ESTIMATION OF TURBULENCE BY SINGLE-SENSOR PRESSURE PROBES

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ABSTRACT

The paper presents a methodology to derive information on the turbulent properties of the flow downstream of turbomachinery blade rows on the basis of unsteady pressure measurements. In particular, it is shown how the turbulent total pressure fluctuation can be isolated using a cylindrical single-sensor fast-response aerodynamic pressure probe. This is achieved by exploiting the flow angle insensitivity guaranteed by the smooth shape of the probe head. The main goal of the methodology is to keep its validity even for highly fluctuating flows such as the one discharged by a turbomachinery rotor, characterized by unsteady flow angle fluctuations larger than the insensitivity of any pressure measurement device. A method to compute the turbulent kinetic energy from the turbulent total pressure for any flow regime is also provided.

Detailed comparisons total pressure probes and laser-doppler velocimetry downstream of turbomachinery rotors are reported to validate the proposed procedure. A very good agreement is found between the different measurement techniques from the qualitative point of view, and a good agreement is also achieved in quantitative terms. In comparison with LDV, maximum differences of ±10% of the turbulent kinetic energy were observed in the wake regions, where any measurement technique suffers an increase of uncertainty.

INTRODUCTION

In this decade fast-response aerodynamic pressure probes (FRAPP) have experienced a significant development that, alongside the first relevant examples of application (Miller *et al.*, 2003, Schlienger *et al.*, 2005, Gaetani *et al.*, 2007a and 2007b), resulted in a progressive growing of interest around this measurement technique. The FRAPP, developed by matching the technologies of the pneumatic multi-hole aerodynamic probes with that of the piezoresistive pressure transducers, represents one of the most comprehensive measurement techniques for applications in turbomachinery. Turbomachinery flows are indeed affected by two classes of unsteadiness: the random turbulent unsteadiness and a periodic unsteadiness induced by the relative motion between adjacent blade rows. The FRAPP were originally conceived to capture this latter deterministic component, being sensitive to the instantaneous fluctuations of static and total pressure, and of flow angles. The interested reader is referred to the review papers of Kupferschmied *et al.*, 2000 and Ainsworth *et al.*, 2002, or to the Ph.D. Thesis of Brouckaert, 2004, for an overview of the FRAPP development in the last two decades.

Since the very first trials of this measurement technique (Heneka, 1983), the use of FRAPP was tentatively extended to turbulence measurements, by accounting for the non-deterministic components of the pressure readings of the probe. This was possible since these probes, encapsulating three (2D probe) or four (3D probe) sensors, capture the effective time-resolved pressure distribution on the probe head, and from this the actual instantaneous flow field. Unfortunately the agreement between turbulence measurements performed with the FRAPP and with other, more suitable techniques (hot wire or laser-doppler velocimetry) was found to be rather poor (Ruck, 1988); this was probably due to the relatively large probe head dimension (about 5 mm) with respect to the hot wires and, especially, with respect to the larger scales of the turbulent vortices.

In fact the problem of the external miniaturization affects the turbulence measurements as well as the measure of the periodic unsteadiness, due to the typical small-scale of turbomachinery applications. On the basis of this consideration, some research groups chose to minimize the probe dimension by drastically reducing the number of sensors, adopting the virtual multi–sensor probe concept. According to this philosophy, three pressure taps / sensors can be replaced by three rotations of a single tap/sensor around the probe axis; therefore two-dimensional measurements can be attained with a single-sensor probe (Kupferschmied *et al.*, 2000), while three-dimensional measurements can be obtained with two single-sensor probes (Pfau *et al.*, 2002) or with a two-sensor probe (Dossena *et al.*, 2004, Porreca *et al.*, 2007).

Unfortunately single–sensor or two–sensor probes cannot measure the actual instantaneous flow, but they can only capture the deterministic unsteadiness (phase-resolved flow). Although this kind of probes should not be able to detect any turbulent (i.e., non periodic) fluctuation, Porreca *et al.*, 2007, have recently shown that, for incompressible flows, turbulence measurements can also be performed with a two-sensor probe.

In the present paper a methodology to obtain turbulence measurements with a single-sensor FRAPP for any flow regime is proposed. The procedure is applied downstream of subsonic and transonic turbine rotors, and its validity is evaluated against more conventional techniques such as total pressure probes and Laser-Doppler Velocimetry.

TURBULENCE ESTIMATION METHODOLOGY FOR SINGLE-SENSOR PROBES

THE SINGLE-SENSOR CYLINDRICAL FAST RESPONSE AERODYNAMIC PRESSURE PROBE

The instrument is a cylindrical single-sensor fast-response aerodynamic pressure probe whose head diameter is of 1.85 mm, operated as a virtual three-sensor probe for 2D aerodynamic measurements in a plane normal to the probe axis (Persico *et al.*, 2005a). The probe was developed around a commercial miniaturized pressure sensor (Kulite XCQ-062, FS = 25 Psi, temperature compensated, extended uncertainty ±80 Pa), to ensure high reliability, low cost and simplification in the probe head manufacturing. Since the sensor is already mounted in a 30 mm long shield, the transducer is axially sub-surface mounted inside the probe. The spatial resolution of the probe, defined as the physical distance between the extreme positions of the tap during the three rotations, is 1.4 mm.

