

EXPERIMENTAL METHODS FOR PERFORMANCE AND RELIABILITY OF STEAM AND GAS TURBINES

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ABSTRACT

Nowadays turbomachines are widely used in power generation, transportation and industry. In order to achieve high efficiency and reliability, the machines are equipped with advanced instrumentation to control and monitor their operation and to evaluate the engineers' design during the development phase. The need to achieve even greater efficiency and flexibility is high, since both steam and gas turbine designs are driven by the size increase in order to cover the high energy demand. This paper presents the experimental methods and instrumentation for the development and operation of steam and gas turbines. Discussed and surveyed are the problems encountered, and techniques used, in making measurements in today's high performance, compact design turbomachines. Applications of the different techniques in research and industry are also reviewed together with their advantages and drawbacks. In addition, the paper presents the recent developments in instrumentation made in the Laboratory for Energy Conversion in ETH Zurich in the field of steam and gas turbines. The paper aims to provide the essential experimental methods for performance and reliability measurements in the development and operation phases.

INTRODUCTION

The progress in turbomachinery the last 50 years is impressive. The power output of large gas and steam turbines has reached 600MW and 1.8GW respectively with efficiencies greater than 60%. In the aviation sector, gas turbines, which are used to power the aircrafts, can generate up to 115,000lbf (510kN) thrust, which is translated to 150MW power output

with fuel efficiency as low as 3.1 litres per 100 passenger kilometres. The outcome is a long-term effort from researchers in industry and academia with the focus primarily on improvements in efficiency and performance. Nevertheless, there is still a margin to improve the efficiency and increase the performance of these machines. New designs are driven by the size increase, which creates a greater challenge in reliability and operational flexibility.

Turbomachinery flows are highly unsteady [1, 2] and measurements in this complicated flow field environment require accurate fast response instrumentation. Today, time resolved measurements are a key element for a successful development of a steam or/and gas turbine. The high computational power enables efficient and fast data processing in four dimensions where the time domain is as important as the standard three spatial dimensions. Nowadays, this is possible not only due to the improvements in data handling but also due to the development of integrated high accuracy measurement systems where they can be manufactured with efficient cost. Integration in packaging of electronics results in high signal to noise ratio and pressure resolution down to 6Pa on the measured raw signal. This was not possible when semiconductors were initially used and therefore today it is an important advantage for every experimental engineer.

Aerodynamic measurements in steam and gas turbines

Total pressure is one of the most important flow quantities since it is directly linked to loss and efficiency measurements. In combination with static pressure, the flow field velocity can

be derived and as a consequence the mass flow rate of the machine can be calculated. Conventional multiple pneumatic probes are widely used in performance measurements in both gas and steam turbines [3, 4]. Nevertheless, since turbomachinery flows are highly unsteady and three dimensional, fast response aerodynamic probes are more than necessary when performance measurements are considered.

The development of fast response instrumentation is strongly related with the progress in the semiconductor industry. The first fast response probes were developed in the 1980s, however a complete work in the entire measurement system was presented by Gossweiler in 1993 [5]. Since then the progress on fast response instrumentation was quite impressive and the technique was established for performance measurements in gas turbines [6]. The need for time resolved measurements in turbomachines has led many researchers to develop their own fast response aerodynamic probes. In that regard, Persico et al. [7] developed a fast response aerodynamic probe using a single commercial pressure sensor. The sensor is embedded in the probe stem with an outer diameter of 1.85mm. Shock tube tests have shown a cavity resonance of 80kHz, however an analytical model to compensate for the signal amplification and phase shift is presented by the authors. The probe provides the unsteady total pressure and yaw angle in the range of $\pm 22^\circ$ in the regions where the flow field is considered to be two-dimensional and there is no reference on the maximum temperature where this probe can be operated. A recent publication by Mersinligil et al. [8] presents the integration and application of a commercial high temperature and high bandwidth (up to 250kHz) fast-response flush mounted single sensor probe. However, due to packaging reasons the diameter size is 2.5 mm big and the sensor is protected against mechanical damage from particle impacts only with RTV coating. As the one of Persico, this probe consists of a single pressure tap and therefore only 2D flow field measurements can be obtained. To overcome this issue Lenherr et al. developed a two sensor fast response high temperature probe [9]. This is equipped with particle shielded pressure taps, which protect the pressure sensors from any particle impact and can be operated up to 260°C. However, this sensor configuration increases the cavity volume between the pressure tap and the membrane of the sensor and therefore the measurement bandwidth is limited to 25kHz uncompensated. Nevertheless the probe is equipped with two pressure taps one for yaw and one for pitch angle sensitive and as a result the probe can provide the unsteady 3D flow field in a miniature size for high spatial resolution with a probe tip diameter of 2.5mm. The aerodynamic calibration of the probe, under well-defined flow field conditions, is performed in freejet facility of the Laboratory for Energy Conversion (LEC) at ETH Zurich. Typical values are $\pm 30^\circ$ and $\pm 25^\circ$ in yaw and pitch angles respectively up to 0.9 Mach number. The smallest fast response aerodynamic probe with two sensors for 3D flow field analysis is developed in LEC lab as well. The probe tip has a diameter of 1.8mm and the miniature size provides uncompensated measurement bandwidth up to 48kHz.

