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# PREDICTING CAVITATION IN FRANCIS TURBINES ON THE BASIS OF SCALE MODEL TESTING

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## ABSTRACT

**The present article describes an ambitious research project being conducted jointly by EDF, HQ and EPFL, with the aim of developing a method suitable for industrial use for predicting cavitation in Francis turbines on the basis of scale model testing. Results concerning the notion of erosion aggressiveness, methods to measure it - accelerometer, pressure fluctuations and pitting measurements -, the correlation between measurements on models and erosion on prototypes, and validation testing done on an actual machine and its model are presented.**

## RESUME

**L'article proposé ci-après décrit un projet de recherche très ambitieux mené conjointement par EDF, HQ et EPFL avec comme objective la mise au point industrielle d'une méthode de prévision de l'érosion de cavitation d'une turbine Francis à partir d'essais sur modèle. Les résultats concernant la notion d'agressivité érosive, les méthodes permettant sa mesure - accéléromètre, variations de pression et mesure de marquage sur échantillons - les corrélations entre les mesures sur modèles et érosion sur prototypes, et les essais de validation menés sur une machine industrielle et son modèle, sont exposés.**

## 1. Introduction

Erosion due to cavitation is still a vital problem with Francis turbines, both in terms of dimensioning such machines and in operating them. Current knowledge and techniques are not sufficient to ensure that cavitation erosion will not occur and despite the very severe guarantees imposed several of these machines at recent power stations have suffered significant damage.

Feedback on hydro behaviour allows the manufacturer to dimension his machine to avoid that problem. But for specially designed machines that are manufactured in limited numbers, as is often the case for hydraulic turbines, there is no universally applicable method to assess the risk. Dimensioning is therefore based either on neglecting cavitation (which can mean the machine is dimensioned small) or on an "in-house" criterion that has been more or less thoroughly validated. But dimensioning has an impact on the cost of the machine, and on the general layout of the power plant.

For the operator, although stronger materials and suitable repair techniques have been developed, the supply of silent hydro turbines in their normal operation range still appears to be a feasible, highly desirable objective because of the significant gain in productivity, decrease in maintenance costs, and improvement to working conditions in the power station that could be achieved. There is therefore still a need in industry to achieve optimal dimensioning and operation of machinery in terms of cavitation erosion, by developing a methodology to quantify risks of cavitation erosion and to predict mass losses from the prototype, through scale model testing.

### The research programme

Electricité de France and Hydro Quebec in the role of Clients, Owners and Operators of many, large hydraulic turbines - with over 500 hydroelectric power stations being operated by the two companies for total installed capacity of over 55,000 MW - and the Ecole Polytechnique Fédérale de Lausanne, in the role of research laboratory and contractual test platform, have each been working for many years on erosion due to cavitation and how to predict it. In addition to their contributions to general knowledge of the subject, each has investigated specific approaches and implemented new methods and tools in this field. We could mention for example the Pressure fluctuation approach (EPFL), Pit counting (EDF) and Acoustic detection (HQ). Combining this competence and these tools today is the opportunity to make a decisive stride forward, to predict cavitation erosion on the prototype from the scale model tests.

This is the challenge EDF/HQ/EPFL have taken up in their joint research programme, with the following aims:
- to firm up and validate the notion of cavitation aggressiveness, and to control, improve and assess the various techniques to measure it;
- to establish a correlation between measurements on models and erosion on prototypes, and to set and validate that correlation through comparisons between measurements on the prototype and on the scale model.

This challenge, which in addition to the conventional research projects will have meant more than 70 manmonths of work in 1993 and 1994, is taking place in three countries at once: prototype measurements in Quebec, pitting measurements on polished metal in France, and scale model testing, among others, in Switzerland. In time, the results of this research could lead to defining a new type of model test to measure erosive potential and to:
- check and correct turbine design in the engineering stage;
- guarantee the operator a product that meets his expectations;
- lower bonuses relating to cavitation because of the reduced uncertainty;
- reduce turbine maintenance expenditure;
- reduce turbine-generator down time.

## 2. Techniques for measuring cavitation erosion

This initial phase in the project consisted in controlling, improving and comparing the various techniques used to measure cavitation erosion.

