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which are too high, for instance for the flood of August, 1984 (ca. 100-year flood flow event). We presume that as long as loose sediment is available on the torrent bed, the calculated values equal the actual conditions, but that as soon as channel bed scouring starts, that is, as soon as the soil characteristics of the underlying material come into play, the volume of transported sediment may decrease considerably, depending on the soil mechanical properties (shear strength etc). In this particular case the torrent lies in flysch and its bed consists of a mixture of clay-sized to gravel-sized particles, that is, cohesive material. The discrepancy between the calculated and the measured values shows that the *erosion processes* in cohesive and non-cohesive material in steep gullies should be studied as soon as possible. In order to perform the relevant calculations we are currently developing methods permitting representative definitions of the following flood runoff parameters: channel gradient, channel cross section, channel roughness, and irregularities, grain size distribution of gully material and transported sediment, etc. Another aspect concerns the nonsteady flow of the flood flow (incl. sediment), a flow which we so far have assumed to be quasi steady.

This problem regarding sediment transport is a typical example of our diverse activities. Especially at present we are continually being confronted with new problems, and the focal points of our research are shifting accordingly. Above all, the rapid increase in forest damage is stimulating, even forcing us, to work more and more intensively as time progresses. In that respect we are facing a most uncertain future.

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Hydraulic machinery model testing

Pierre Henry

1. Introduction

The use of model tests is of considerable importance in the context of hydraulic machines. In fact, flows are so complex that it is still impossible to do a complete calculation taking into account the viscous effects. Because of this, the final configuration of a hydraulic machine is always defined using the results of model tests.

We shall also see later that it is very difficult to perform a field acceptance test, and that in many cases the most accurate and most economical method is to do acceptance tests on a model. This technique also has the great advantage that it can be employed before the prototype is manufactured.

Model tests are also very important to verify the results of flow calculations specially with three-dimensional flow analysis programs.

2. Description of the IMHEF installations

The Hydraulic Machines and Fluid Mechanics Institute (IMHEF) of the Swiss Federal Institute of Technology, Lausanne, has an extensive installation for model testing of hydraulic machines and it can be used for all types of reaction machines, i.e. [1], [2].

Table 1. Main characteristics

Head	H	$= 2$ m to 100 m
Discharge	$Q_{max.}$	$= 1{,}3$ m
Dynamometer power	P_D	$= 300$ kW
Pump power	P_P	$= 900$ kW
Speed	$N_{max.}$	$= 2500$ RPM

- Francis *(figure 1),* Kaplan and bulb turbines
- radial, diagonal and axial pumps and pump-turbines.

The installation has two test platforms which are used alternately. This feature permits installation of a model on one test platform when the other one is in operation. The time available for testing is accordingly larger. The hydraulic energy (head) is supplied to the models by a single 3-stage diagonal pump: its particular feature is that both closed-circuit and open-circuit machine tests can be done with a large 1000 m³ tank. *Figure 2* shows a perspective view of the circuit.

The main characteristics are given in *table 1.*

To calculate the efficiency of a machine, which is the most important guaranteed factor, the head, flow, torque and speed of rotation must be measured. Of these four, flow and torque are particularly difficult to measure.

The IMHEF installation comprises two series transducers for flow measurement, i.e. an electromagnetic flowmeter and an ultrasonic flowmeter. These two instruments are calibrated on the spot using a high-precision volumetric tank.

For vertical axis machines, torque is measured using a hydrostatic pivot and strain gauge load cells. The friction torque of the bearings and seals of the model is also measured. The accuracy obtained is better than $\Delta T / T = 0.1\,\%$.

IMHEF has two torque measurement techniques for horizontal axis machines (bulb turbines):

- using a generator cradle-mounted inside the bulb (Neyrtec system);
- using a right-angle gearbox cradle-mounted (Aströ system).

The two systems have their advantages and disadvantages. The maximum power of the Neyrtec system is about 30 kW while that of the Aströ system is 150 kW.

With the Neyrtec system strict geometric similitude can be obtained, while the Aströ system has a bearing under the bulb.

The measurement of cavitation phenomena and pressure fluctuations requires a number of additional measurement systems to establish, for example, dissolved oxygen and nuclei content, and instruments such as quartz pressure gauge, strain gauge torquemeter, FFT signal analysis system, etc.

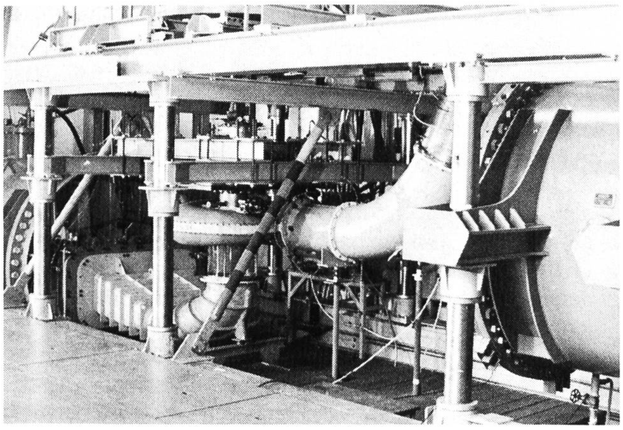


Figure 1. Model of Itaipu (Brazil) Francis turbine (outlet diameter 400 mm) during acceptance tests at IMHEF.

