

Flow Field Measurement at the Distributor of Francis Turbines

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Abstract

Unsteady flow at the stator level in reaction turbines was experimentally investigated in a doctoral project. The goal is to develop an integrated expertise to measure the unsteady flow at the stator level of reaction turbines using PIV and other measurement techniques. In this paper, we present the experimental efforts and results of the flow measurement at the stator level in a model Francis turbine with PIV and miniature pressure sensors. Flow fields between the two neighboring guide vanes are measured with PIV and a specific optical access. Instantaneous results such as velocity vector map and average results such as velocity fluctuation vs. phase angle and velocity magnitude contours were presented. The pressure distribution around the pressure side and suction side of the two neighboring guide vanes was measured with miniature pressure sensors with a specially designed mounting method on the surfaces without any geometry alteration. Static and dynamic pressure distribution and spectral analysis are presented. Based on the measurements, the effects of operation points on the flow behavior are analyzed.

Introduction

A major present requirement of turbomachinery is for more compact designs and a wide operating range, which enforces the unsteadiness in the machine [5]. Unsteadiness in hydraulic turbines can cause problems such as vibrations, noise, efficiency drop, and mechanical damage, etc., and are increasingly receiving attention [1]. The causes of unsteadiness are numerous and complicated: e.g. flow separation, wakes and Karman vortices encountered at trailing edges of vanes or at runner exits, draft tube rope-vortices at partial load, non-uniform flow between static and moving parts such as at the spiral casing exit or at the inlet of the draft tube, etc. [1]. Therefore it is necessary to consider the unsteadiness in hydraulic turbines, and experimental data are extremely important for improving our knowledge of it and for verifying the numerical results.

The flow leaving the guide vanes trailing edges is not uniform in either the circumferential or span-wise directions [2]. It is influenced by Reynolds number, blade geometry, angles of attack, inter-blade distances, roughness, etc. Sometimes, Karman vortices develop and can cause serious damage if the excitation frequency of the vortices coincides with one of the eigen frequencies of the vanes [4]. The loss caused by the stator is a concern because the disturbance in the flow from the guide vane wakes cause losses in the runner and affects the machine performance [2]. The wakes from the distributor may also interact with the downstream runner blades, affecting pressure distribution and boundary layer transition. This rotor-stator interaction is the main cause of the unsteadiness [3] in hydraulic turbines and makes the flow fields very complex. Also, the interaction between the stator vanes and the flow causes

structure fatigue or even failure on the stay vane or guide vanes at some operation conditions and reduces the machine lifetime.

Recently, some authors analyzed the unsteady flow at the double passages or rotor-stator interaction in hydraulic machines. G. Wuibaut (2001) studied the rotor-stator interaction in a centrifugal pump with PIV [6]. E. Th eroux (2003) performed numerical modeling of unsteady flows field in radial hydraulic turbomachines with the method of the reduced frequency parameter [3]. G. D. Ciocan (2006) analyzed experimentally rotor-stator interaction in a pump-turbine with LDV, PIV and unsteady total pressure probe [5].

In previous work, we used PIV to measure flow fields around the mid-span of a single guide vane in a 2D water channel [1]. That preliminary work helped to develop the expertise to measure unsteady flows around real guide vanes, in particular, the more complex flows arising in the distributor of reaction turbines. This paper provides an experimental approach for characterizing the unsteady flow fields in an industrial model of Francis turbine. Detailed measurements are performed for 5 operating points at partial load, at the best efficiency point (BEP) and at light overload conditions.

Experimental Setup and Instrumentation

All the measurements were performed on the test rig in LAMH (LABoratoire de Machines Hydrauliques) which is an independent turbomachinery laboratory in Laval University, Quebec, Canada. The test rig can work as a closed or open loop, fed by a semi-axial pump. Test limits are $1 \text{ m}^3/\text{s}$ as regards flow rate, 2000 rpm for the rotational speed of the turbine, 50 m for the net water head and 225 kW for the power furnished. The flow rate is measured with an ABB Flowmaster flow meter, providing an accuracy of $\pm 0.3\%$ on efficiency measurement.