For transonic and supersonic flow field conditions, typically found at the stator exit of the last stage on a low pressure steam turbines, cylindrical probe geometries become very sensitive to the Reynolds number. As a consequence, small variations in the Mach number from the calibrated one may result in static pressure changes of more than 10%. The wedge geometry is often chosen since the flow field around it, is independent of the Reynolds number as described in [3, 10]. A probe for transonic and supersonic measurements in steam turbines is presented in Figure 1 by Schatz et al. [10]. As described in the next section of this paper, this probe combines as well an optical extinction system for wetness measurements in the last stages of LP steam turbines. The wedge surfaces for the yaw and pitch angle sensitivity are shown in the same figure together with the respective total and pitch pressure taps.

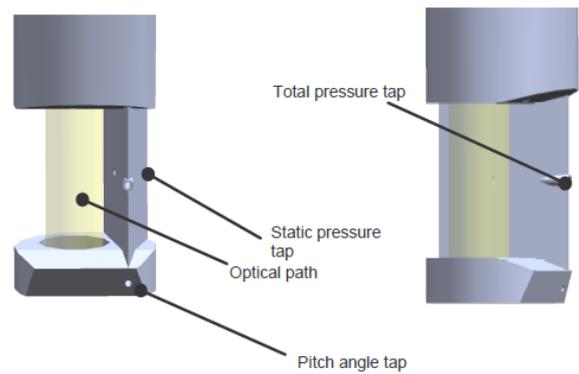


Figure 1: Combined optical and pneumatic probe for transonic measurements in steam turbines by Schatz et al. [10].

As described previously, fast response instrumentation for gas turbines has been widely used from many researchers and today is considered an established technique [6, 9, 11, 12]. However, for the development of steam turbines, experimental studies of the unsteady aerodynamic excitation of low-pressure steam blades have been only conducted in down-scaled air models, as reported in [13]. The literature review in unsteady flow field measurements reveals the lack of instrumentation in fast response aerodynamic probes in real wet steam environment. Most of the researchers have performed unsteady pressure measurements with flush mounted pressure sensors on the stator or casing of LP steam turbines [14, 15]. The challenge in operating flush mounted sensors is to maintain high robustness from droplet impacts present in the last stages the machines. Therefore, according the current literature survey, only one attempt could be found in the open literature dealing with time-resolved flow field measurements in the flow path of LP steam turbines. This is presented by Gerschütz et al. [16] where two different probes were manufactured, as shown in Figure 2. Both consist of two pneumatic pressure taps for balancing in flow direction and one total pressure tap equipped with Kulite® sensor for unsteady total pressure measurements. The probes can operate up to 275°C and have a tip diameter of 6mm. The main drawback of these probes is that they provide the unsteady pressure fluctuations in a flow region where the flow is considered again two-dimensional. In addition, the cavity

between the pressure sensor and the perforated protective screen as shown in Figure 2, can be potentially clogged from water and corrupt the unsteady pressure signal.

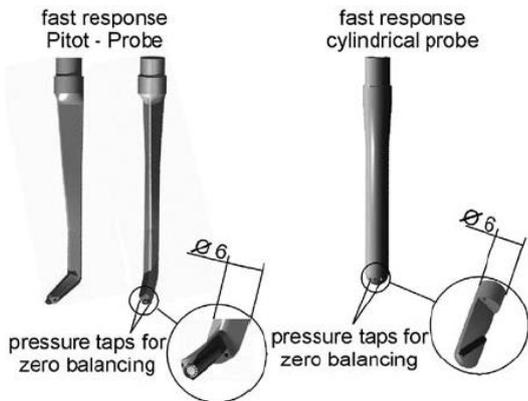


Figure 2: Single sensor fast response probe by Gerschütz et al. [16].

Aeromechanical integrity measurements in steam and gas turbines

Strain gages

Strain gages for reliability measurements are more than necessary since both steam and gas turbine designs are driven by the size increase in order to cover the lack in energy demand. Strain gage measurements are widely used to investigate the static and dynamic stresses imposed on engines parts, at different operating conditions [15]. On a new engine, strain gages are used to evaluate the designer’s calculations. During the development phase, strain gages are used for the rig protection and as the engine matures, they are used to investigate field service problems.

Although the strain gages are simple sensors, based on resistance measurements, their installation necessitates the prediction of the stress distribution due to vibrations and the best location and direction for measuring the strain. In that regard, Szwedowicz et al. present in [17] an approach for the computation of the optimum gage position on tuned bladed disks regarding the determined sensitivity, orthogonality, gradient and distance criteria. The developed algorithm optimization tool presented in their work, allows for an effective numerical search of suitable solutions of the defined optimization function. The investigation of the optimum installation position is also discussed in [18], highlighting the fact that the gage location is often a compromise between the requirements for sensing different strain fields resulting from different vibration modes and the necessity to limit the number of gages used.

Once the position has been found the connection with the acquisition device is not a trivial issue. On the rotating parts, the connecting wires must often pass through a slip ring generating high noise on the measured signal. As a consequence, a newly developed telemetry system with wireless data acquisition boards (see Figure 11) is presented in the current paper and combines the high sampling rate of 200kHz with high signal to noise ratio. This is an integrated system that couples the unsteady pressure measurements using

flush mounted pressures with the measurements from strain gages. The strain gages are connected to the acquisition boards with a very thin (135µm thick) flexible printed circuit in order to minimize the interactions with the flow field and at the same time keep the geometry of the blade identical with the initial design. The installation of the strain gages and flush mounted pressure sensors with the miniature flexible printed circuits is presented by Kammerer et al. in [19] with measurements on a radial compressor.

