ONBOARD MEASUREMENTS OF PRESSURE AND STRAIN FLUCTUATIONS IN A MODEL OF LOW HEAD FRANCIS TURBINE
PART 1: INSTRUMENTATION

M. FARHAT, S. NATAL, F. AVELLAN, — *Swiss Federal Institute of Technology, LMH, Lausanne, Switzerland*

F. PAQUET, PY. LOWYS, M. COUSTON, — *Alstom Power Hydro, Grenoble, France*

ABSTRACT

In this first part of a 2 papers series, we present the experimental procedure for onboard measurement of pressure and strain fluctuation in a model of low head Francis turbine. 28 miniature pressure sensors are fitted in the pressure and suction sides of two consecutive blades. A specific technique for sensors mounting has been developed allowing a direct manufacturing of the pressure sensors in the runner blades. This prevents from any geometry alteration of the hydraulic profile. Furthermore, miniature piezo electric strain gauges, 70 times more sensitive than conventional gauges, are embedded in pressure and suction side of 2 runner blades. Data acquisition is ensured by 32 channels onboard digitiser, having 12 bits resolution, 64 K-samples memory depth and 20 kHz maximum sampling frequency. Both static and dynamic calibration procedures of the pressure transducers are described. Analysis of experimental results and comparison with CFD calculation are presented in the second part (Ref. 7).

RÉSUMÉ

Dans cette première partie d'une série de deux articles, nous présentons la procédure expérimentale adoptée pour la mesure des fluctuations de pression et de déformée mécanique sur l'aubage d'un modèle de turbine Francis à basse chute. 28 capteurs de pression miniature, de type piézo-résistif sont montés dans les côtés extrados et intrados de deux aubes consécutives. Une procédure de montage basée sur la fabrication direct des capteurs dans les aubes nous a permis d'éviter toute altération des profiles hydrauliques. Par ailleurs, 2 jauges de contrainte de type piézo électrique, 70 fois plus sensible que les jauges conventionnelles, sont collées sur l'extrados et l'intrados de deux aubes. La numérisation et l'enregistrement des signaux sont assurés par un système d'acquisition embarqué doté de 32 canaux et ayant une fréquence d'acquisition maximale de 20 kHz et une profondeur de mémoire de 64 k-échantillons. Les étalonnages statique et dynamique sont présentés. L'analyse des résultats ainsi que la comparaison avec les résultats de calcul numérique sont présentées dans la deuxième partie (Ref. 7).

INTRODUCTION

Onboard measurement of fluctuating parameters in turbine models is gaining in complexity as instrumentation and data processing improve. These tests, which are not covered by existing codes, provide reliable data for turbine designers. Measurement of stress and pressure fluctuation on the runner blades, which is addressed in the present paper, is one of these modern tests. Such measurements are particularly indicated for large turbines operating under a wide range of heads and outputs. In fact, such turbines are subjected to significant dynamic forces, which may lead to fatigue cracking. Besides the static component, the fluctuating part of the pressure signals at different location of the runner blades may be obtained and processed in order to analyse the dynamic load in the prototype blades.

The Laboratory For Hydraulic Machines of the Swiss Federal Institute of Technology has developed during the past ten years an experimental procedure for advanced instrumentation of turbine models along with an onboard signal acquisition system with the collaboration of major turbine manufacturers and energy utilities. This procedure has been already applied to a prototype of a Francis turbine (Ref. 1), models of Francis turbines and pump-turbine as well as Pelton turbine model (Refs. 2, 3). We have shown how onboard measurement of pressure fluctuation may be of a great help in analysing complex flows in hydraulic runners such as rotor-stator interaction, part load instabilities and Karman vortices phenomenon.