The probe aerodynamic accuracy was evaluated in a calibrated nozzle, resulting in an extended uncertainty equal to ±0.5% of the kinetic head for the pressure measurements and equal to ±0.3° for the flow angle. Specific tests showed that the pressure reading of the probe is weakly sensitive for meridian flow angles (pitch angle) inside ±10°. The FRAPP measurement errors caused by high pitch angles, evaluated during the aerodynamic calibration, are reported in Table 1. Note that the probe does not exhibit a symmetrical behaviour around 0°.

Pitch Angle	Static and total pressure	Mach number	Yaw angle
-10°	8% of the kinetic head	0.02	0.7°
+10°	1% of the kinetic head	0.01	0.3°

Table 1: Errors of the cylindrical FRAPP readings due to high meridian flow angles

The transfer function of the line-cavity system connecting the probe tap to the pressure sensor was determined by means of tests in a low-pressure shock tube (Persico *et al.*, 2005b). The probe bandwidth is 80 kHz after digital compensation, largely suitable for phase-resolved and turbulence measurements downstream of turbine rotors.

ESTIMATION OF THE TOTAL PRESSURE UNRESOLVED UNSTEADINESS

In analogy with the Reynolds decomposition for stationary turbulent flows, a turbulent flow characterized by a dominant periodicity (and its harmonics) can be expressed by the so-called triple decomposition (Telionis, 1981). A generic quantity f acquired in a fixed point in space can be written as:

$$f(t) = f_{DC} + f_{AC}(t) = f_{DC} + f_P(t) + f_R(t) = f_{\det}(t) + f_R(t)$$

where f_{DC} and f_{AC} are the time-averaged and the time-resolved components; this latter is further divided in a periodic component f_{P} and random – turbulent – component f_{R}; f_{det}, sum of f_{DC} and f_{P}, is the deterministic component used in this paper. The deterministic component is better defined on phase (φ) rather than on time, and is obtained by computing phase-locked averages on the instantaneous signal:

$$f_{\det}(\varphi) = \frac{1}{N}\sum_{n=0}^{N-1} f\left(\frac{T}{\Phi}\cdot\varphi + n\cdot T\right)$$

where N is the number of periods available for the phase-locked average, Φ is the total number of phases and T is the fundamental period (for example, the rotor blade passing period for a measurement taken in the absolute frame).

By applying these techniques to a time-resolved measurements with a multi-sensor FRAPP, the deterministic components are computed for the multiple pressure measurements, and the unresolved unsteadiness is directly obtained by subtracting the periodic and time-averaged components to the original pressure signal on an instantaneous basis. Finally, the RMS of the unresolved components is computed for any phase of the period, to provide an estimate of the evolution of the unresolved unsteadiness during the period:

$$RMS\ f_R(\varphi) = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1} f_R^2\left(\frac{T}{\Phi}\cdot\varphi + n\cdot T\right)}$$

A similar approach is clearly not possible for a single-sensor probe, because the multiple pressure readings are taken at different times. However the problem of the not instantaneous multiple measurements can be partially overcome if smooth shapes of the probe head are used. For cylindrical probes the smooth shape of the head guarantees an insensitivity of ±10° for the yaw angle, that can be exploited to derive the actual instantaneous fluctuation of total pressure. Once the pressure tap is aligned with the flow direction and the instantaneous flow angle fluctuation remains inside the insensitivity range, the pressure measurement is representative of an instantaneous total pressure measurement. In absence of periodic phenomena, the measured unsteadiness is produced only by turbulence and thus, from the RMS of the total pressure fluctuation, some information on the turbulence field can be obtained.

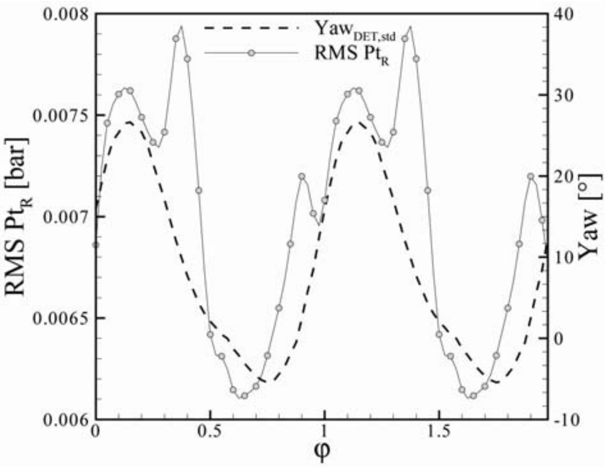

Fig. 1: Evolution of the phase-resolved yaw angle and of the RMS of the unresolved total pressure unsteadiness during the period

Downstream of a turbine rotor the unresolved unsteadiness is superimposed to the large deterministic unsteadiness induced by the movement of the rotor blades, that easily exceeds the insensitive range of the probe. As a consequence for cylindrical probes it is normally not sufficient to orient the probe along the mean flow direction to measure the instantaneous total pressure.