While significant effort to minimize the flow interaction with the strain gage wires is made, it is often the case that the flow field is highly distorted. This is more pronounced in steam turbine vibration measurements since most of the glues do not resist the harsh environment and as consequence the wires are covered with a metal sheet, which is then welded on the rotor blades surfaces. In addition, often the blade thickness is so small, in particularly at the tip, which does not allow the machining of any groove. This has the advantage that the geometry of the blade does not change from the initial design, since no grooves are machined, but on the other hand the flow field can be strongly influenced by the presence of these components on the blade surfaces. This effect on the flow field is shown in Figure 3 with the time resolved total pressure downstream of the second to last stage from a four stage LP steam turbine [20]. The results are obtained from a single traverse where the FRAP-HTH probe (see Figure 6) was traversed radially with a spatial resolution of 11mm. The horizontal axis is the blade-passing period for 10 rotor blades of the L-1 stage with 96 blades covering one rotor revolution. The data are phase locked averaged over 80 rotor revolutions for 96 rotor blade passing events. As shown in Figure 3, the total pressure fluctuations for the 66th rotor blade have been doubled covering 50% of the blade span. As a consequence, the blade loading has changed and therefore the results from the vibration measurements will be affected. In order to overcome this challenge the tip timing technique presented in the following paragraph enables non-intrusive vibration measurements and therefore undistorted flow field.

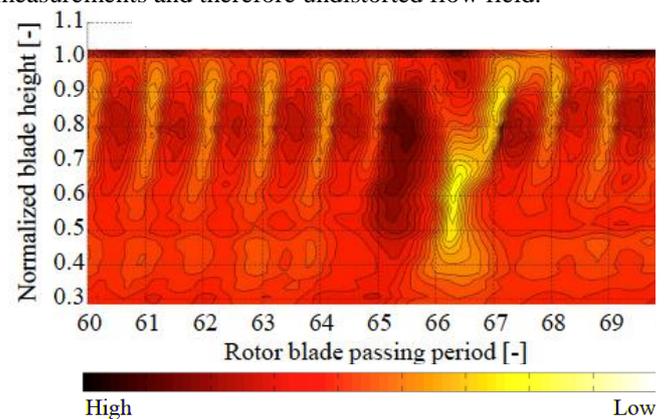


Figure 3: Unsteady total pressure at the exit of the second to last stage from a LP steam turbine. Flow field distortion (RBP period 65 to 68) due to strain gages installation on the rotor blades.

Tip timing

Measurements with the tip timing technique are also used to determine the mechanical vibrations of the rotating blades. Today, this is a well-established non-intrusive technique, which allows the analysis of blade fluttering and mistuning up to a certain eigenfrequencies. The blade tip timing equipment is typically comprised by a set of sensors (optical, eddy current or capacitive sensors), which are installed on the casing of the machine, and they are used to measure the arrival times of rotating blades. These arrival times, in comparison to the blade passing frequency, are used to determine the blade deflections and therefore the vibration characteristics [21]. As presented in [21] for the purposes of tip timing data analysis, there are two distinct classes of response, the synchronous and asynchronous. Synchronous resonances are assembly modes that are excited at multiples of the rotational speed. Asynchronous resonances are mainly due to aerodynamic instabilities such as rotating stall and flutter.

Particle and droplet measurements with optical probes

Measurement techniques using optical methods have a wide application in performance as well as reliability for gas and steam turbines. In the aviation sector, the recent volcanic eruption in Iceland in 2010 brought a special attention to the topic due to the unclear safety margins that the engines could be operated. Atmospheric ice and subcooled water ingestion due to severe weather conditions have as well negative effects on the aircrafts' engines performance and reliability. On the other hand, the erosion phenomena in the last stages of LP steam turbines are still under investigation and the accelerated erosion rate, of the last rotor driven by the size increase, is a major challenge. In turbomachinery, measurement techniques for particle-laden flows are mainly focused on liquid droplet measurements. They are distinguished between fog droplet measurements with droplet diameters from 0.1 to 10 μm and coarse droplet measurements with diameters from 10 μm and above [22, 23].

Fog water droplet measurements for steam turbine applications

Regarding droplet measurements for turbomachinery applications, there is a significant number of publications dealing with the development of different probes to measure droplets' size and concentration. The most promising technique for measuring these small droplets in the submicron range is the optical extinction method as described by the Beer-Lambert law. This principle is utilized in the well known optical extinction probes, which are used in steam turbines since 1970s with some of the first attempts made by Walters et al. [24] and Young et al. [25]. However, the probe tip diameters are relatively large (dia. 20mm) and a consequence the interaction with the flow field can be considered high. According to the literature review the smallest optical extinction probe was built by Schatz et al. as presented in [10] and shown in Figure 1. This probe has a tip diameter of 10mm and combines an optical and pneumatic part for the time averaged flow field measurements with the nulling technique.

Since the probe surfaces are prone to water contamination many times these probes are heated to improve the accuracy of the results. A probe for the same flow field environment capable to measure transonic flow velocities and fog droplets in one system was developed by Wu et al. [26] and shown in Figure 4. As presented in the same figure the difference of this probe from the one of reference [10] is the position of the pneumatic part relative to the optical part. The wedge surfaces with the pressure taps are placed 50mm away from the optical path affecting the spatial resolution of the measurements.

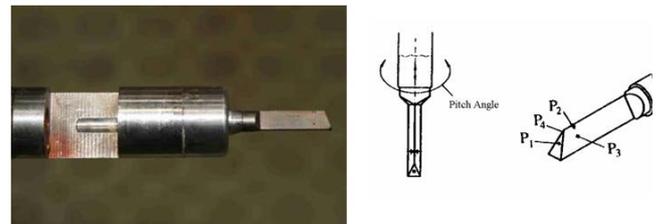


Figure 4: The tip from a combined optical and pneumatic probe by Wu et al. [26].