An $n_q=46.2$ model Francis turbine provided by GE is used (**Figure 1**) and the main parameters are: wicket gate height 91.45 mm, wicket gate circle diameter 486 mm, wicket gate chord length 80 mm, number of guide vanes 20, number of stay vanes 19, runner diameter 406.4 mm, and number of runner blades 14. The camera and the laser arm are shown in **Figure 1**. The global measurements of flow rate, head and efficiency have been performed before the flow field and pressure measurements. The 5 operation points at $Q_{11}/Q_{11n}=0.55, 0.65, 0.75, 1.0$ and 1.08 with the corresponding guide vane opening $\alpha=11^\circ, 13^\circ, 15^\circ, 20^\circ$ and 22° are selected for all the measurements and the efficiency vs. Q_{11}/Q_{11n} is shown in **Figure 2**.

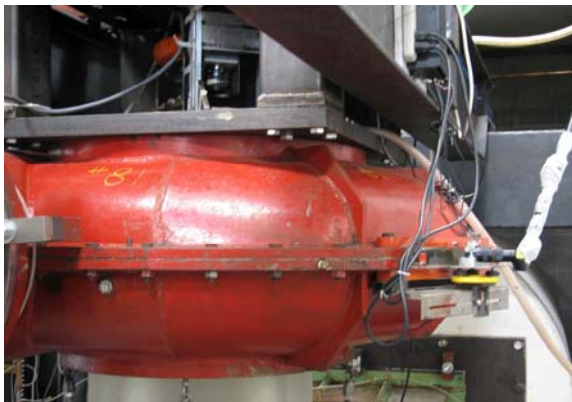


Figure 1 Turbine model

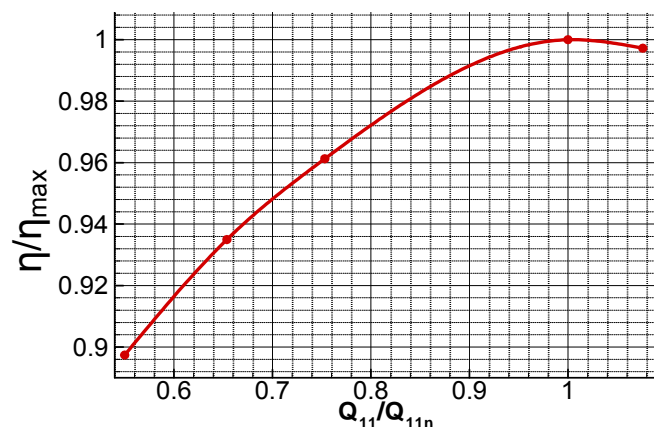


Figure 2 Operating points

Particle Image Velocimetry

The 2D velocity field between the guide vanes is investigated with a Dantec PIV system, incorporating a double-cavity, 120 mJ, Nd: Yag laser with 3 to 5 ns pulse intervals, a wavelength of 532 nm and a maximum frequency of 15 Hz, two digital Hisense CCD-cameras equipped with 28 mm, 60 mm or 105 mm lenses and a Flowmap 2100 processor. The PIV setup is illustrated in **Figure 3**.

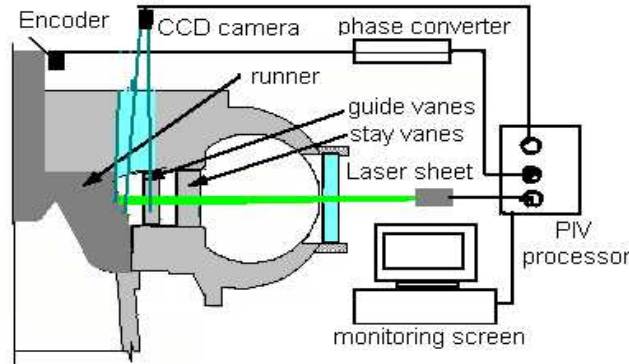


Figure 3 2D PIV measurement setup

Windows made of Plexiglas are installed into the head cover and the spiral casing for optical access. The optical path from the recording camera to the measuring field includes three media of different optical indices: air, acrylic and water. To minimizing the optical distortion of the images and the laser sheet plans, the acrylic windows have been machined with two perfectly flat faces. Due to the special geometry of the measuring field, a non-standard calibration target was designed referring to the standard calibration target provided by Dantec Dynamics. With images of the target, the geometrical transform matrix coefficients between the image plane and the object plane can be determined through a least squares fitting algorithm. The calibration image and the data points of the 2D PIV calibration are shown in **Figure 4**.