A more accurate estimation of the turbulent unsteadiness downstream of a turbine rotor can be obtained by orienting the probe along the *phase-resolved* flow direction, imaginarily tracking the periodic flow angle fluctuation. This achievement is possible if, beside the classical rotations required for the reduction of the periodic quantities (45° in this case), a number of extra-rotations are imposed to the probe during the acquisition. The angular span between the extra-rotations is determined on the basis of the flow angle insensitivity. For the present cylindrical probe, rotations of 9° guarantee that, for any phase during the period, the pressure tap is oriented along the periodic flow direction with an uncertainty of ± 4.5°, less than the half of the insensitivity range. The number of extra-rotations depends on the amplitude of the flow angle deterministic unsteadiness, evaluated through preliminary measurements.

At first the phase-locked average of all the pressure readings for the different rotations (r) is computed:

$$P_{\det}(r,\varphi) = \frac{1}{N}\sum_{n=0}^{N-1} P\left(r, \frac{T}{\Phi}\cdot\varphi + n\cdot T\right)$$

For a fixed phase, the maximum deterministic pressure among the R rotations represents the phase-locked total pressure and the corresponding angular position (*Ang(Pt(φ))*) roughly estimates the phase-locked flow angle:

$$\begin{aligned} Pt_{\det}(\varphi) &= Max(P_{\det}(r,\varphi)) \quad for \quad r = 1,\dots,R \\ Yaw(\varphi) &= Ang(Pt_{\det}(\varphi)) \pm 4.5° \end{aligned}$$

It is assumed that the instantaneous component of the pressure signal acquired at that angular position for that phase represents the effective unresolved fluctuation of the total pressure. Once the total pressure turbulent fluctuation is isolated at any phase, its RMS can be calculated:

$$RMS\ \ Pt_R(\varphi) = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1}\left(P\left(Ang(Pt_{\det}(\varphi)), \frac{T}{\Phi}\cdot\varphi + n\cdot T\right) - Pt_{\det}(\varphi)\right)^2}$$

In this way the periodic evolution of the level of unresolved total pressure unsteadiness is evaluated for any measurement grid point. An example of application of the proposed methodology is reported in Figure 1. The periodic evolution of the RMS of the unresolved total pressure unsteadiness is coherent with the flow field, being high in the rotor wake (high yaw angle) and lower in the free-stream region.

The main shortcoming of this procedure is that, once the angular position is selected at a certain phase, the turbulent fluctuation of the two flow angles is assumed to remain inside the insensitivity range of the probe. The role of this hypothesis will be evaluated through comparisons with different measurement techniques.

DERIVATION OF TURBULENCE QUANTITIES

Despite the random total pressure unsteadiness has a clear physical interpretation, it is of great interest to derive some more common turbulence quantities, such as the turbulent kinetic energy κ, defined as:

$$\kappa = \frac{1}{2}\left(\overline{u_R^{\,2}} + \overline{v_R^{\,2}} + \overline{w_R^{\,2}}\right)$$

where u_R, v_R and w_R represent the three unresolved - turbulent - components of the flow velocity. In view of application to total pressure measurements, a more physical representation of the turbulent terms is achieved by introducing an intrinsic coordinate system. This intrinsic coordinate system is defined as follows:

- The streamwise direction is defined according to the angular orientation of the probe tap axis, $Ang(Pt_{DET}(\varphi))$, that roughly estimates the deterministic flow angle (u_R component).
- The normal direction lies in the blade-to-blade plane (v_R component).
- The binormal direction is the normal to the other two directions (w_R component).

Following the approach proposed by Wallace and Davis, 1996, the unresolved total pressure measurement can be correlated with the square of the turbulent velocity component in streamwise direction. By using the relation between total and static pressure in compressible flows and the ideal gas equations of state, and taking the ratio of specific heats equal to 1.4, this relation can be expressed as:

$$Pt_R = (1 - 0.175 M_{\det}^4) \cdot P_R + \rho_{\det} V_{\det} (1 + 0.5 M_{\det}^2) \cdot u_R$$

In which M, V and ρ represent respectively the Mach number, the velocity magnitude and the gas density.
The average of the squares of the unresolved total pressure unsteadiness equates the RMS of the total pressure measured by the probe, leading to:

$$\left(RMS\ Pt_R\right)^2 = \frac{1}{N}\sum_{n=1}^{N} Pt_n^2(n) = \overline{Pt_R^{\,2}}$$

$$\overline{Pt_R^{\,2}} = (1 - 0.175 M_{\det}^4)^2 \cdot \overline{P_R^{\,2}} + 2\rho_{\det} V_{\det} (1 - 0.175 M_{\det}^4)(1 + 0.5 M_{\det}^2) \cdot \overline{P_R u_R} + \rho_{\det}^2 V_{\det}^2 (1 + 0.5 M_{\det}^2)^2 \cdot \overline{u_R^{\,2}}$$

By using the Hinze's formulation for the acoustic turbulent fluctuation (Hinze, 1975) in isotropic flows, expressions for the terms involving the turbulent static pressure fluctuations can be obtained:

$$P_R = 0.7 \rho_{\det} u_R^{\,2} \quad \Rightarrow \quad \begin{cases} \overline{P_R^{\,2}} = 0.49 \rho_{\det}^2 \cdot \overline{u_R^{\,4}} \cong 0.49 \rho_{\det}^2 \cdot \overline{u_R^{\,2}}^{\,2} \\ \overline{P_R u_R} = 0.7 \rho_{\det} \cdot \overline{u_R^{\,3}} \cong 0 \end{cases}$$