Coarse water droplet measurements for steam turbine applications

As it has been described so far, the majority of the developed probes for steam turbine applications have a minimum tip diameter of 10mm and a detectable droplet size up to 10 μm , mainly implementing time averaging techniques such as light extinction. These probes are suitable for fog droplet measurements and therefore erosion phenomena cannot be fully studied. Cai et al. in [27] have developed an integrated probe system for coarse water droplet measurements up to 400 μm . As shown in Figure 5, the system consists of a fine droplet measurement subsystem using the light extinction technique and a coarse droplet measurement subsystem using the forward light scattering technique. The probe has a tip diameter of 20mm and it incorporates as well a pneumatic part for the time averaged flow field measurements. In their results at the last stage of a steam turbine, the authors present the droplet trajectories and speeds under various operating conditions. A noteworthy work from the same research group for coarse droplet measurements is by Xueliang et al. [28]. In this report, the authors present a video-probe system capable to take images of coarse water droplets ($D_p > 10\mu\text{m}$), in order to measure the diameter and velocity. The probe is calibrated using standard monodispersed glass beads up to 77.2 μm in diameter, as well as in a spray environment with a known concentration and diameter. The main drawbacks of the last two approaches are the relative big size of the probe tips ($D_p > 20\text{mm}$) affecting the spatial resolution of the measurements and the low measurement bandwidth on the aerodynamic part constraining the results to a time averaged flow field analysis.

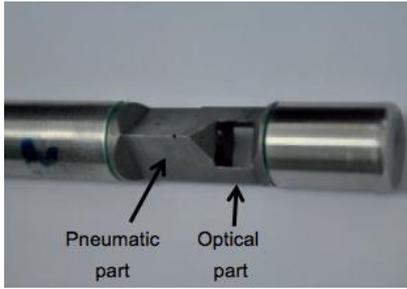


Figure 5: Photograph of the combined optical and pneumatic probe by Cai et al. [27].

RECENT DEVELOPMENTS

Pressure measurements

Probe technology

Time resolved measurements in the biphasic regime of steam turbines are very challenging, due to the harsh environment of fog and coarse water droplets. The droplets' range is from 0.1 up to 200 μ m or even 400 μ m in diameter and when the probe is inserted into the flow path droplets can potentially clog the pressure taps or even damage the miniature piezoresistive pressure sensors when they are exposed. A recent development of a fast response aerodynamic probe for unsteady measurements in wet steam is presented in [29, 30]. The design and operation of this probe is based on the previous developments made over the last 25 years in the Laboratory of Energy Conversion. Similarly to the probe developed by Lenherr et al. [9], the FRAP-HTH probe (see Figure 6) has two piezo-resistive sensors encapsulated into a probe tip diameter of 2.5mm which can be operated up to a temperature of 260 $^{\circ}$ C. The new feature of this probe is a miniature cartridge heater, which increases the probe tip temperature 5 to 10 $^{\circ}$ C above the flow saturation temperature, in order to operate the probe with unclogged pressure taps. In addition, the two pressure taps are equipped with a metal shield for protecting the miniature piezoresistive sensors from direct water droplet impacts.

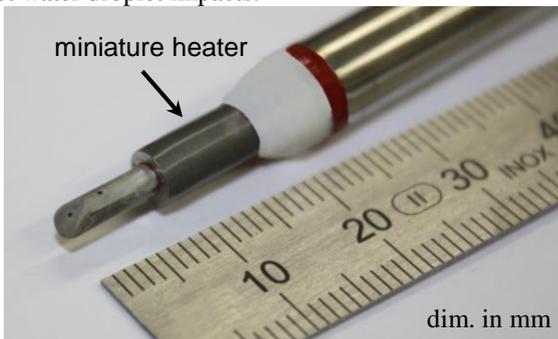


Figure 6: The fast response aerodynamic probe (FRAP-HTH) with the miniature heater for unsteady flow field measurements in wet steam [29].

Figure 7.a and b shows the absolute yaw angle and Mach number results respectively with the FRAP-HTH probe from a single traverse downstream of the last stage from a 1/2.2 scale steam turbine. For this operating condition the mass

flow, inlet temperature and exit pressure are 67t/h, 266 $^{\circ}$ C and 8kPa respectively considered as a high load operating point. The calculated wetness mass fraction in the meridional plan is 8%. It is interesting to notice the flow underturing at 50% span in Figure 7.a, due to the presence of the part span connector installed on the last rotor. The effect of part span connector is also depicted in the absolute Mach number at 50% blade span with a deficit in the flow velocity. The peak-to-peak fluctuations are large at the tip region for both flow quantities and they are progressively reduced towards the hub. The peak-to-peak to fluctuations at 90% span are ± 6 deg and ± 0.11 for the yaw angle and absolute Mach number respectively.

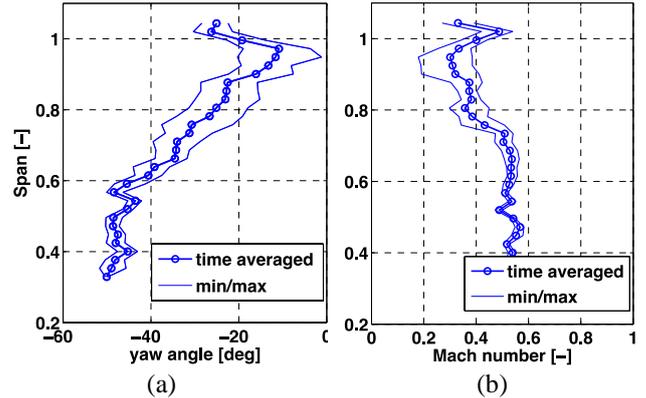


Figure 7: Absolute flow yaw angle (a) and Mach number at the rotor exit of L-0 stage from a four stage LP steam turbine.

