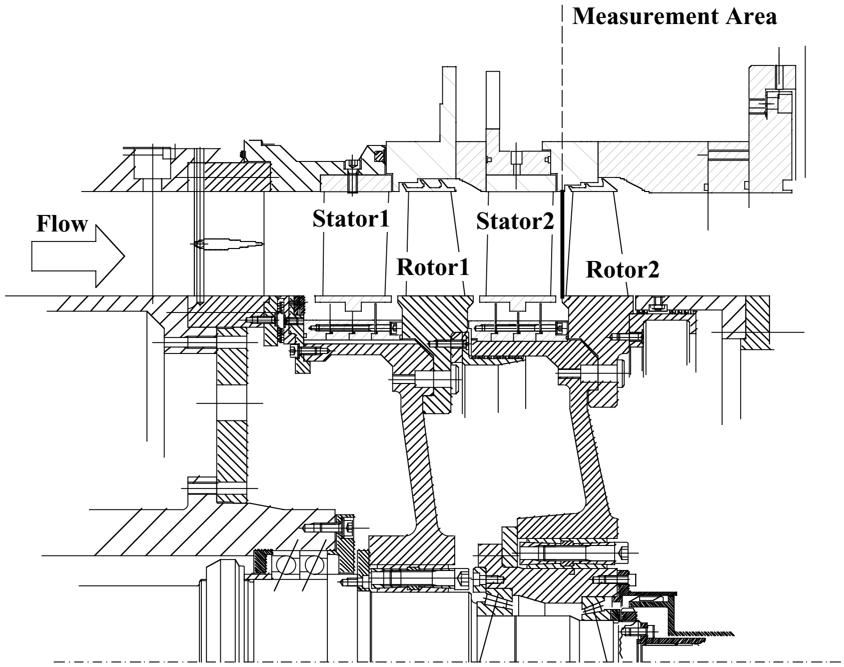

Figure 4: Measurement Area after 2nd Stator of Axial Turbine

The probe evaluation primarily focuses on the ability of the individual probes to measure total pressure. The analysis distinguishes time-resolved flow field measurements (total pressure coefficient C_{pt}) expressed in terms of distance-time diagram (DT) from time- or pneumatically averaged data. The results are post-processed by a mass averaging procedure in circumferencial direction for different span locations and illustrated as C_{pt} profiles.

Time-Resolved Flow Measurements

The circumferencial axis of the DT is taken at 75 % of blade span, cutting through a secondary flow dominated flow field. In this environment, a high flow pitch angle is expected, leading to a major contribution of the pitch-wise flow vector component to the total pressure measurement. The distance-time diagrams of Fig. 5 (V3S, V4S and V5S) show similar features. The three techniques register the unsteady flow field and respond fast enough to the time varying periodic pressure fluctuations. The effect of the larger sensor cavity for the V4S and V5S as opposed to the V3S is not affecting the response of those probes at the given frequencies.

The results of the V4S and V5S probes show higher C_{pt} values than the V3S probe in the area of the blade pressure side (PS) at 60 % pitch (Fig 5f, 5d), where positive pitch angles are usual. The V3S probe lacks the dynamic head in pitch wise direction leading to the lower C_{pt}.

On the blade suction side (SS) at 0 % pitch (Fig. 5e,5d) the total pressure measurements of the V4S and V5S are lower than the corresponding V3S results. The pitch angle at the suction side is negative and shows values of -20° relative to the global rig coordinate system. In the local probe system the pitch angle becomes positive leading to an equivalent flow around the probe tip as seen in Fig. 1b. The probe stem affects the static pressure field around the probe head (down wash) and falsifies the computation of total pressure, if not compensated in the probe calibration.