In the present study, a low head turbine model is instrumented and tested. Recent developments in pressure transducers industry have allowed manufacturing miniature transducers directly in the runner blades. With such significant improvement, blades as thin as 2 mm may be instrumented without any geometry alteration. Furthermore, miniature piezo electric strain gauges, which are 70 times more sensitive than conventional gauges, are also embedded in the runner blades. It should be noticed that similar measurements have been already performed on the corresponding 50 MW prototype (Ref. 4). In the present paper, which stands for the first part of a series of two papers, we will present the procedure for onboard measurement of pressure and stress at different locations of the runner as well as in the draft tube and the upstream pipe. Results analysis is presented in the second part of these 2-papers series.

THE TURBINE MODEL

The turbine model tested in the present study is a low head Francis turbine having 13 blades runner rotating in a 20 wicket-gates distributor. The corresponding prototype generates 50 MW power under 31 m head. The tests are carried out in one of the *LMH* test rigs for turbine models.

EXPERIMENTAL SETUP

The pressure sensors

28 miniature piezo resistive pressure sensors are mounted on suction and pressure side of two facing blades according to a recent method developed in collaboration with *UniSensor* Company. The sensors chambers, each connected to the blade surface through a pipe of 1.8 mm diameter and 0.5 mm height, as well as the cable paths are first drilled in the runner blades. The sensors are then directly manufactured in the blades and protected by a plastic compound having the same density as water. The 5 wires of each sensor are led through cable paths into the annular chamber located in the runner crown for signal conditioning. This new mounting procedure have allowed a significant improvement in the measurement quality and make it possible to mount a pressure sensor in a blade area as thin as 2 mm without any geometry alteration. Obviously, this is of major importance with regards to the topic of our measurements since any modification in the hydraulic profile would have an unpredictable influence on the fluctuating pressure field. Fig. 1 shows a runner blade equipped with 14 pressure sensors at its pressure side during the wiring process as well as a sketch showing the transducers locations and numbering.

Furthermore, 3 piezo electric sensors (*Kistler 701*) are flush mounted in three locations of the upstream pipe while 4 similar pressure sensors are mounted in the suction cone 90° apart.

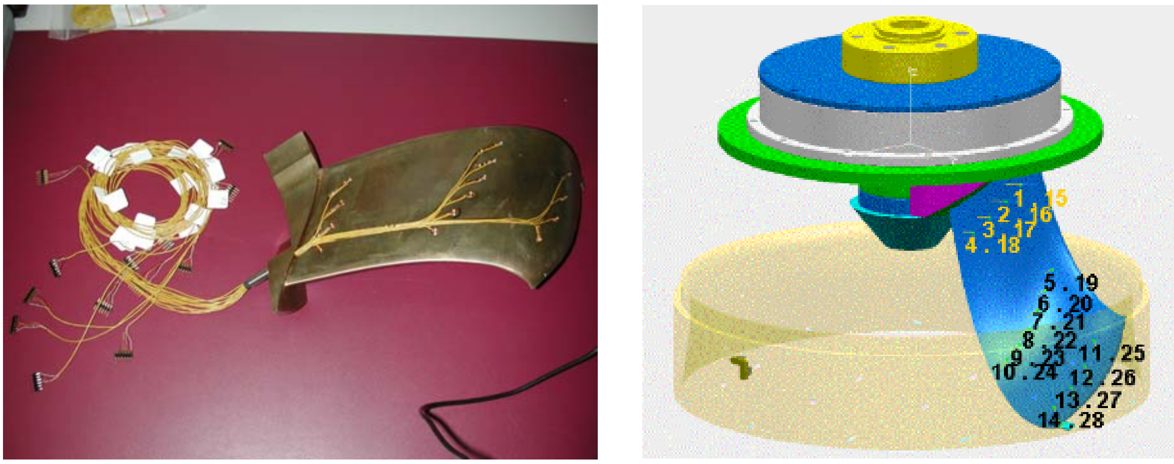

Fig. 1 Left: View of a runner blade during the mounting of 14 pressure transducers
Right: Pressure transducers numbering

Signal acquisition and conditioning

The onboard electronic for signal conditioning is made of 32 preamplifiers and anti-aliasing filters and is fitted in the runner crown as show on Fig. 2. Amplification factors may be selected from 1 to 1000. The conditioning electronic is connected to eight acquisition boards located in the turbine shaft (Fig. 2). Each of these boards has four channels inputs and four 12-bits A/D converters. The maximum sampling frequency is 20 kHz and the memory depth allows the storage of 64 k-samples per channel. A host computer is used to monitor this 32-channels acquisition system through an *ArcNet* based communication network. A 4-channels slip ring located at the top of the turbine shaft ensures the power supply as well as data transmission. Transfer rate of digitized data as high as 1.5 Mbits/sec is thereby reached.