### 2.1 Actual evaluation of cavitation erosion risk

Up to now, erosion risk has been subjectively evaluated by considering cavitation development as related to the cavitation type, to the cavity size, and to the actual net head of the prototype. Inlet edge cavitation is more erosive than travelling bubbles. Larger cavities lead to greater damage than smaller cavities and, obviously, high head machines are more sensitive to the erosion risk than low head machines, since local velocities are higher. Hydraulic machine manufacturers used to define a "safety" margin as related to the cavitation erosion risk. However, this empirical margin, taken between the $\sigma$ plant and the $\sigma_0$ or $\sigma_1$ values determined during the cavitation tests, mixes two completely different physical phenomena, cavitation erosion and efficiency alteration due to cavity development.

A preferable procedure based on flow visualisation is followed by considering the cavity length as a measure of the cavitation "intensity". The erosion risk evaluation is then related to the decision of which cavity extent on the blades is acceptable for a given time operation for the considered operating point and the blade material. This empirical erosion prediction procedure is based on statistical erosion data and takes into account material properties. Cavity length measurements do not require any supplementary instrumentation other than that used for current flow visualisation tests, i.e. stroboscopic light, camera, windows in the cone and marked blades. Cavity length measurements can be tedious if image processing software is not used. However, flow visualisation is the surest way to control the cavitation behaviour of the runner and should always be performed.

Paint erosion tests can be used in complement to determine the extent of the eroded area downstream of the leading edge cavity or to examine any possible erosion on the non visible pressure side of the blades. Moreover, this technique makes it possible to determine the blade area to protect with a resistant alloy overlay. Paint erosion tests require that the paint be soft enough to be sensitive to the cavitation attack but resist the washing of the flow. Repeatability of the tests leads to a rigorous protocol in cleaning the blade surface, in painting, and drying.

### 2.2 Cavitation aggressiveness

To go from this simple evaluation of the risk of cavitation erosion to actual prediction of that erosion, the research programme set out to define and validate the notion of cavitation aggressiveness. It is well known now that cavitation erosion is the result of the collapse of cavitation vapour structures near the wall. Several fluid mechanisms are indicated - microjet, shock pressure wave, collective collapses - to explain the high level of stresses applied on the wall. They are still being investigated by many research teams all over the world in order to clarify the importance of each. Nevertheless, it has been established that under cavitation, the wall is submitted to pulses which are of very short duration (microseconds), very high pressure (gigaPascal), and very small radius (0.01-1 mm).

This is what we define as cavitation aggressiveness: the set of impacts applied on the wall by the collapse phenomenon. This concept is very interesting as by using it a clear distinction can be made between flow influence and material behaviour in the erosion process. From the definition, it follows that aggressiveness cannot be characterised by one quantity only. If all the blows were the same, three parameters would describe aggressiveness:

- the number of pulses per surface unit per second,
- the pressure level of the pulse,
- the duration of the pulse,
- the characteristic size of the surface submitted to the pulse.

Of course all pulses are not the same On the contrary, they are very scattered in size, duration and pressure, so that different representations can be used such as histograms. Until now, no measurement can provide all this information, even if some are approaching this aim. In an industrial environment, we are constrained to use remote sensing methods such as high frequency accelerometer measurements that must be checked and calibrated by local methods such as pressure fluctuations or pitting measurements and the DECER technique. This is the purpose of the experiments described hereafter.

### 2.3 Accelerometer measurements

Recent research in particular by Hydro Quebec (Bourdon et al.) has shown that accelerometer measurements can be used to detect cavitation erosion in hydraulic machines. This method uses a high frequency accelerometer mounted as close as possible to the cavitation spot. To obtain the forces due to cavitation, it is necessary to first measure the transmissibility function, which is the ratio of the output acceleration autospectrum and the input force autospectrum (Fig 1). This is achieved by using a miniature instrumented hammer to excite the cavitation device at the spot where cavitation erosion takes place.

The transfer function then allows recovery of the autospectrum of forces on the profile during cavitation tests from the autospectrum of the accelerometer. So a root mean square value of the inferred forces $F_i$ can be calculated in a frequency band.