Figure 8 shows the unsteady total pressure fluctuations from a single traverse at the rotor exit of the last stage with the same operating conditions as described in the previous paragraph. The results are non-dimensionalized with the time average total pressure and they are plotted for one rotor revolution (70 rotor blades) from hub to tip.

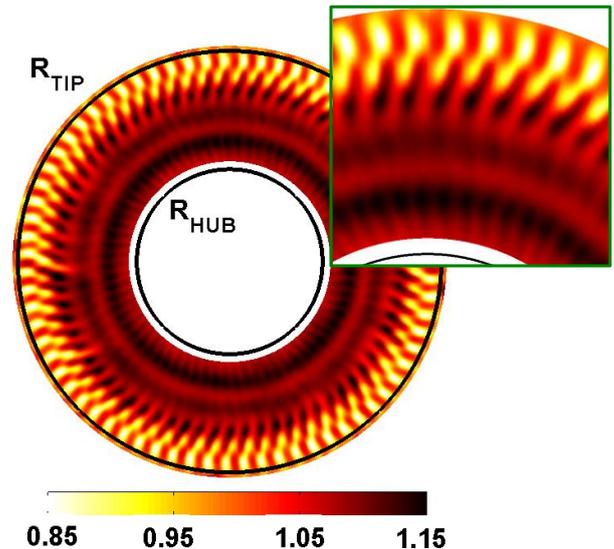


Figure 8: Unsteady total pressure $P_{tot}/P_{tot,avg}$ from a single traverse at the exit of a LP steam turbine. The radial axis is the blade span and the azimuthal axis is the blade count over one rotor revolution.

As presented in Figure 7.a and b the same trend is observed for the total pressure in Figure 8 with the peak-peak fluctuations getting the maximum value at the blade tip and progressively being reduced to the hub.

Flush mounted sensor technology

The need to measure the unsteady pressure fluctuations on the surface of the stators or rotating blades requires flush mounted pressure transducers smaller than 1mm in order to fit in the very thin blade profiles. Besides the miniature size the challenges of robustness and high signal to noise ratio are as of a great importance. As shown in Figure 9, the pressure sensor developed by Mansour et al. [31] utilizes one of the smallest absolute piezoresistive sensors available in the market with cross section dimensions of 300 x 180µm and a length of 0.9mm, which makes it particularly prone for achieving a small packaged assembly with high measurement bandwidth up to 210kHz without the perforated protection screen [31]. As shown in Figure 9 and Figure 10, in the second version of this surface mount pressure sensor, the same piezoresistive pressure chip is packaged under a perforated protective screen with a thickness of 0.05mm which contents 11 pressure holes. This design offers greater protection from particle impacts with a measurement bandwidth at 55kHz. The overall dimensions of this pressure sensor are 1.75mm x 0.81mm x 0.52mm. The sensor is connected to the acquisition system through a flexible printed circuit of 0.135mm in thickness, reducing its interaction with the flow boundary layer of the installed surface (stator or rotor).

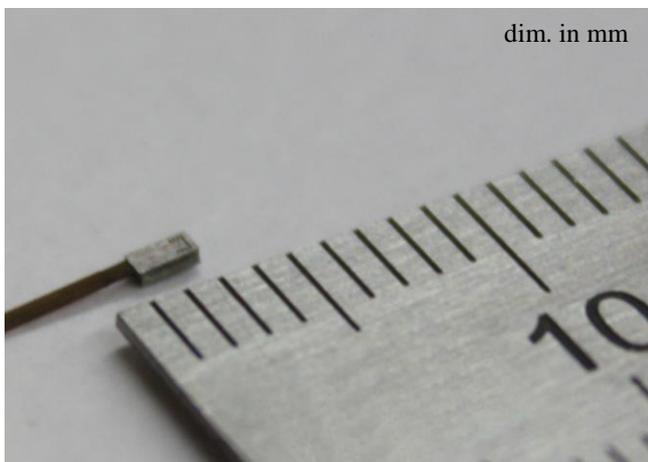


Figure 9: Surface mounted pressure sensor.

The packaging and bonding techniques that were used ensure optimal spatial resolution, measurement bandwidth and protection in harsh conditions. Moreover the present design provides a high degree of reliability and low levels of thermal disturbance to the sensors as the flow can experience large temperature and pressure fluctuations.

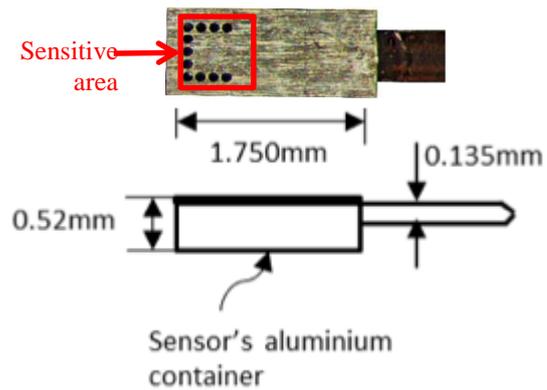


Figure 10: Surface mounted pressure sensor [31].

Multi-sensor Wireless data acquisition board

The sensors' voltage signals are acquired using an in-house developed wireless data acquisition system boards as presented in Figure 11. The wireless measurement system consists of a fast and high resolution A/D recorder and a logger. They are designed to operate in the rotating frame of reference up to steady accelerations of 15'000 g.