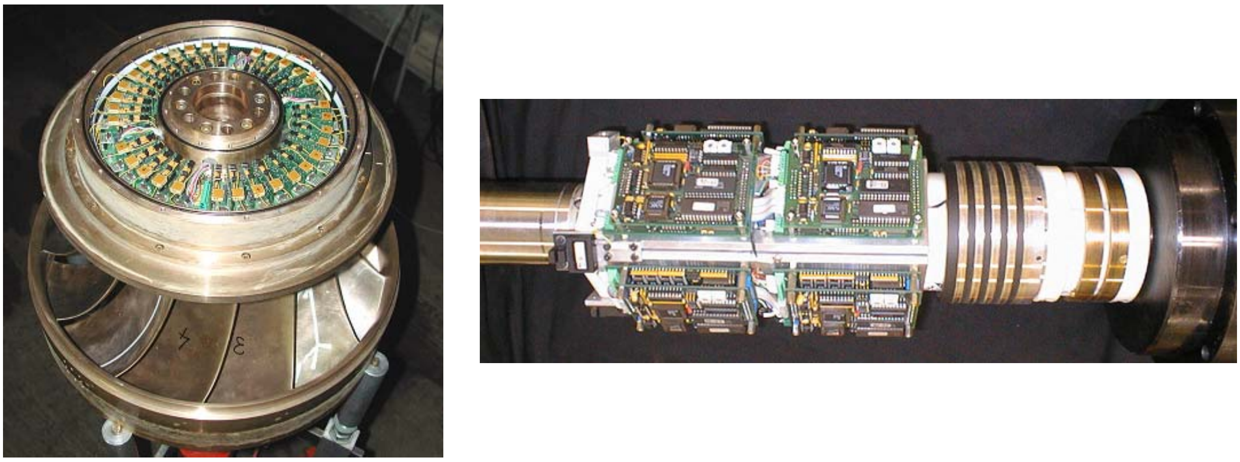

Fig. 2 32 channels conditioning electronic fitted in the crown (left)
and the 8 acquisition boards located in the shaft (right)

Measurement of fluctuating parameters from the static part of the turbine, such as draft tube and spiral casing, are also possible with the help of similar acquisition boards connected to the same *ArcNet* network as the onboard acquisition units.

The synchronization of the data sampling of active boards is performed through a master-slave scheme. First, the slave boards in rotating and static parts of the turbine are armed. The master board, located in the rotating part, is then armed in its turn. Once the master is triggered by the onboard tachometer signal, it outputs a *TTL* signal to trigger onboard salve modules. This trigger signal is itself simultaneously output from rotating to static part through a wireless photodiodes. Hence, all active modules are synchronously triggered within 5 µs time frame.

Static calibration of pressure sensors

In order to perform the static calibration of pressure transducers, the instrumented runner is placed in a pressurised tank. Voltage outputs of pressure sensors are then averaged and compared to the readings of a high precision reference pressure transducer. A typical result of such a calibration is given on Fig. 3 where an excellent linear response is observed. The measurement error, plotted in the same figure, is highly related to the mounting procedure of the transducer and found to be less than 0.5 % of the measurement range. It should be noticed that piezo-resistive transducers are used to be sensitive to the temperature change. In order to overcome the problem of zero drift, the test rig is systematically shut down every 30 minutes to reset the transducers offsets.