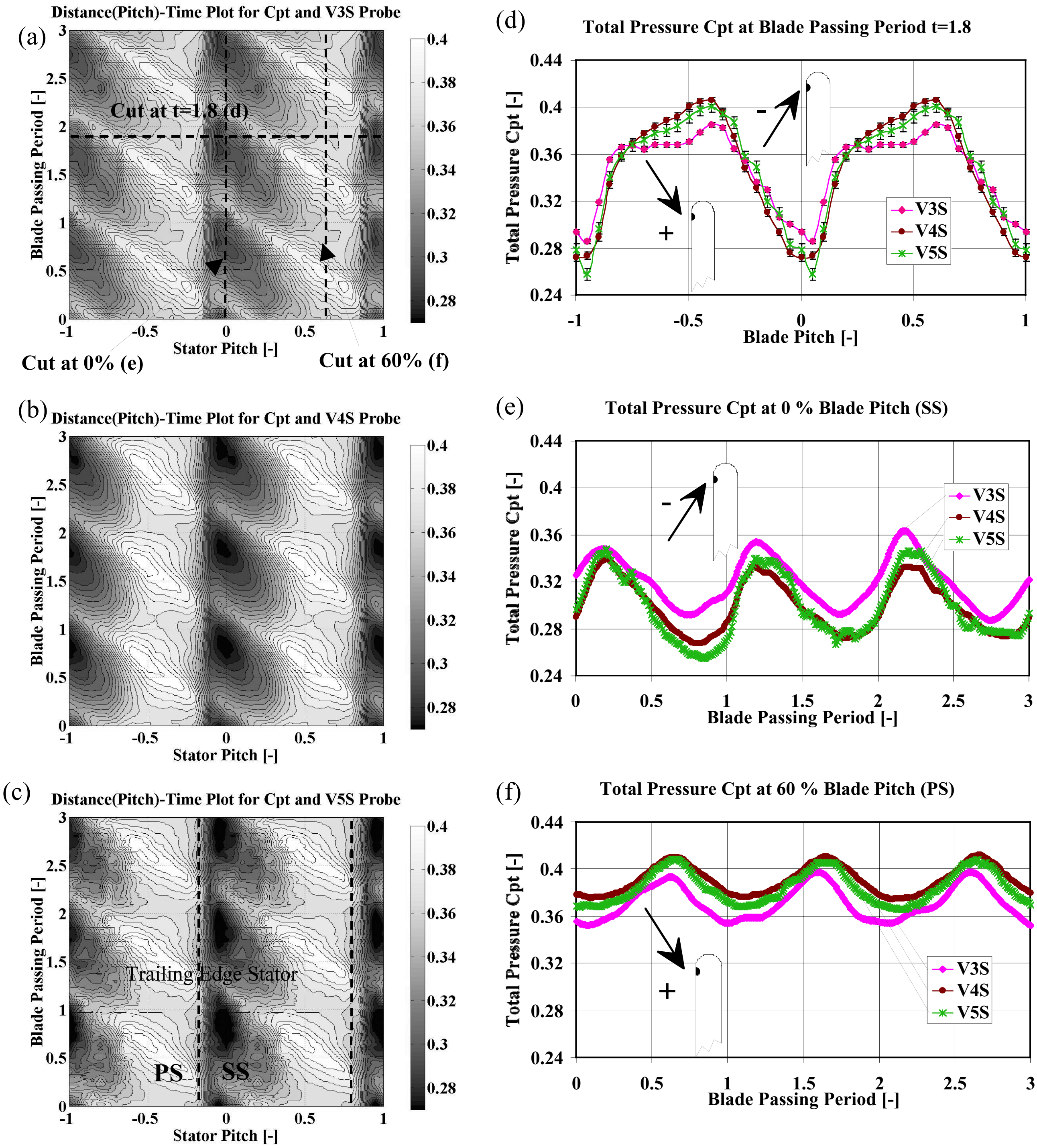

Figure 5: Distance-Time Diagram for C_{pt} at 75 % Span of 2nd Stator Blade
(a) V3S FRAP, (b) V4S Dual Probe, (c) V5S Single Probe &
DT-Cut for C_{pt} at different locations, t=1.8 (d), 0 % Pitch (e), 60 % Pitch (f)

Pneumatic- and Time-Averaged Flow Measurements

The results of the unsteady flow measurement are time-averaged and compared to 5-hole probe data using the 5-hole probe results as reference test case. The results of the total pressure area plots are mass-averaged in circumferencial direction, leading to total pressure profiles with respect to blade span (see Fig. 6a). The differences of the measured dynamic heads are referred to the 5-hole probe case and plotted in Fig. 6b.