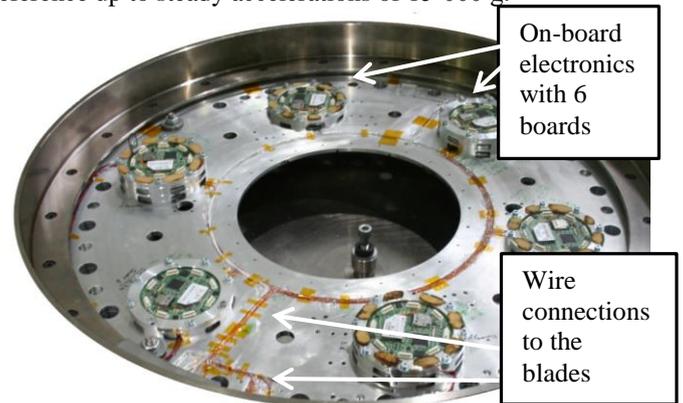


Figure 11: Wireless data acquisition boards installed on the rotor disc.

Each board has 4 analogue input channels synchronized from a single optical signal, and the boards can be stacked up to 4 boards offering 16 simultaneous analogue voltage acquisition channels. Each of board can acquire either 2 piezoresistive pressure sensors, 4 strain gages or Pt₁₀₀ operated in a constant current mode. The boards have a diameter and a height of 65mm and 9mm, respectively. The fast-pressure sensors are operated with a constant current of 1mA through individual programmable current sources. The boards are specifically design to acquire dynamic signals up to a sampling frequency of 200kHz. The data are temporarily stored on an on-board mini solid state disk, before being sent to an external computer through an embedded Wi-Fi module.

Each acquisition channel is equipped with a dedicated signal conditioning modules with a tunable gain ranging from 1 to 128. For the current application a gain of 128 is used, resulting in a peak-to-peak white noise RMS value of 160µV setting the minimum pressure resolution of approximately 6pa on the measured raw signal; providing a measurement resolution which is an order of magnitude higher than the sensor measurement accuracy.

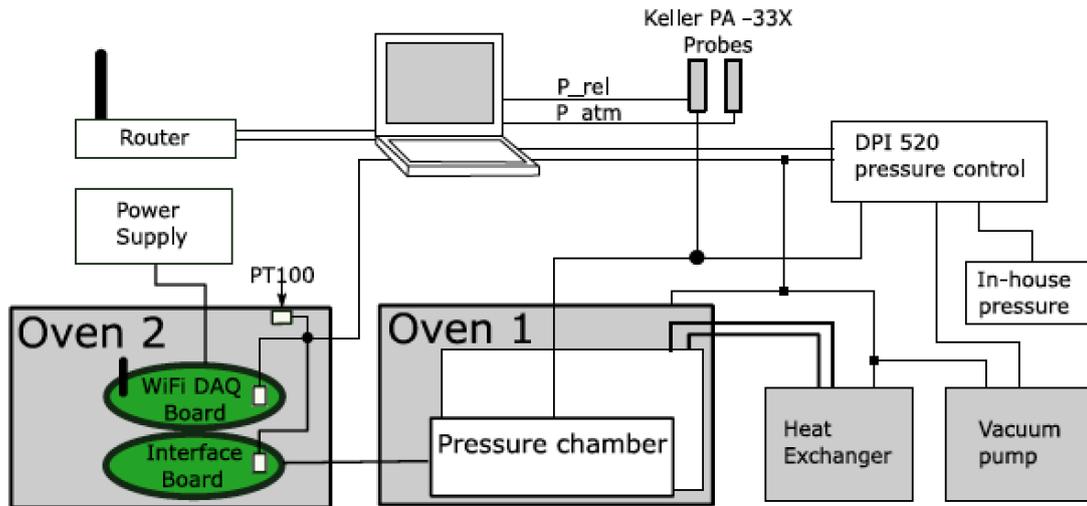


Figure 12: Measurement system calibration schematic for the wireless data acquisition boards (Oven 2) and the surface mounted pressure sensors (Oven 1).

The entire measurement system is calibrated in the static calibration facility at the Laboratory for Energy Conversion of ETH Zurich. As shown in Figure 12, the pressure sensors are installed in oven 1 and the wireless acquisition boards in oven 2. With this configuration, the pressure and temperature of the two ovens can be adjusted independently. The acquisition boards are calibrated from 25 to 65°C in order to account for the different temperatures between the measurement location and the location where the boards are mounted. On the other hand, the pressure sensors are calibrated from 300 to 1800mbar in pressure and from 15 to 95°C. The constant current operation mode allows pressure sensor sensitivity variations of below 0.074%/°C. It is worth noting that results have shown that the sensitivity of the pressure output for both pressure sensors experiences a very similar behavior besides the fact that the RTV coating would normally influence the sensor's pressure behavior.

As shown in Figure 13, the pressure transducer assemblies were installed on the rotor blade at 20% and 85% span in both pressure and suction sides. In order to minimize the interaction with the flow boundary layer, all pressure transducer assemblies including the flexible printed circuits were installed into small grooves machined on the blade surface. The flexible printed circuits are then brought through the hub platform and the wiring to the acquisition board takes place on the rotor disk. The wireless data acquisition and signal conditioning boards were installed on the rotating frame onto the rotor disk. A short description on the unsteady pressure data from sensor S1 and S8, as highlighted in Figure 13 located on the suction side at 20% span are presented in Figure 14.