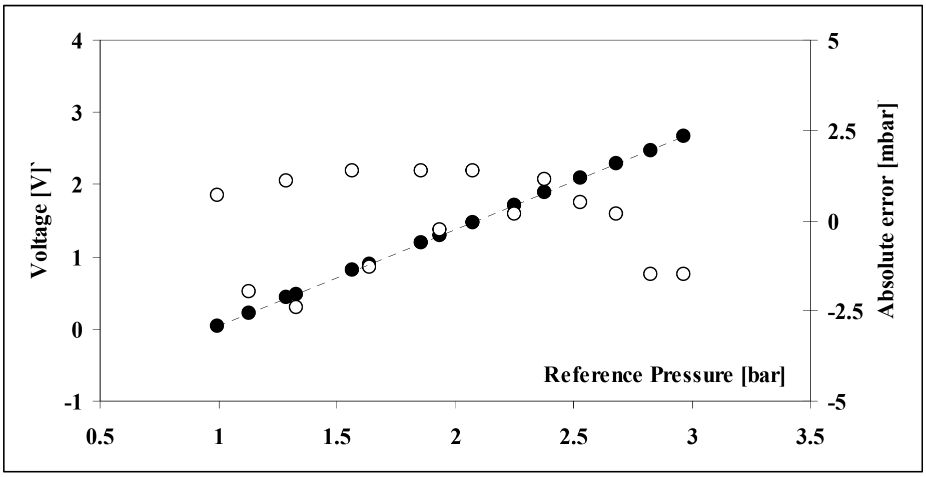

Fig. 3 Typical result of the static calibration of a pressure sensor mounted in the runner

Dynamic calibration of pressure transducers

The dynamic calibration of the pressure transducers is carried out in a large vessel with the help of *EPFL* spark generated bubble device (Ref. 5). This device allows to discharge up to 50-Joule electric energy between two immersed electrodes within few microseconds. An explosive growth of a vapor bubble takes place followed by the bubble collapse. Strong shock waves are thus generated during both the growth and the collapse of the bubble. The resulting pressure pulse is used to excite the pressure transducer in a large frequency band. A *Kistler 701* pressure transducer, placed close to the tested transducer, is taken as a reference transducer for frequency response estimation. The result is illustrated on Fig. 4 where the transfer and the coherence functions are plotted. An excellent coherence is observed above 150 Hz up to 25 kHz.

The lack of coherence for frequencies below 150 Hz is rather due to a lack of excitation energy. An alternative dynamic calibration technique has been used to investigate transducers response for low frequency band. A type transducer is flush mounted in the upstream pipe of a model test rig beside the reference transducer. A fluctuating flow rate of the flow in the pipe is obtained with the help of a rotating valve connected to it (Ref. 6). The resulting fluctuating pressure field in the pipe is used to excite the tested transducer. The rotation frequency of the valve is varied from 0 to 150 Hz to cover the low frequency band needed. The result is presented on Fig. 4 where the frequency response exhibits an almost constant gain with an excellent coherence for frequency ranging from 0 up to 150 Hz.