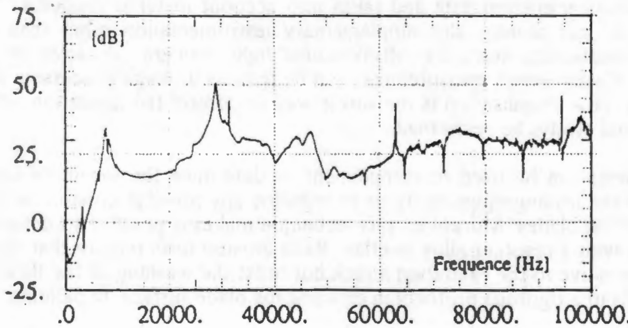


Figure 1. Example of acoustic transmissibility function (vortex)

Extensive studies of the cavitation erosion of a 2D NACA profile show an excellent correlation between direct electrochemical erosion measurement and acceleration levels, above 10 kHz. The erosion rate is found to be proportional to the mean square value of the profile acceleration signal in the 15 to 30 kHz band.

However, the advantage of the vibratory measurement is to define the aggressiveness of a given cavitation development in terms of mechanical engineering units, which defines a loading of the materials that metallurgists can include in their own erosion model. Indeed, this new procedure had to be validated ad refined in different cases, in particular through comparison with the local methods described hereafter.

### 2.4 Pressure fluctuation measurements

In a previous work (Avellan et al, 1992), the EPFL team introduced the model of Cavitation Erosion Power based on the assumption that severe erosion is usually due to the repeated collapses of transient vortices shed by a main cavity attached to the leading edge of the blade. They also assumed that the intensity of a single collapse is related to the potential energy $E_c$ of the travelling cavity corresponding to its maximum volume $V_c$: $E_c = (p_{max}-p_v)\ V_c$ were $p_v$ is the vapour pressure and $P_{max}$ is the maximum pressure responsible for the cavity implosion.

With $f_c$ designating the frequency of release of the erosive structures, the erosive power becomes: $E = (p_{max} - p_v) f_c V_c$

Using the assumptions proposed by the EPFL

- the erosive cavities' length scale is represented by the length $l$ of the pocket: $V_c \approx l^3 \approx h^3$
- the Strouhal number is a representative parameter of the rate of generation for erosive cavities: $f_c \approx f \approx St\, U/l$,

the erosive power can be assessed through the relationship $E = 1/2 K\rho (Cp_{max} + \sigma) St U^3 l^2$ with K constant.

These two assumptions are confirmed through visualisation, and it has been verified that this term is in fact significant of high pressure fluctuations suffered by the profile, which is illustrated by the relationship between the maximum standard deviation between pressures and the erosive power noted for two incidences of a profile assembled on the EPFL cavitation tunnel (Fig 2). The linear dependency revealed here substantiates the claim that the purely hydrodynamic notion of erosive power actually represents the aggressivity of the cavities associated with a cavitation pocket.

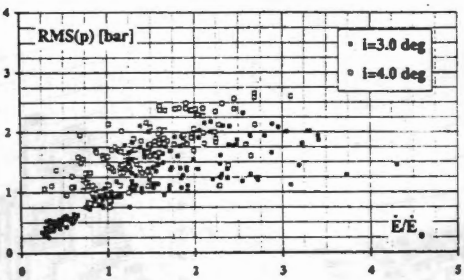


Figure 2. Standard deviation of pressure fluctuations according to erosive power

### 2.5 Pitting measurements

In association with other French laboratories, EDF has developed the technique of measuring the pits or marks left by cavitation on polished metal surfaces, and has used it on pumps and valves. The principle of pitting measurements is very old, since in 1955 Knapp used pit counting on aluminium to show the influence of velocity on the number of pits. Measurement apparatus now available give access to many more details such as individual size of pits, total volume, etc.

Three metals can be selected depending on the desired level of aggressiveness of the cavitation:
- 316L stainless steel for high level,
- pure copper (99.95%) for medium level,
- pure aluminium (99.999%) for low level.

Samples are carefully polished with an optical quality (roughness lower than 0.05 µm). Then, the impinged surfaces are analysed by novel means described hereafter. This provides a great deal of information, but it must be pointed out that, since the metal is deformed only by the blows that are violent enough to overcome the yield strength of the metal, it only gives information on the more aggressive pulses. Impinged surfaces are measured by a 3D laser profilometer.