By making the further assumption reported above, the following equation can be finally derived:

$$\overline{Pt_R^{\,2}} = 0.49 \rho_{\det}^2 (1 - 0.175 M_{\det}^4)^2 \cdot \overline{u_R^{\,2}}^{\,2} + \rho_{\det}^2 V_{\det}^2 (1 + 0.5 M_{\det}^2)^2 \cdot \overline{u_R^{\,2}}$$

from that the turbulent kinetic energy of the streamwise turbulent velocity component can be easily computed. Under the assumption of isotropic turbulence, the turbulent kinetic energy can be finally computed

With respect to the expression proposed by Wallace and Davies, 1996, the assumption of neglecting the term $\overline{u_R^{\,3}}$ needs some discussion. In fact, only $\overline{u_R}$ is rigorously zero (by definition), while the cubic term is actually negligible only if the peak velocity fluctuations are statistically symmetrical with respect to the mean value. However the solution of the complete equation is more complex than the straightforward analytical solution available by neglecting the cubic term; comparative tests showed that the two equations gave very similar results, that do not justify the higher complexity of solving the complete equation..

The assumptions and simplifications required to estimate the turbulence from a single sensor pressure probe will be evaluated by means of comparisons with other measurement techniques in the following sections.

COMPARISON WITH TOTAL PRESSURE MEASUREMENT DOWNSTREAM OF THE LFM TURBINE ROTOR

The first step of the proposed methodology is the estimate of the unresolved total pressure unsteadiness. To verify the validity of this procedure, the data extracted from the FRAPP were compared with measurements performed with a fast-response total pressure probe (FRTPP) characterized by a large flow angle insensitivity.

THE LFM FAST-RESPONSE TOTAL PRESSURE PROBE

A fast-response miniaturized total pressure probe was developed on the basis of a commercially available piezoresistive transducer (Kulite, model XCQ-062, FS = 25 Psi, temperature compensated, extended uncertainty ±80 Pa). The transducer is encapsulated in a metallic tube with a diameter of 3 mm. To enhance the flow angle insensitivity (Dénos, 2002), the transducer's membrane is mounted with a recess of 0.8 mm. In Figure 2 the pressure coefficient $KPt = \dfrac{Pt - P}{Pt - Ps}$ is plotted against the yaw angle; within the yaw angle range ±22°, total pressure measurements variations remain largely inside the measurement uncertainty, while for the flush mounted sensor the insensibility to the yaw angle reduces to less than ±10°. Once it is aligned with the time-averaged flow direction, the FRTPP is a time-resolved measurement device if the flow angle fluctuation remains within ±22°.

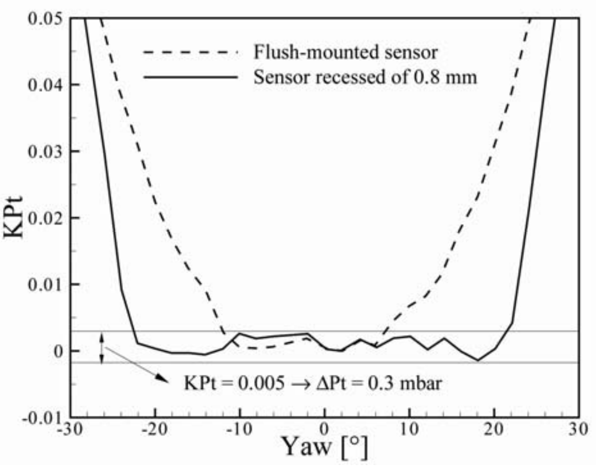

Fig. 2: Aerodynamic behaviour of the FRTPP with flush mounted or recessed sensors

This improved aerodynamic performance is obtained at the expense of a reduction of frequency response with respect to the flush-mounted configuration (order of magnitude hundreds of kHz). Dynamic calibrations of the FRTPP in the shock tube indicate a good linearity in the frequency response, with a dynamic behaviour typical of an under-damped second order linear system, characterized by a natural frequency of 49.5 kHz and a damping factor of about 0.1.

The time-resolved nature of the measurements performed with the FRTPP allows to derive the unresolved total pressure unsteadiness with the standard procedure. Once the deterministic component is extracted, the unresolved component is computed by subtracting the deterministic component to the instantaneous signal.

TEST RIG AND MEASUREMENT PROGRAM

The cylindrical single-sensor FRAPP and the FRTPP were applied downstream of the high pressure turbine stage installed in the LFM closed-loop test rig operated at the Politecnico di Milano. Full details on the test rig are reported in Gaetani *et al.*, 2007a. During these tests the stage was operated in subsonic flow conditions (expansion ratio of 1.4, rotational speed of 6800 rpm), the rotor blade passage frequency was 2.83 kHz. The midspan diameter is 0.35 m and the blade height is 50 mm.

Measurements were performed at about 20% of the rotor axial chord downstream of the rotor trailing edge. The area of investigation was chosen is such a way that the phase-resolved flow angle fluctuation remains inside the FRTPP insensitivity range. Therefore, measurements above 80% span were excluded since the tip leakage vortex causes larger flow angle fluctuations. The measurement grid was obtained by moving the probes in radial direction (19 points) and by rotating the stator to simulate the pitchwise traversing (12 points). The pressure signals of both the probes were acquired at 1 MHz for a period of 1 second, in order to achieve good statistical reliability. The raw pressure data were phase-averaged to obtain 40 intervals on a single rotor blade passing period, corresponding to a physical sample rate of about 113 kHz.