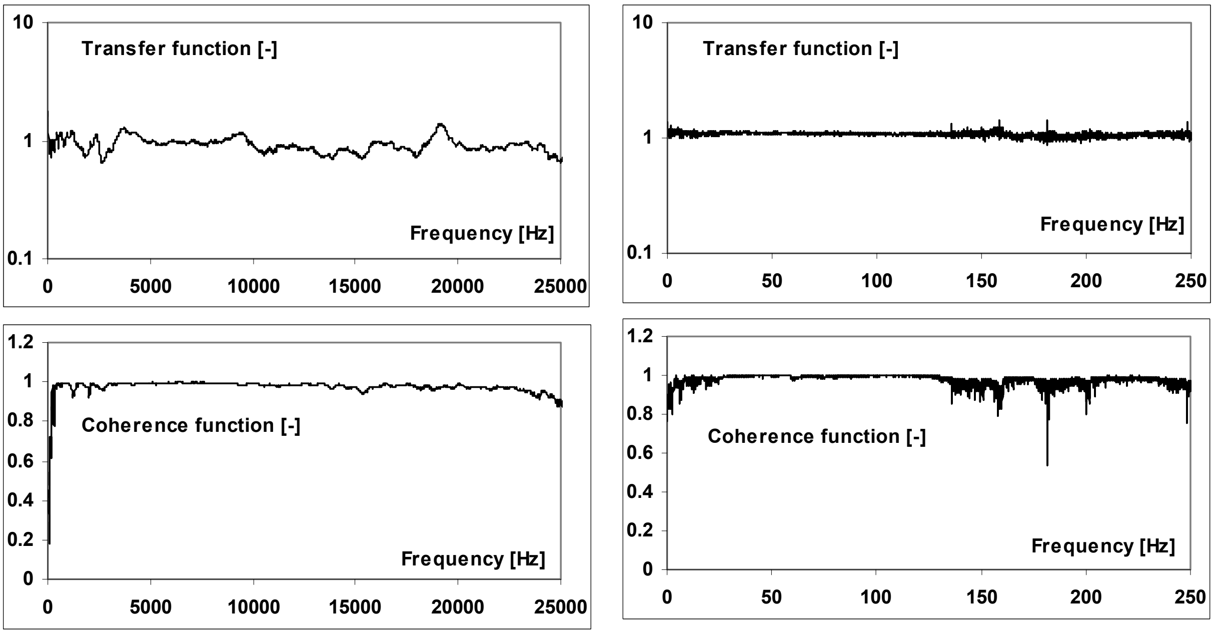

Fig. 4 Dynamic Calibration of a pressure transducer. Transfer and coherence functions. left: high frequency band (with the spark generated bubble), right: low frequency band

Strain gauges mounting

2 miniature piezo electric strain gauges are mounted in the suction and pressure side of 2 different blades close to the trailing edge and the runner crown. Those sensors are 2mm long and 1mm wide and exhibit sensitivity, which is 70 times higher than conventional gauges. 2 similar gauges, fitted in the blade basis, are used for compensation.

Effect of the runner rotation

A last control of sensors is made with rotation of the runner in air without axial flow. The effect of centrifugal load is measured for each sensor. Fig. 5 illustrates the effect of the rotation speed on the response of pressure sensors 1, 2, 3 and 4 as well as the two strain gauges. One may observe a parabolic increase of the pressure as the rotation speed increases. Obviously, this is due to the inertia force of the protective plastic compound, which acts on the sensor. This force depends on the radial distance of the sensor and the mass of the plastic compound as well as the rotation speed. Nevertheless, we have neglected the rotation speed effect on the pressure signals since it is less than 2 % of the pressure load under the nominal static head.

Concerning strain gages, centrifugal load leads to strain values of same order of magnitude as the effect of the pressure load. For this reason the effect of rotation speed on the mean strain measurement is systematically taken into account.

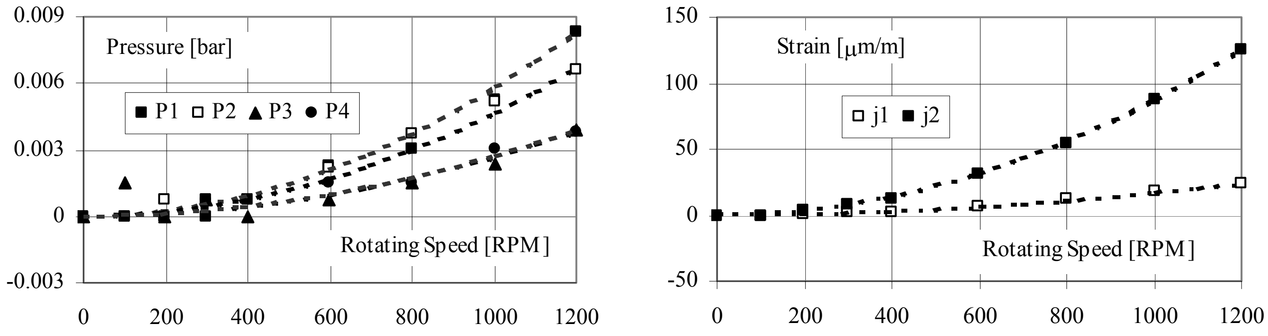

Fig. 5 Effect of runner rotation speed on the response of the pressure transducers (left) and the strain gauges (right). Tests are performed in air.