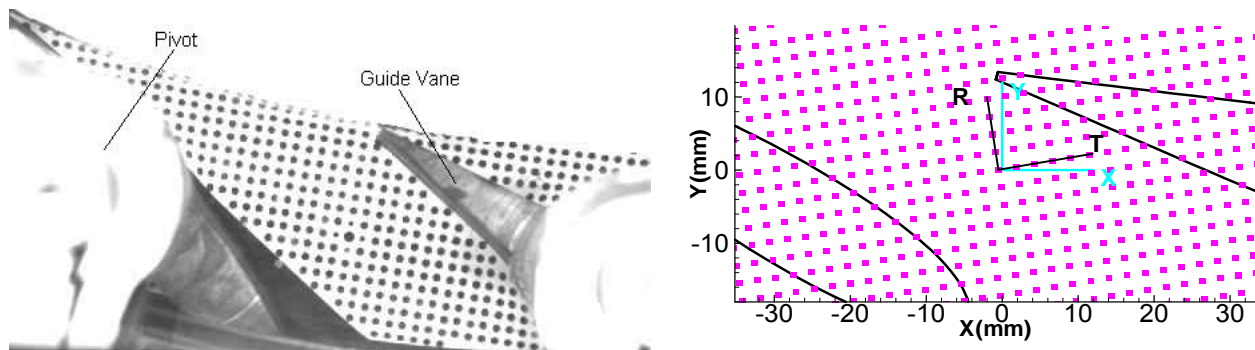


Figure 4 Calibration image and data points for 2D PIV measurement

Silver coated hollow glass spheres, 10 microns in diameter, were used as seeding particles. The laser sheet of 1 to 2 mm thick was used to illuminate the measuring field. The lighted field was recorded by a camera fixed on the top of the head cover with resolution of 1280x1024 pixels for an investigation area about 140 x 120 mm². Series of image pairs at 100 μ s to 150 μ s depending on the flow speed were acquired synchronously with the two laser pulses. The PIV system was triggered and synchronized by an encoder installed on the turbine shaft. The Dantec Flowmap 2100 processor and FlowManager software were used to monitor the

measurements and to process the data. For each operation point, 10 phase positions in an inter-blade passage channel, with the phase shift 2.57° , are measured and 1200 image pairs are recorded for each phase position.

Two-dimensional vector maps are obtained by performing a FFT based correlation algorithm on the acquired image pairs. The analysis sequence is selected to get the results:

- a) Apply a mask to image pairs to remove the area not interesting
- b) Apply 16 by 16 adaptive correlations with 50% overlap to the masked images to get the raw vector maps
- c) Validate the raw vector map with a Matlab local median validation script
- d) Dewarp the validated vector maps with the imaging model
- e) Perform statistical analysis
- f) Calculate phase-average velocities and fluctuating velocities

Miniature pressure sensors

Ten miniature piezo-resistive pressure sensors were fitted in the pressure and suction side surfaces of two consecutive guide vanes at mid-span. One hydraulic inter-guide vane channel is thus instrumented to measure the pressure fluctuation. The wires of sensors are led through cable paths which were first drilled in the guide vane body and are collected into a bundle at the pivot and led out from the shaft for signal conditioning. This procedure makes it possible to mount a pressure sensor in an area as small as 3 mm without any geometry alteration and thus leads to a quite high measurement quality. The two guide vanes with miniature pressure sensors amounted on are shown in **Figure 5**.