Once computerised, the surface is analysed by software developed by the CREMHyG for EDF, which first effects the identification, localisation and quantification of the pits. Second, based on the previous work of J.L. Reboud and R. Patella, it provides the characteristics of the pressure wave which is at the origin of each pit.

To describe and quantify a pit, different geometric data can be used such as:

- Pit depth $h_i$: maximum depth of the pit from the reference level.
- Pit surface $S_i 10\%$: area where $h>0.1\, h_i$.
- Pit radius $R_i 10\%$: calculated from the surface $S_i 10\%$.
- Pit volume $V_i$: integrated total volume between reference level and pit on $S_i 10\%$.

The first parameters that are representative of the pitting are the total number of pits N and the total sum of pit volumes VT. Dividing them by test duration t and analysed area A, we have:

- Pitting rate: $n = N/At$
- Volume damage rate: $v_d = VT/At$

The process provides a list of pit characteristics. It can be presented in 3D histograms: the pits are split into depth and radius classes, and the histogram shows the contribution of each class to the total number (Fig 4) or volume (Fig 3).

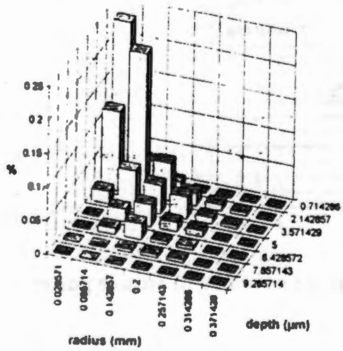


Figure 3. example of histogram: volumic contribution (%) versus classes of radius and depth (copper/vortex/10.87 m/s)

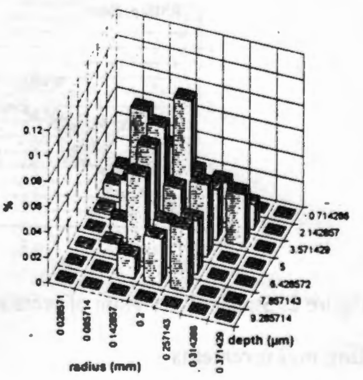


Figure 4. Example of histogram: number contribution (%) versus classes of radius and depth (copper/vortex/10.87 m/s)

On the one hand the pitting rate and volume damage rate do not give sufficient information. But on the other hand, histograms are too difficult to handle. Therefore it is necessary to define other meaningful values to characterise the pitting. Characteristic sizes (radius and depth) of the pitting must be defined. Classic mean values are not meaningful since many little pits do not contribute to the volume damage. EDF's research teams have found on many tests that only 20% of pits can make up 90% of the volume. So they suggest adopting ponderated mean volume values (Dorey et al, 1993).

Characteristic radius: $R_v = \dfrac{\sum R_{i10\%} \bullet V_i}{V_T}$ Characteristic depth: $h_v = \dfrac{\sum h_{i10\%} \bullet V_i}{V_T}$

### 2.6 DECER measurements

The DECER technique, developed and improved by Hydro Quebec and the university of Paris, is based on the measurement of the electrochemical cavitation activated current. An isolated titanium sensor is mounted where the erosion takes place. Sensors have to be preincubed to proved a fair on-line signal. An auxiliary electrode and a reference electrode have to be mounted also, so that a potentiostat measures the passivation current.

The DECER provides a fair on-line measurement that is directly proportional to the mass loss rate of titanium. This parameter is a good measure of the local erosive aggressiveness of cavitation. Of course the correlation between the mass loss rate of titanium and the mass loss rate of another metal can be influenced to some extent by the cavitation type.

### 2.7 Compared measurements

These different methods for measuring cavitation aggressiveness have been tested and compared on three devices which present a wide range of flow cavitation intensities and patterns. High speed jet is very aggressive and mass loss can be achieved very quickly. In the vortex device, blows of cavitation collapse can be isolated. As for profile, the cavitation pattern and collapse conditions are very similar to industrial features.

All these methods have been found to be well adapted to describe aggressiveness evolution. They have been proven to give representative values in a wide range of cavitation aggressiveness. With further improvements they seem to be able to provide an absolute measurement that may be used in any facility.