Test procedure

For a large number of operating points, covering the efficiency hill chart, several simultaneous acquisitions of the pressure and strain signals are performed. At the same time, the operating parameters are averaged and several photographs of the cavitation pattern are systematically taken. In order to control the zero drift of the pressure sensors, the test rig is shut down every 30 minutes to reset their offset.

CONCLUSION

In this first part of a 2 papers series, we have presented the experimental procedure for onboard measurement of pressure and strain fluctuation in a low head turbine model. 28 miniature pressure sensors are fitted in the pressure and suction sides of two consecutive blades. One hydraulic channel is thus instrumented. We have developed a specific technique for sensors mounting based on a direct manufacturing of the pressure sensors in the runner blades, which prevented from any geometry alteration of the hydraulic profile. Furthermore, miniature piezo electric strain gauges, 70 times more sensitive than conventional gauges, are embedded in pressure and suction side of 2 runner blades. Data acquisition is ensured by 32 channels onboard digitiser, having 12 bits resolution, 64 K-samples memory depth and 20 kHz maximum sampling frequency. Both static and dynamic calibration procedures of the pressure transducers are described. Results analysis is presented in Ref. 7.

ACKNOWLEGMENTS

Authors would like to thank their colleagues of the *Laboratory for Hydraulic Machines* as well as *Alstom Power Hydro* for their valuable help in setting up the procedure for onboard measurements. They are particulary gratefull to M. Djatout, L. Bezencon, D. Rouiller, and Ph. Faucherre. Authors would also like to thank *UniSensor AG* for the fruitful collaboration in setting up the mounting procedure of the pressure sensors.

REFERENCES

Ref. 1 FARHAT M., BOURDON P., LAVIGNE P., SIMONEAU R., "The Hydrodynamic Aggressiveness of Cavitating Flows in Hydro Turbines". Proceedings of the ASME Fluids Engineering Division Summer Meeting , June 22-26, 1997, Vancouver, Canada.

Ref. 2 FARHAT M., AVELLAN F., SEIDEL, U.; "Pressure Fluctuation Measurements in Hydro Turbine Models". 9th ISROMAC Conference, February 10-14, 2002, Honolulu, Hawaii, USA.

Ref. 3 AVELLAN F., ETTER S., GUMMER J.H., SEIDEL U.; "Dynamic Pressure Measurements on a Model Turbine Runner and their Use in Preventing Runner Fatigue Failure". Proceedings of the20th IAHR Symposium, August 7-9, 2000, Charlotte, North Carolina, USA.

Ref. 4 LOWYS P. Y., DOYON J., COUSTON M., VUILLEROD G., “Dynamic behavior of low head Francis turbine”, Proceddings of the IARH 2001, Trondheim, Norway.

Ref. 5 F. PEREIRA, M. FARHAT, F. AVELLAN, "Dynamic calibration of transient sensors by spark generated cavity". Proceedings of IUTAM Symposium on Bubble Dynamics and Interface Phenomena, Birmingham, England, September, 1993.

Ref. 6 G. BLOMMAERT; "Etude du comportement dynamique des turbines Francis : contrôle actif de leur stabilité de fonctionnement". EPFL Ph.D Thesis N° 2222. 2000, Lausanne, Switzerland.

Ref. 7 LOWYS P. Y., PAQUET F., FARHAT M.; "Onboard Measurements of Pressure and Strain Fluctuation in a Model of Low Head Francis Turbine. Part 2: Results Analysis”, Proceedings of the 21st IAHR Symposium, Sep. 9-12, 2002, Lausanne, Switzerland.