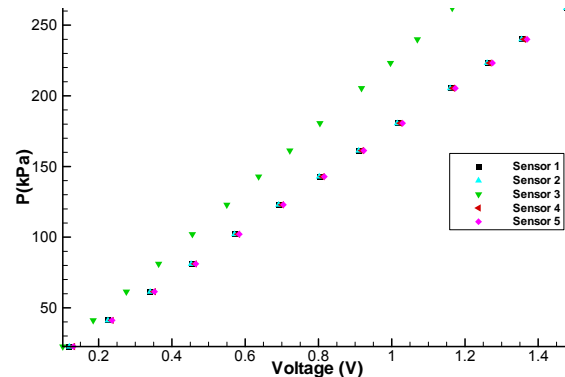
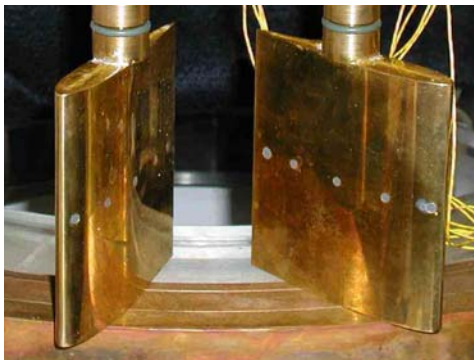


Figure 5 two guide vanes with miniature pressure sensors fitted and static calibration

In order to calibrate statically the pressure sensors, the instrumented guide vane is placed in a pressurised tank. The pressure in the tank is controlled by compressed air and monitored with a balance DH 710 with the measurement accuracy 10 Pa. Standard deviations of the voltages are recorded to check the signal. The static calibration results of the 5 miniature pressure sensors on one guide vane are shown in **Figure 5**, where an excellent linear response is observed.

Ten SGCM-401 signal conditioners which possess a high frequency response up to 50 kHz, with amplification factors from 1 to 1000, were used to condition the sensors. *DASYLAB* software from DasyTec is selected to monitor the acquisition process and to control PCI 6036-E data acquisition card from National Instruments. The acquisition frequency is 1 kHz.

Analysis of Tests

Based on PIV measurements, instantaneous fields such as velocity vector maps and average results such as velocity fluctuation vs. phase shift angle and fluctuating velocity magnitude contours were presented. Based on the pressure measurements, the static, dynamic pressure distribution and spectral analysis are available.

A typical instantaneous velocity vector maps at BEP is shown in **Figure 6 a)**. We see that no evident unsteady flow structures are transported in the inter-guide vane channel at BEP although small recirculation zones exist along the guide vane surfaces. No back flow or detachment zone was found at light overload condition, small recirculation zones and back flows exist along the guide vane surfaces for a few phase positions at BEP, and for most of phase positions at partial load positions.

Based on the statistics of measured image pairs, the averaged velocity at each phase position, the phase average values and the difference between those could be calculated with the velocity being decomposed to:

$$U(i) = \bar{U} + \tilde{U}(i)$$

$$\text{with } \bar{U} = \frac{1}{10} \cdot \sum_{i=0}^9 U(i).$$

Velocity fluctuation distribution with the different phase position at a fixed spatial position in the inter-guide vane channel is shown in **Figure 6 b)**. U_r represents for radial velocity and U_t for tangential velocity. Radial velocity fluctuation is up to 9%, and tangential velocity fluctuation is up to 6% for both BEP and light overload condition, and 20% for radial velocity fluctuation and 6% for tangential velocity fluctuation at part load with $Q_{11}/Q_{11n}=0.75$.