APPLICATION, COMPARISON AND DISCUSSION

In Figure 3 the measurements taken with the FRAPP and the FRTPP are reported. In particular both the phase-resolved and the unresolved total pressure unsteadiness are provided in order to evaluate the validity of the technique described in this paper. To assess the capturing of the phase-resolved component, the mean total pressure field in the rotating frame is reported at the top of Figure 3. The data in Figure 3 suggest a good agreement between the two techniques, the FRTPP being able to resolve the main total pressure gradients downstream of the turbine stage. From the quantitative point of view, differences between the two measurements statistically lie in the range ±2 mbar.

Whatever is the physical interpretation of the total pressure field, for the aims of the present discussion, the evaluation of the unresolved unsteadiness is of major interest. In the two bottom frames of Figure 3 the RMS of the total pressure is compared, estimated with the proposed methodology for the FRAPP and with the standard methodology for the FRTPP. A very good agreement is observed between the two techniques from the qualitative point of view. High levels of unresolved unsteadiness are found in the wake region for $\theta/\Delta\theta_R = 1.1$ or

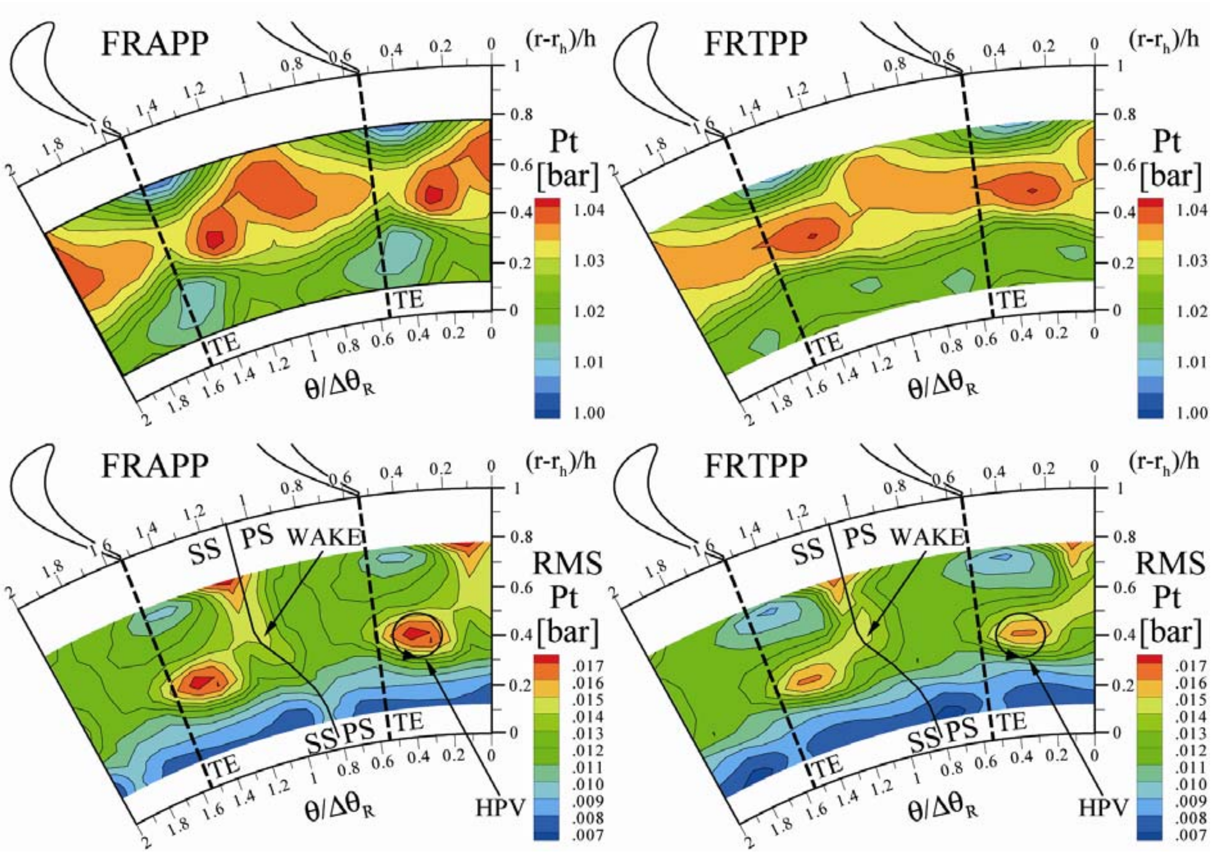

Fig. 3: Comparison between phase-resolved (top) and unresolved (bottom) total pressure measurements with the FRAPP (left) and the FRTPP(right)

0.1, and in the hub passage vortex (HPV) core ($\theta/\Delta\theta_R$ = 1.4 or 0.); note that these viscous flow structures, marked in Figure 3, were identified on the basis of phase-resolved flow quantities (not reported for sake of brevity, see Gaetani *et al.*, 2007b, for an overview of the phase-resolved flow field downstream of the LFM turbine rotor). A good agreement is also found in more strictly quantitative terms, with differences being statistically in the range ±0.5 mbar, with peaks of 1 mbar in the high turbulence regions. Indeed turbulent fluctuation of the flow angle outside the insensitivity range might lead to a slight overestimation of the unresolved total pressure unsteadiness for the FRAPP. However, these differences are comparable to the transducer uncertainty, so their quantitative relevance is not significant.