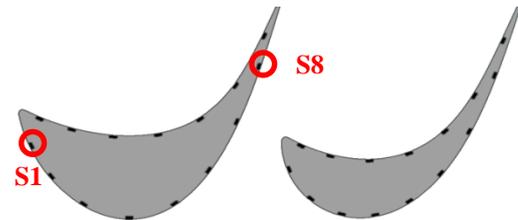


Figure 13: Pressure sensors at 20% span (left column) and 85% span (right column) [31].

Figure 14 shows both sensors raw pressure signals non-dimensionalized by the maximum absolute pressure measured by sensor S1 over 4 stator 1 blade passing periods. As it can be seen on Figure 14 sensor S1 is mainly affected by the periodical impingement of stator 1 vane wake, with four clear periodical peaks in measured fluctuating pressure over four stator 1 vanes passing period. However, as seen in Figure 14, sensor S8 does not exhibit the same type of fluctuating pressure pattern, with much wider frequency content. Due to its location, sensor S8 is affected by the presence of the rotor hub passage vortex migrating from the pressure side to suction side of the adjacent blade across the passage and centered around 20% span.

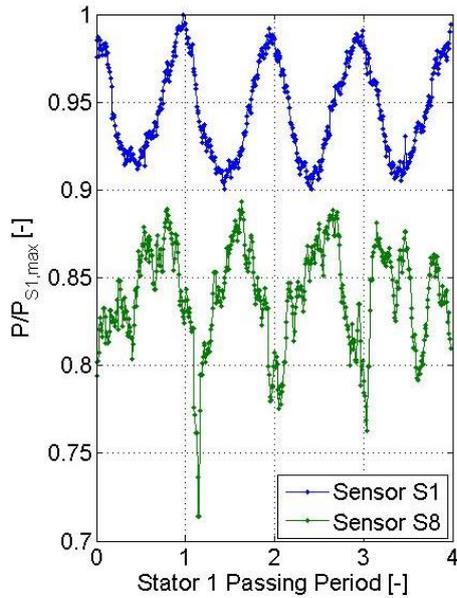


Figure 14: Pressure fluctuation of Sensor S1 and Sensor S8 located on the suction side at 20% span over four stator 1 vane passing periods [31].

Optical extinction measurements

The knowledge of droplet size distribution and concentration allows us to calculate the wetness fraction and the isentropic turbine efficiency as well as to provide significant data for erosion modeling. For that purpose, a miniature optical extinction probe with a diameter of 9.4mm was designed, manufactured and tested in LEC lab. Although this is a well-known measurement technique this new development is equipped with a heater, which maintains all optical components of the probe clean from any water contamination and therefore the accuracy of the results is improved. The probe tip is presented in Figure 15.

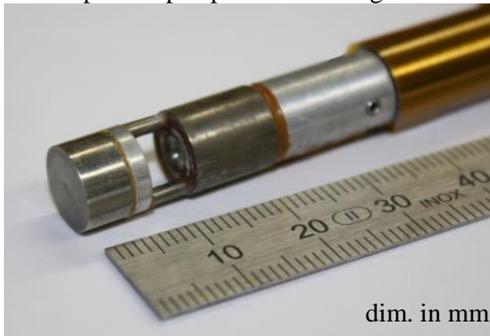


Figure 15: The optical extinction probe tip

In order to test the performance of the heater, the probe was tested under representative steam flow conditions in a freejet facility as well as in a steam generator. The flow conditions are Nusselt number representative of the last stage of a low-pressure steam turbine with 0.35 Mach number, 44°C flow temperature and static pressure of around 8kPa. Three different conditions were tested where the Nusselt number was varied with the maximum value of $Nu=108$ when the wetness fraction of 10% was used in the calculations. During these measurements two thermocouples were installed on the probe

tip, one on the center of the collimating lens and one on the center of the mirror. As shown in Figure 16, a minimum temperature overhead of 20°C is achieved in all test cases for both the mirror as well as the lens. The mirror though shows a lower overhead temperature of about 50% compared to the collimating lens for all test cases. This is explained by the lower power density (60% reduced), which is installed in the upper part of the probe tip compared to the lower part where the lens is installed.

An ultrasonic atomizer was characterized in terms of droplet size and concentration with an established Phase Doppler Anemometry (PDA) system in order to have a reference spray environment for the proof of concept of the newly developed optical extinction probe. Measurements were performed and results have shown a good agreement between the PDA technique and the extinction probe at various axial locations from the nozzle exit of the droplet generator. The maximum deviation is less than 2.5 μ m and 1.2 μ m for the Sauter mean (D_{32}) and most frequent diameter respectively.

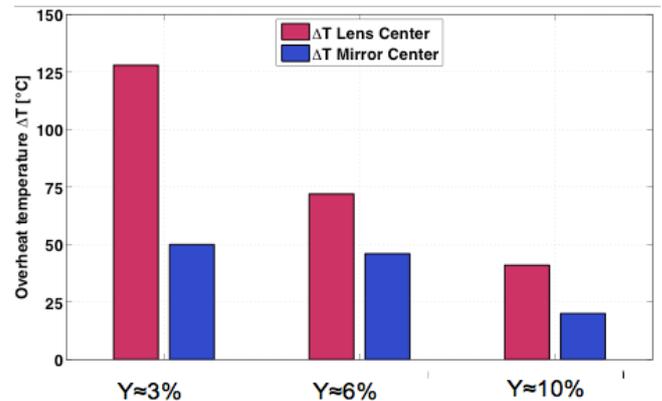


Figure 16: Heater performance tests at three representative flow conditions from the last stage of a low pressure steam turbine.