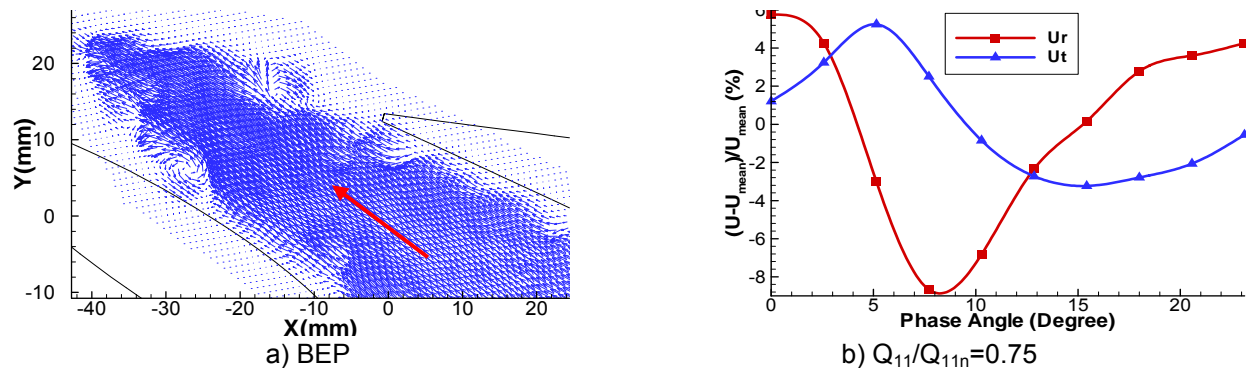
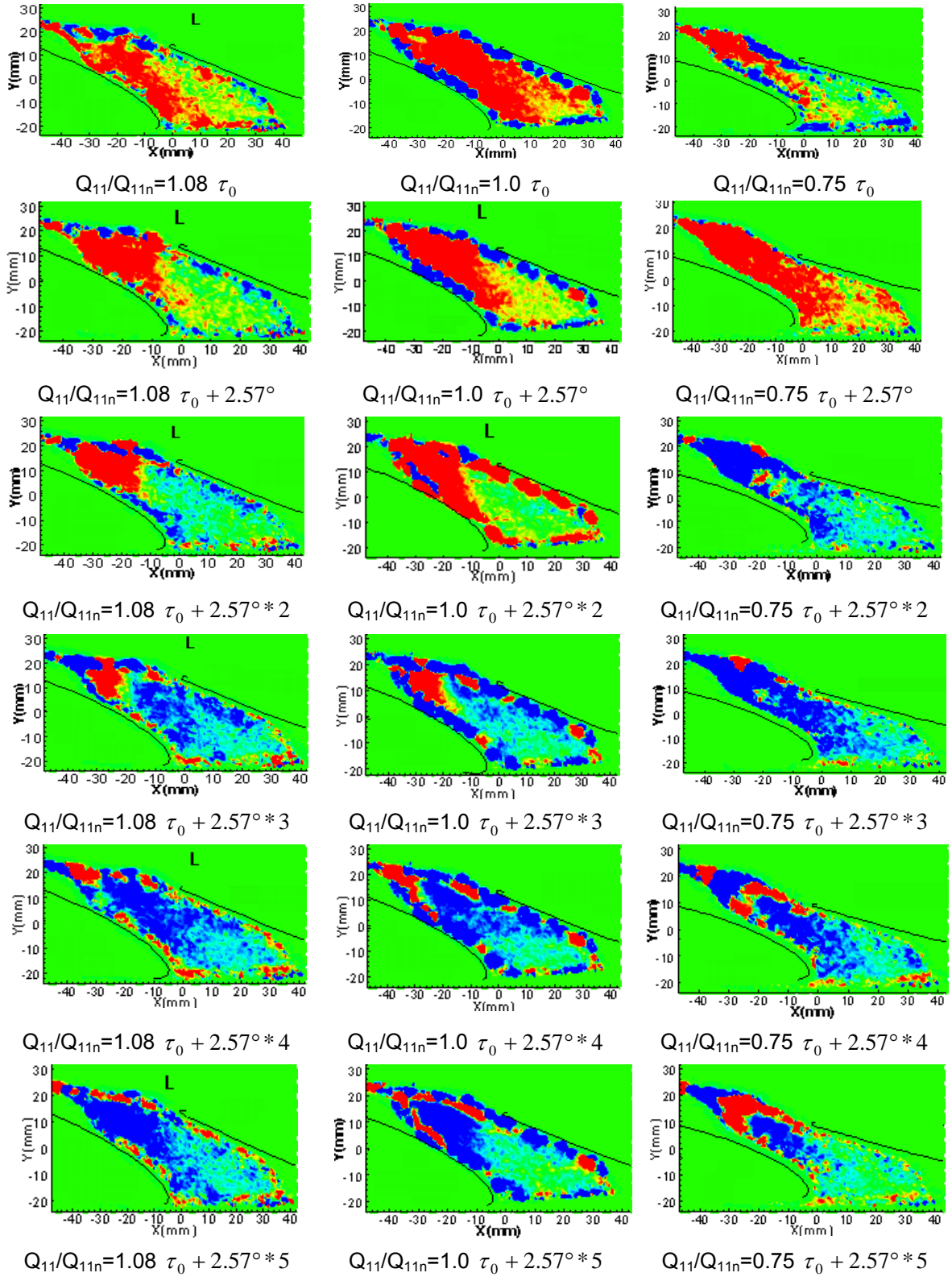