It is common experience that total pressure measurement obtained with a FRTPP can be successfully used to mark regions of high turbulence (Wallace and Davies, 1996, Paniagua et al., 2007). Therefore the agreement between the FRAPP and the FRTPP measurements in Figure 3 shows that the combination of data-acquisition/data-reduction techniques applied to the FRAPP allows to correctly isolate the turbulent component of the unsteady total pressure, overcoming the limitations of cylindrical probes in terms of insensitivity. In addition, while the FRTPP cannot be used when the periodic flow angle fluctuation outgoes the probe insensitivity, the methodology developed for the cylindrical FRAPP removes any constraint regarding the phase-resolved flow angle fluctuation. As a relevant consequence the FRAPP can provide information on turbulence even in the tip leakage vortex region, where the flow angle fluctuation commonly exceeds the 45° for measurements taken in a fixed position close to the rotor trailing edge.

COMPARISON WITH LDV MEASUREMENTS DOWNSTREAM OF THE TU-GRAZ TURBINE

In this section a more rigorous validation of the proposed methodology is reported, by comparing FRAPP measurements with LDV data downstream of the TU-Graz transonic turbine rotor.

TEST RIG, INSTRUMENTATION AND MEASUREMENT PROGRAM

The test turbine at the Institute for Thermal Turbomachinery and Machine Dynamics of the TU-Graz is an open-loop continuously running cold-flow facility, which allows to reproduce engine representative conditions in full flow similarity (corrected speed and pressure ratio). Detailed information on the design and construction of the facility can be found in Erhard and Gehrer, 2000, and Neumayer *et al.*, 2001. A transonic one and a half stage turbine is installed in the test rig, characterized by 24 vanes, 36 rotor blades followed by 24 second stator vanes. The main geometrical and operative characteristics in the present configuration are reported in Schennach *et al.*, 2007a. LDV and FRAPP measurements were performed inside the gap between the rotor and the second stator. For the aims of the present study, measurements taken in a traverse placed 55% of the rotor axial chord downstream of the rotor are reported.

Optical measurements were performed by a two-component LDV-system (DANTEC FiberFlow with two BSA processors) operated in back-scatter configuration by a COHERENT 6W argon-ion laser operated at approximately 400 mW in all lines. This geometry resulted in a probe volume of about 0.11 mm diameter and 2.5 mm radial depth. Depending on the position in the flow the acquisition rate was about 400 Hz in the wakes and 2 kHz in the main flow. The optical access was realized through a small plane-parallel glass window of 9 mm thickness and 120 x 23 mm surface dimension (HERASIL high-temperature quartz glass). Droplets of DEHS oil (Di-Ethyl-Hexyl- Sebacin-Esther) were added by PALAS AGF 5.0D seeding generator 0.3 m upstream of the first stator row as seeding material. An estimate of the droplet diameter in the measurement volume is 0.6–0.7 µm (Woisetschläger *et al.*, 2003).

As in the LFM test rig, the stators were moved to simulate a pitchwise traversing system. The measurement grid consists of 20 positions in circumferential direction for both the techniques, and 15 and 8 positions along the blade span for the FRAPP and the LDV respectively.

Regarding the LDV data acquisition/reduction, for each measurement point about 80,000 velocity burst were collected. These data were phase-locked on the rotor wheel and then phase-averaged using a linear regression method as described by Glas *et al.*, 2000, to finally obtain 40 windows over one rotor blade passing period. The phase-resolved and the unresolved component of the *u* and *v* velocity components (with *u* and *v* the axial and circumferential components respectively) are then computed with the standard procedure. The TKE is finally calculated by assuming that the turbulent kinetic energy associated with the third component w_R (not recorded) is equal to the average between that of the u_R and v_R components.

$$\kappa_{LDV} = \frac{1}{2}\left(\overline{u_R^{\,2}} + \overline{v_R^{\,2}} + \overline{w_R^{\,2}}\right) = \frac{1}{2}\left(\overline{u_R^{\,2}} + \overline{v_R^{\,2}} + \frac{1}{2}\left(\overline{u_R^{\,2}} + \overline{v_R^{\,2}}\right)\right) = \frac{3}{4}\left(\overline{u_R^{\,2}} + \overline{v_R^{\,2}}\right)$$

The FRAPP pressure signals were acquired for one second at a sampling frequency of 1 MHz. The data were phase-averaged to obtain 20 intervals (or windows) in the blade passing period. It was not possible to match the temporal resolution of the LDV, because with 36 rotor blades rotating at 10700 rpm the physical sample rate for 20 evaluation windows results about 130 kHz, that allows to resolve fluctuations up to 65 kHz, close to the limits of the probe bandwidth of 80 kHz. Differently with respect to the LDV, the turbulent kinetic energy estimated with the FRAPP is derived by assuming complete isotropy (with Vs_R the streamwise component of the turbulent velocity fluctuation):

$$\kappa_{FRAPP} = \frac{1}{2}\left(\overline{u_R^{\,2}} + \overline{v_R^{\,2}} + \overline{w_R^{\,2}}\right) = \frac{3}{2}\overline{Vs_R^{\,2}}$$