In order to extend the knowledge of the droplet in the coarse diameters range, an optical backscatter probe for coarse water droplet measurements was developed by Bosdas et al. and presented in [32]. This probe has an embedded high bandwidth miniature photodiode capable of measuring particle speeds up to 200m/s. The probe tip is 5.5mm in diameter and the probe was used for droplet measurements with diameters from 40 up to 110 μ m. As shown in Figure 17, light is guided in the probe tip through an optical fiber and then it is focused three probe diameters far from the tip forming the measurement sample volume. For this purpose a monochromatic ($\lambda=632$ nm) He-Ne laser is used. When the droplets cross the focused sample volume, they scatter light in all directions, but the installed photodiode captures the scatter light at specific backscatter solid angle through a set of collective lenses. In addition, the probe tip is equipped with a purging system in order to maintain the windows clean from water and avoid any beam deflection. The purging flow is attached to the surface of the windows in order to minimize any interaction with the surrounding flow field.

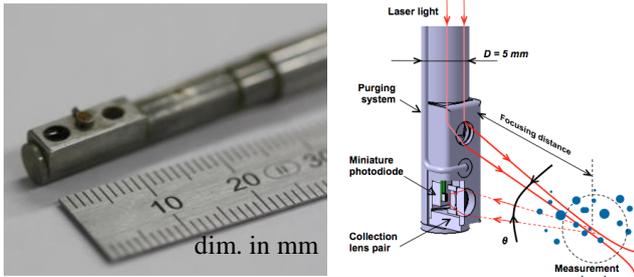


Figure 17: FRAP-OB probe tip with purging interface for windows protection [32].

The FRAP-OB is calibrated in a monodispersed calibration facility described in [32]. The probe calibration is performed using an in-house droplet generator. Monodispersed droplet generation in the kHz range is based on the Rayleigh breakup jet. For the current work the device was tuned to produce monodispersed water droplets with an accuracy of $\pm 2\mu\text{m}$ in diameter that are generated continuously with a frequency and air-backpressure set by the user. For independent reference measurements of the droplet size the shadow imaging technique was utilized. The droplets are imaged with a high-resolution camera that is triggered with a strobe light in order to capture images of the generated droplets. For the maximum amplification factor the accuracy of this technique results in an error of $\pm 0.69\mu\text{m}$ in diameter. The calibration of FRAP-OB probe is completed when the probe's output voltage signal is correlated with the measured droplets' diameter from the pictures obtained with the reference camera. As shown in Figure 18, the calibration curve is modeled by an exponential curve fit. The uncertainty analysis presented in [32] has shown an accuracy of $\pm 5.4\mu\text{m}$ and 2.3m/s for the diameter and speed measurements respectively for the overall system.

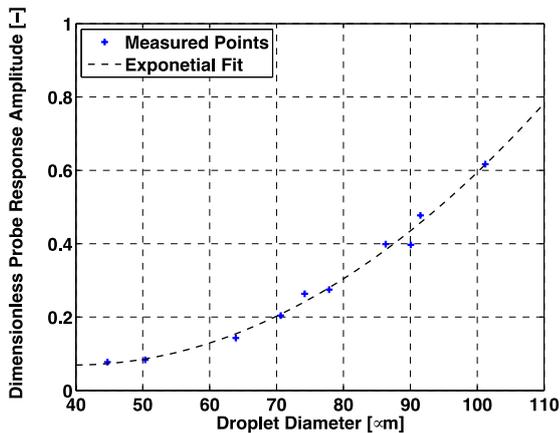


Figure 18: FRAP-OB calibration curve using a monodispersed water droplet generator [32].

CONCLUSIONS

- Today, the measurement system integration enables accurate time resolved measurements, which are the key element for a successful development of a turbomachine. The high volume of the recorded data can be processed fast and efficiently due to great computational power and this contributes to the

analysis of the complicated four dimensional flow field in steam and gas turbines.

- For the fast response aerodynamic probe a compromise between miniaturization, robustness, bandwidth and the capability of the probe to measure the three-dimensional flow field has to be made. The best compromise is found with a two sensor probe with a tip diameter at 1.8mm and a measurement bandwidth of 48kHz. For high temperature applications up to 250°C the probe tip diameter is 2.5mm providing a measurement bandwidth of 25kHz.
- Unsteady flow field measurements in wet steam are even more challenging due to the presence of coarse water droplets in the biphasic regime of LP steam turbines. In addition, the high flare angles of the machines necessitate only probes capable to measure the three-dimensional flow field due to the high ($>40\text{deg}$) flow pitch angles. Flush mounted sensors are prone to droplet impacts, thus the newly developed heated probe tip with encapsulated sensors is the most appropriate approach to provide high accuracy and robustness.
- Strain gage measurements are required for vibration analysis however there is always a challenge when transmitting the signals either with slip rings or telemetry systems. The newly developed system, with on-board electronics presented in the current paper, offers an improved measurement resolution thanks to a high signal to noise ratio and combines the aeromechanical assessment of rotating blades with flush mounted pressure sensors and strain gages.
- Droplet measurements in steam turbines require probes capable to resolve diameters from 0.1 up 400 μm . A compromise between miniaturization and detectable range has to be made. Combined optical probes are normally large (dia. 20mm) relative to the flow features resulting in low spatial resolution and high blockage effects in the downscaled steam turbine test rigs. A novel miniature fast response optical backscatter probe was presented in the current paper and calibrated for droplets from 40 to 110 μm in diameter with the possibility to extend the measurable range. The same backscatter technique can be used for solid particles as well.

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