Figure 6 Typical instantaneous velocity vector maps

Fluctuating velocity magnitude contours at the 10 phase positions of light overload, BEP and partial load conditions with $Q_{11}/Q_{11n}=1.08, 1$ and 0.75 are presented and compared in **Figure 7**. We see some phenomena of the flow: the flow at the exit of the stator is strongly non-uniform for all three operation points. At full-load, the flow is more uniform in the middle of the inter-guide vane channel but the velocity fluctuation and the velocity gradient are stronger along the guide vane surfaces compared to light overload. The velocity fluctuation is much stronger at the part load condition. Based on the analysis above, we conclude that the guide vanes can correctly the guide flow at the best efficiency point and light overload points.



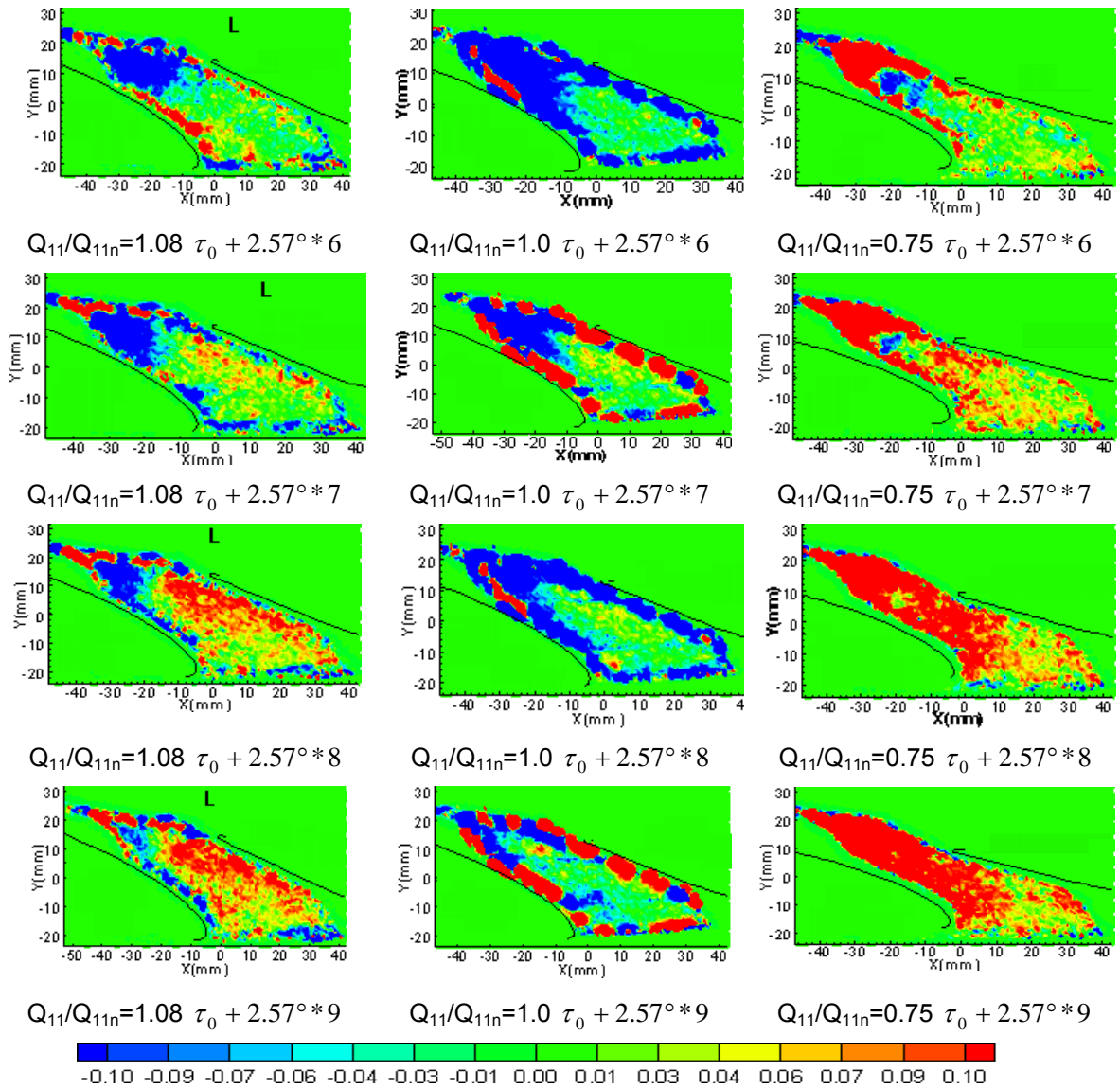


Figure 7 Velocity magnitude fluctuation contours for different operation points

Figure 8 shows static pressure distribution and mean pressure fluctuation around the guide vanes for different operation points, where H is for the test head, P_{mean} is the temporal average pressure head at each position.

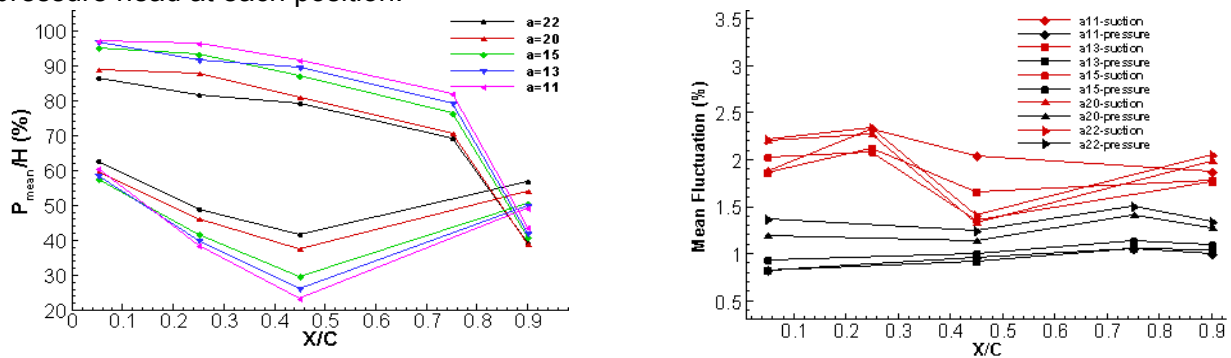


Figure 8 Static components of pressure and mean pressure fluctuation around guide vanes