In particular:

- The rms values of the pressure fluctuations varies approximately in a linear way with the cavitation erosion power, leading us to believe that it stands as a good basis for prediction of the cavitation erosion in hydraulic machines. Nevertheless, further work has to be done to improve the model of cavitation erosion power, namely, direct measurements of the volume of travelling vortices.
- Pitting results give a great deal of information on aggressiveness. The increase of volume with velocity is due both to the increase in pit sizes (depth and diameter) and to the increase in pit number. In the near future, it will be possible to deduce the impact pressure and size distributions from pit measurements. Yet its implementation on machines remains difficult.
- The inferred forces method using a high frequency accelerometer is very interesting because it is a remote measurement. Measured forces have proved to be characteristic of the violence of the impacting process. Yet the results depend on the sensor, mounting and signal processing. Peak analysis could also provide useful additional information.

## 3. Correlation between measurements on models and erosion on prototypes

The notion of erosion aggressiveness, the control of the various techniques proposed to measure it, and comparative evaluation of these techniques have all been achieved. The second phase in our research programme therefore concerned the establishment of the correlation between the measurements on models and erosion on prototypes and their validation through comparing measurements on model and prototype.

### 3.1 Accelerometer method

The procedure consists in installing a high frequency accelerometer as "close" as possible to the runner subjected to cavitation erosion. In this case proximity should be examined by minimising the pathway of the solid borne noise. Bourdon shows that measuring acceleration with a sensor placed on the stationary part of the lower guide bearing is equivalent to that placed on the hub of the rotating runner, provided the transmissibility function between the blades and the actual location of the sensor is determined, as shown in Figure 7. An impulse force hammer can be used to determine this transmissibility function by successively hitting each blade. Obviously, this is done in air and the water added mass effect on the runner should be taken into account. An instrumented bubble spark generator developed at IMHEF makes it possible to provide short pressure pulses in order to complete the impulse force hammer data. After calibration, it can be used in water to overcome the problem in evaluating the water added mass. Moreover, the frequency range of excitation is extended as is shown by the energy spectrum in Figure 5. This spectrum is calculated from the 50 kHz low pass filtered signal of a Bruel and Kjaer hydrophone, type 8103, located 0.2 m from the spark centre. The corresponding photograph of the shock wave taken 5 $10^{-6}$ s after the spark ignition is given in Figure 6.

The transmissibility function makes it possible to infer forces or pressure acting on the blades and thus to provide the load induced by cavitation. This load can then be transposed to the prototype scale by using the law derived from the concept of mean erosive power of cavitation. For the two homologous operating points, the inferred force would be scaled by the term: $\lambda_L \lambda_E^{3/2}$ where $\lambda_E$ is the prototype to model energy ratio and $\lambda_L$ is the prototype to model length scale.

In the case of the experiment described by Bourdon, the length scale $\lambda_L$ between the model and the prototype is 13.2 and the energy scale $\lambda_E$ is 2.2, leading to a theoretical ratio of 575 for the forces acting on the runner. However, the measurements lead to 4N RMS inferred forces on the model and 3750N RMS on the prototype, which is not very far from the theoretical value of 2300N RMS, owing to the fact that the spiral case of the model was different from the prototype spiral case.