PHASE-RESOLVED FLOWFIELD COMPARISON

To develop an appropriate discussion on the two measurement techniques, the FRAPP and the LDV are firstly compared on a periodic basis. The unique common quantity directly measured by the two techniques is the flow angle in the blade-to-blade plane, indicated as α (taken positive if according with the peripheral velocity). In Figure 4 a snapshot of the instantaneous α angle field is reported for the LDV and the FRAPP. It should be noted that, due to the 2-to-3 ratio of the stator and rotor blade numbers, adjacent channels are phase-lagged by 1/2 of the rotor blade passing period, or 1/3 of the stator blade passing period (which is the dominant periodicity affecting the rotor aerodynamics). Therefore, by looking at the three channels indicated in Figure 4, the periodic evolution of the flow field can be drawn.

The agreement between the distributions of flow angle measured with the FRAPP and the LDV is reasonably good, marking at least two of the three wakes theoretically present in these snapshots (low relative momentum turns into high absolute flow deflection). It is interesting to note that in this plane the flowfield is significantly affected by the second vane potential field, that locally modifies the flow angle in the proximity of the leading edge. This probably causes the absence of a clear wake trace for the channel at t/SBPP = 0.00. In addition, the high radial gradients of α angle between 20% and 30% span for t/SBPP = 0.00 and 0.33, and between 30% and 40% span for t/SBPP = 0.67, mark the presence of a coherent clockwise vortical structure, that can be identified as the rotor hub passage vortex. The qualitative agreement between the two techniques is noteworthy also in the resolution of this flow structure. More details on the instantaneous flow field in the rotor – second stator spacing can be found in Paradiso *et al.*, 2008, and Schennach *et al.*, 2008.

In quantitative terms, the maximum differences are observed in the wake, where:

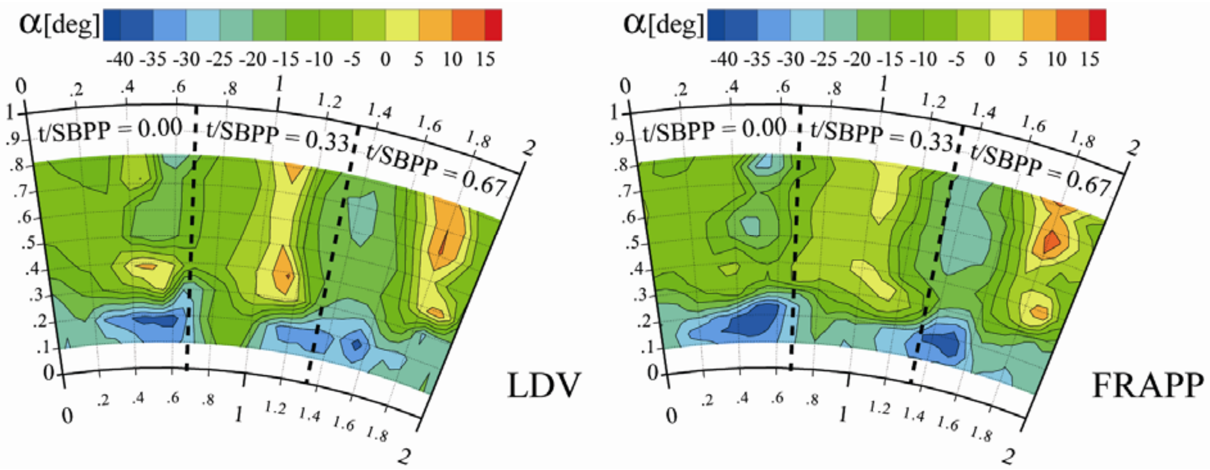

Fig. 4: Phase resolved blade-to-blade flow angle downstream of the TU-Graz transonic rotor

- the uncertainty of the LDV increases; for example, the estimate of the error in the measurement of the local velocity magnitude increases to 5% in the wake region, see Schennach *et al.*, 2007b;
- the physical dimension of the FRAPP may affect the resolution of the gradients;
- the use of calibration matrixes evaluated in uniform and permanent flows may also contribute to enhance the uncertainty of the FRAPP in the wake regions;
- both the techniques are unable to measure the radial velocity component, the FRAPP being also weakly sensitive to radial flow angles (see Table 1).

A better agreement is found in the free-stream regions where the smoother gradients imposed by the potential field weakly affect the measurement accuracy for both the techniques.

TURBULENCE FIELD COMPARISON AND DISCUSSION

The distributions of the turbulent kinetic energy derived from the LDV and FRAPP measurements are reported in Figure 5. Time-resolved measurements of entropy being seldom available, the turbulent kinetic energy is an efficient marker of the loss regions. By analyzing the LDV map the wakes and the vortex regions can be clearly identified. With reference to the identification based on the flow angle, the hub vortex region is characterized by about twice turbulence kinetic energy with respect to the wake. An increase of κ also is visible at the top grid border, where probably the lower leg of the highly dissipative tip leakage vortex is detected.