The pressure profile of the V5S probe follows the profile path of the pneumatic 5-hole and fast response V4S probe within a bandwidth of 2 %. The three techniques fully resolve the 3D flow vector and produce equivalent results for most of the blade span (10 % to 90 %), except at the tip region in vicinity of the end wall. The V3S probe shows continuous underestimation of total pressure (2% to 4 %) along blade span compared to other techniques.

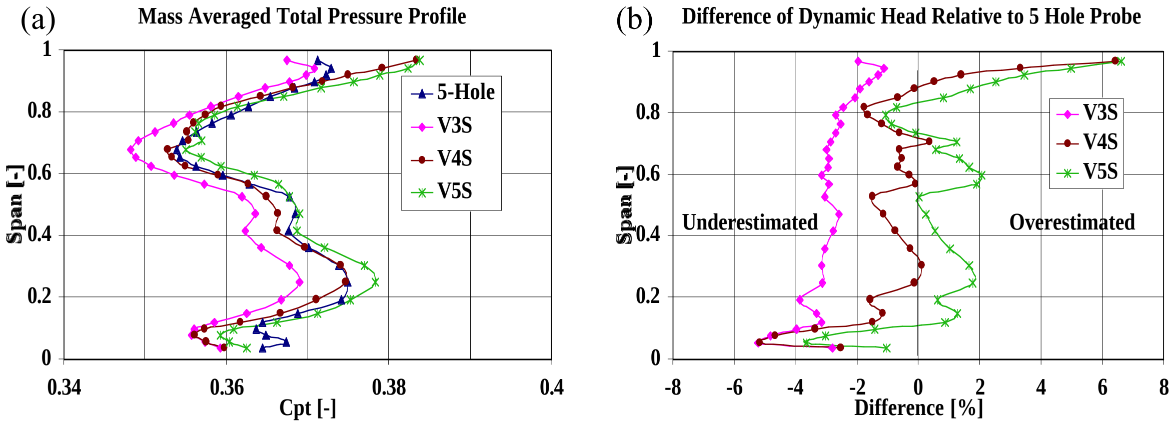

Figure 6: Comparison of Time and Mass Averaged Total Pressure Profiles
(a) C_{pt} Flow Profiles, (b) Relative to 5-Hole Probe in [%] of Dynamic Head

Close to 100 % span the V3S and 5-hole probe lead to similar results (less than 2 %) and differ from the V4S and V5S by more than 6 %. A possible explanation for this difference in total pressure could be the probe intrusion and blockage effect as well as high radial pressure gradient close to the leakage in-flow into the labyrinth cavity (see Fig. 4). The probes were all calibrated within an undisturbed free jet flow field. Any dynamic effects that develop around the probe tip and influence the pressure measurements could not be quantified. Most flow features within the length scale of the probe shaft diameter, e.g. shear flow layer or vortex sheet, could bias the 3D flow field around a pitch sensitive probe and thereby affect the measurement accuracy of the probe technique.

Mean Difference of Dynamic Head (V3s,V4s,V5s) in [%]		
	10 % to 90 % Span	*0 % to 100 % Span*
V3S (FRAP)	- 2.9	- 2.9
V4S (Dual Probe)	+ 0.9	+ 1.5
V5S (Single Probe)	- 1.1	- 1.7

Table 4: Mean Differences of Dynamic Head relative to 5-Hole Cobra Probe

Finally, the mean differences of total pressure for the different probe techniques (Fig. 6b) are listed in Table 4 for two sections of blade span. The overall results of the V5S technique are equivalent to V4S results for most of the main flow area.

CONCLUSIONS

A new method to measure unsteady 3D flow with a single 1-sensor pressure probe was presented. The detailed calibration model uses five pressure measurements in virtual 5-sensor mode at a given measurement point. The measurements are used to derive the complete 3D flow vector. The concept was applied to a miniature fast response probe for unsteady flow measurements within a two stage axial turbine. The obtained results were compared to three alternative probe techniques. The proposed concept of the virtual 5-sensor probe captures adequately the time resolved total pressure field. This improves the accuracy of total pressure measurement compared to V3S techniques. The resulting pitch angle error bandwidth from the proposed calibration model allows the accurate computation of the entire dynamic head of the 3D flow vector. The derived total pressure, using the presented V5S mode, is comparable to any results obtained from 5-hole or alternative 3D unsteady flow measurement techniques.

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