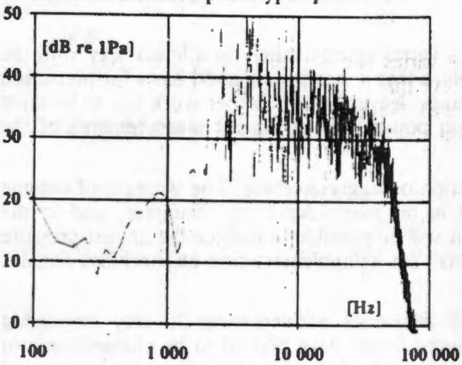

Figure 5. Energy spectrum of the spark pressure impulse

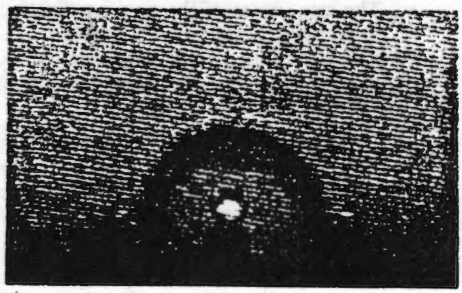
Figure 6. Spark ignition shock wave

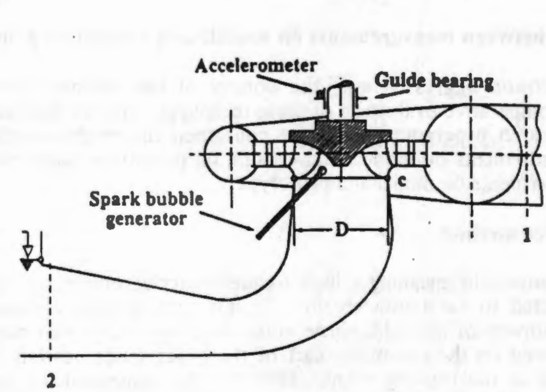

Figure 7. Measure of transmissibility function on a hydraulic machine

### 3.2 Pitting method

The procedure consists in submerging samples of polished metal on one blade of the model, at places subjected to cavitation erosion.

- Histogram of pressure and size of pulses

The intensity of the attack of the wall by cavitation can be described by the statistical pressure pulse distribution. Since pits are the result of tiny pressure pulses, pitting can reveal the more violent part of this distribution.

Once pitting has been measured, the values of the pressure pulses can be deduced from pit geometry, assuming:

- each pit is the result of a spherical pressure wave characterised by
  P pressure when the pulse hits the wall
  L radius of the spherical wave at the same instant
- the damage is only due to elastoplastic deformation of the material (no hardening or phase change or strain rate effect).

In these conditions, P and L can be derived from R and h by using formulae developed by Reboud et al. They used a model of elastoplastic deformation to establish those correlations. The calculation requires metal characteristics such as velocity of longitudinal waves, Young's modulus, yield limit for simple shear stress, Poisson's ratio, density, and also sound velocity in the liquid. Wave passage time is set on a particular assumption.

This process, applied to the list of pits, provides a list of values of P and L that can be presented in histograms. It represents the number of pulses per surface unit per second that have enough power to damage the material, that is to say the higher part of the whole pulse histogram.

- Similitude considerations

Simple considerations on similitude can be quoted to establish transposition of the pulse histograms between model and prototype. First of all, Sigma similitude must be applied on the model. It must also be checked that the test is free of scale effects such as Froude effect, Reynolds effect, or others.

In these conditions, it has been shown that, except for bubble cavitation, the Strouhal number governs the production of vapour structures. In other words, the number of vapour structures is proportional to the flow velocity and inversely proportional to the scale. As for their sizes, they are obviously proportional to the scale. This can also be applied to pulses, since they are the direct consequences of the collapse of these structures. Assuming that the collapse is analogous to a shock such as water hammer, pulse pressure can be considered as proportional to $\rho c V$ where $\rho$ is the density of the liquid, c the sound velocity and V the flow velocity.

Taking these considerations into account, the histogram of the model can be transformed in the following manner to obtain the prototype histogram:
- the sizes will be multiplied by the scale ratio,
- the pressure will be multiplied by the flow velocity ratio,
- the rate of pulses per surface unit per second will be divided by the 3rd power of the scale ratio.

Of course, the transposition will be valid only for the pulses that have been "recorded" by the metal samples in the model test. Since it is difficult on the model to reach the same velocity as on the prototype, pulses are expected to be weaker on the model. This implies that the metal used in the model test must be "soft" enough.

### 3.3 Validation by comparison of tests on model and prototype

The last phase in our research programme, currently underway, concerns the validation of the transpositions between erosion on the model and erosion on the prototype proposed hereafter, by comparison between tests on the model and on the prototype.

#### 3.3.1 Measurements on prototype

The prototype tests were carried out on a 270 MW Francis prototype, which was chosen as a research machine in view of its particular cavitation erosion history. Although the initial erosion rate on the machine had been reduced by the use of tougher materials and a restricted operating range, there were still indications of significant cavitation erosion on this prototype. During a first series of tests on this prototype, in June 1993, the following were performed:

- Accelerometer measurements

The machine was monitored on a continuous basis by dedicated cavitation detection high frequency accelerometers and data acquisition systems. Detailed cavitation signatures covering the operating range of the machine were taken, including time and frequency domain signals from two high frequency accelerometers and a wideband acoustic emission sensor operating in the 100-1000 kHz frequency range. In the course of that programme, transmissibility functions between the runner blades and the monitoring accelerometers were also measured. A total of four accelerometers, three at the lower guide bearing and one at the draft tube access door just below the runner, were used during these special tests.