The static pressure gives information about loading of the vane for various positions. We can see that the pressure difference between the pressure side and suction side reduces near the best efficiency point. The magnitude of pressure fluctuation is below 3%. The power spectra of pressure signals are available based on FFT. A typical result is shown in **Figure 9**. For most operation points and measurement positions, the only obvious peak on the frequency spectra is the passing frequency of the runner blades $Z_r * f_{rotation}$. This corresponds to the numerical results of Eric Th eroux (2003) [3].

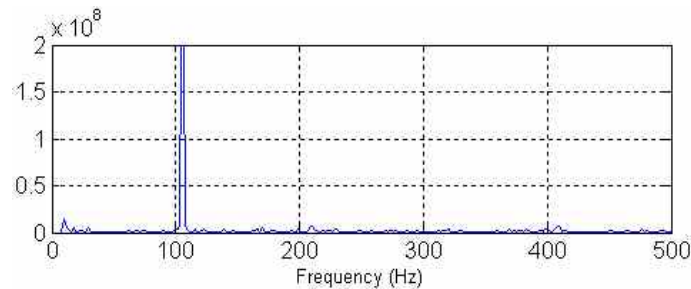


Figure 9 Power spectra of pressure signals around guide vanes

Conclusions

Flow field and pressure field measurements were performed at the stator level in a model Francis turbine with PIV and miniature pressure sensors. This constituted the second step in developing the expertise to characterize unsteady flows around distributor vanes of model Francis turbines. The following conclusions are reached.

PIV measurements are very useful for providing the velocity fluctuation with phase shifts, 2D instantaneous velocity vector map and the spatial structure of the flow.

A special amounting method for miniature pressure sensors on the guide vane surfaces leads to a quite high measurement quality. It provides static pressure components, mean pressure fluctuation percentage and the flow characteristic frequencies by spectral analysis. The results coincide to the numerical one.

Acknowledgements

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