Despite the very different methodologies and assumptions made in the two approaches, the κ computed on the basis of the FRAPP measurements shows a relevant agreement with that derived from LDV. This is valid not only in the free-stream regions, where values in the range 200-400 m^2/s^2 detected by the two methods, but also in the wake as well as in the hub passage vortex regions. In particular, differences are of the order of ±100 m^2/s^2 on local values of about 1000 m^2/s^2 in the wakes and about 2000 m^2/s^2 in the vortex cores. Higher quantitative differences are instead found at the tip grid border, where the anisotropy of the turbulence in the tip leakage vortex could affect the calculation of κ for both the measurement techniques.

However, the present results demonstrate that the proposed methodology allows to obtain reasonable estimates of turbulence quantities even in highly complex flow fields with single sensor FRAPP.

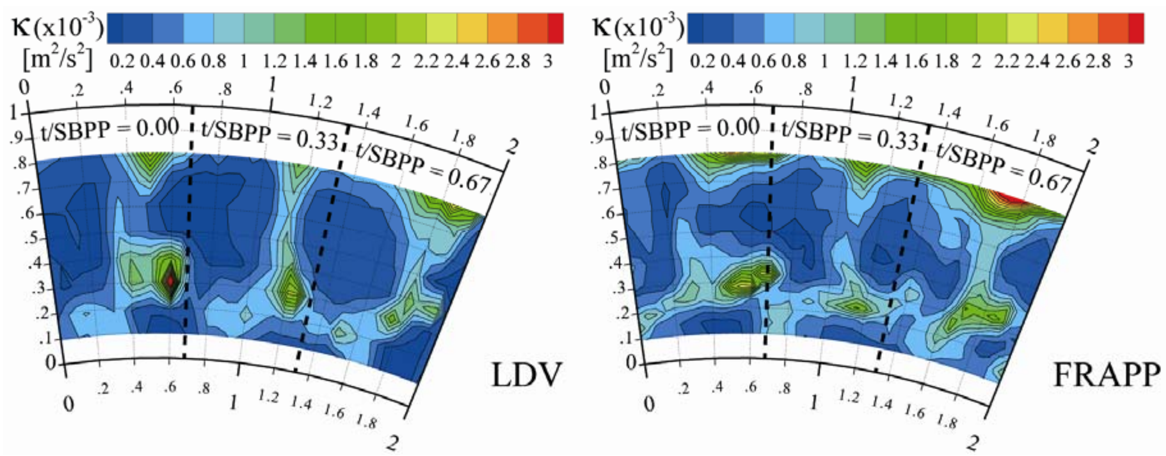

Fig. 5: Turbulent kinetic energy distribution downstream of the TU-Graz transonic rotor

CONCLUSIONS

In this paper a methodology to extend the use of single-sensor fast-response aerodynamic pressure probes (FRAPP) to turbulence measurements has been proposed. Information on turbulence are relevant for both the development and validation of turbulence models and to support the experimental identification of loss regions. Differently with respect to other methodologies available in literature, the estimate of turbulence is performed by exploiting the insensitivity of the probe head to the flow angle fluctuations.

As a key-feature of the paper, the methodology allows to derive the unresolved total pressure unsteadiness also in cases of periodic flow angle fluctuations exceeding the insensitivity of the probe. This is achieved by aligning the pressure probe tap along the phase-resolved flow direction, for any phase in which the fundamental period is divided. The application of the methodology can therefore be extended to measurements downstream of turbomachinery rotors, characterized by periodic flow angle unsteadiness exceeding ±10°. Once the unresolved total pressure unsteadiness is isolated, its RMS is used to analytically compute the turbulent kinetic energy of the flow field under the hypothesis of isotropic turbulence.

The methodology has been validated against two different measurement techniques: a fast-response total pressure probe (FRTPP) and laser-doppler velocimetry (LDV). The comparison with the FRTPP (flow angle insensitivity of ±22°) has shown that the unresolved total pressure unsteadiness is well estimated by the FRAPP, both from the qualitative and quantitative point of views (differences inside the transducer uncertainty). Furthermore, the methodology proposed here is of wider application range than the FRTPP, since it does not suffer from periodic flow angle fluctuations that, in turn, could exceed the insensitivity range of the any total pressure probes. Comparison with LDV measurements allow to assess also the procedure to compute the turbulent kinetic energy from the turbulent total pressure. The estimation of the turbulent kinetic energy has been found to be in excellent qualitative agreement with that of LDV. In quantitative terms, maximum differences of ±10% have been detected in the wake and vortex regions.

These results indicate that, by means of an appropriate data reduction technique, reliable information on the turbulence field downstream of turbomachinery rotors can be obtained with single-hole fast-response aerodynamic pressure probes. In the regions of high three-dimensional flows, where the validity of the isotropic hypothesis is questionable, the methodology provides useful information from the qualitative point of view and represents a valuable interpretation tool to identify the viscous structures downstream of turbomachinery rotors.

ACKNOWLEDGEMENTS

The authors are grateful to Prof F. Heitmeir and Prof. J. Woisetschläger for having made available the TU-Graz test rig for the FRAPP measurements. Special thanks also go to Dr. O. Schennach for having performed the LDV measurements reported in this paper.

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