- Pitting measurements

For the special pit counting tests, four circular 4 cm diameter polished 316L stainless steel disks were embedded for each test in blade 4 of the runner (Fig 8). Complete repainting of the runner with an epoxy based paint complemented any possible marking of the polished specimens by assessment of paint removal on all blades.

Figure 8. Stainless steel disks embedded in blade 4 of the prototype runner.

- Pressure fluctuation measurements

During a second series of tests, in August 1994, the non stationary pressures were measured by sensors mounted on one blade of the runner, with the signal transmitted through the runner's shaft.

Partial results of this prototype test are presented in a parent paper at this symposium (Bourdon, P., Simoneau, R., Dorey, J.M., "Accelerometer and pit counting detection of cavitation erosion on a laboratory jet and a large Francis turbine", 17th IAHR Symposium, Beijing, September 1994).

3.3.2 Measurements on model

The model runner was built on the basis of the geometry observed on site of one of the prototype blades with characteristic erosion. This runner, measuring 300 cm in diameter and made of metal was instrumented with the following apparatus:

- one blade with four pressure sensors with a measuring range of 0 to 200 bar (Fig 9);
- one runner with four replaceable pure copper samples;
- one runner with four electrochemical sensors.

The model also has a contact ring to supply the electrochemical and pressure sensors.

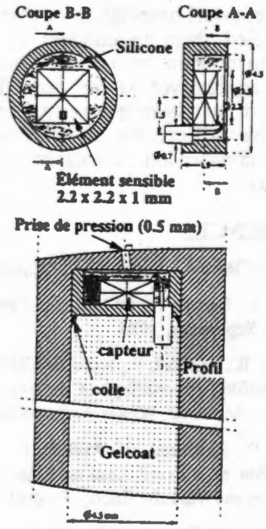


Figure 9. Detail and mounting of a sensor.

The runner and its model were mounted in the IMHEF Universal test rig (maximum pumping power 900 kW, test heads up to 100 m, maximum flow rate of 1.4 m3/s, maximum generated power at 2500 rpm 320 kW, Fig 10). In addition to the classic instrumentation on such a test rig, two high frequency accelerometers were mounted on the bearing of the turbine shaft. A fast-action camera was used to record the cavitation patterns.

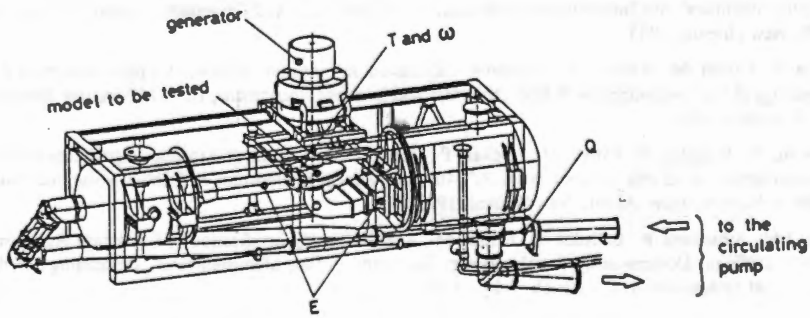


Figure 10. Model of a Francis turbine installed on the IMHEF Universal test rig #1.

To respect the dynamics of the phenomena under observation, special care was taken in these tests to synchronise the acquisition of the various measurements: pressure, acceleration, flow parameters, and visualisation of the cavitation patterns.

## 4. Conclusion

The exceptional association of three partners, each with unique competence in specific fields, has enabled them to conduct a major research programme concerning the prediction of cavitation erosion on a Francis turbine on the basis of scale model testing. The notion of erosion aggressiveness has been firmed up and the various methods presently available to measure it have been improved, compared and evaluated. Correlations between measurements on models and erosion on prototypes have been proposed. Validation of those correlations through comparison of measurements taken on a prototype and a scale model is currently underway.

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