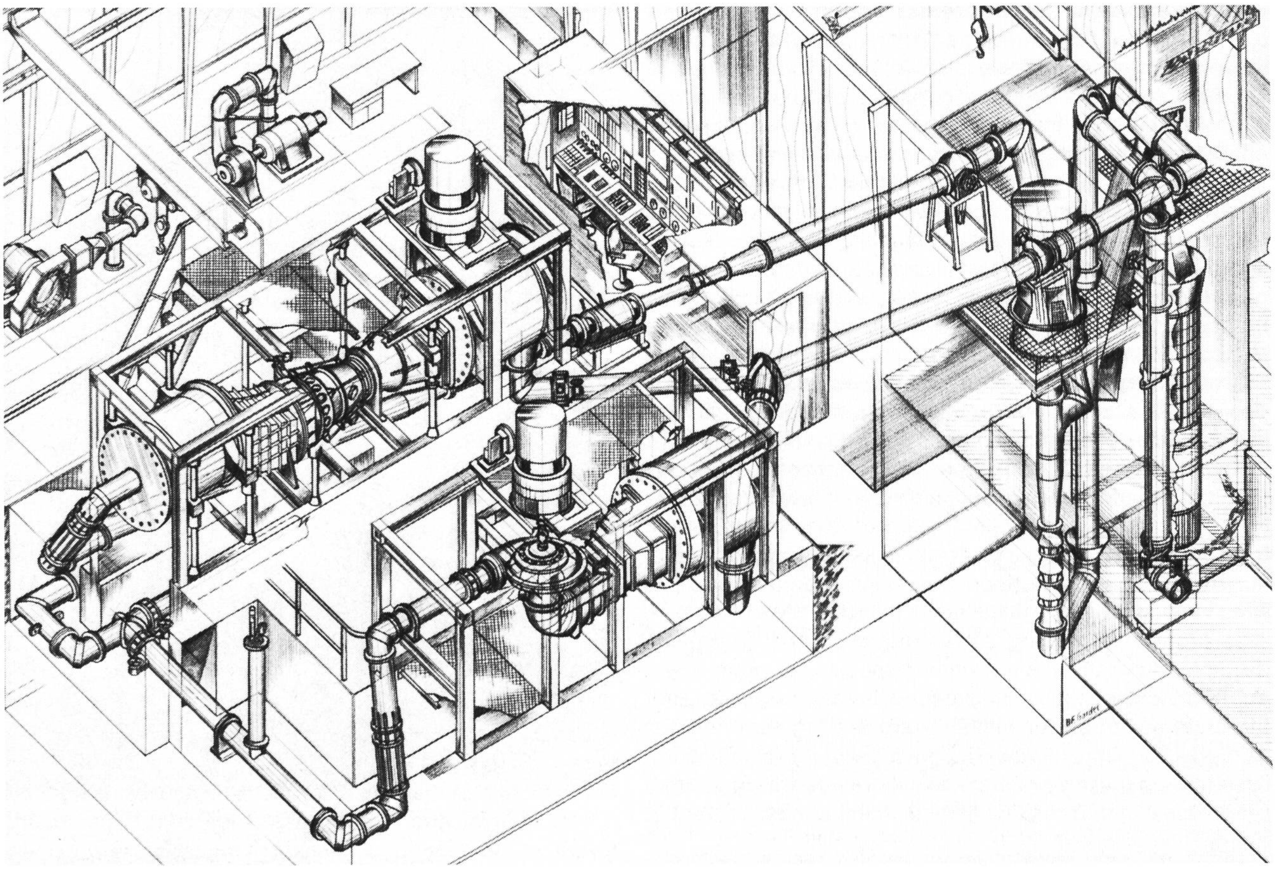


Figure 2. General view of IMHEF test installations showing two test platforms on the same circuit.

3. Model tests

At present the model tests most often required are:
- measurement of all the characteristics of the machine (head, flow, output efficiency) in the form of an efficiency hillchart;
- measurement of efficiency and power for the points to be guaranteed;
- measurement of the maximum runaway speed with and without cavitation effect. For Kaplan and bulb machines the runaway speed is measured with both synchronized and desynchronized blades. The discharge at runaway speed is also an important value which allows the maximum discharge of the machine when used as a spate evacuator to be determined;
- measurement of efficiency variation due to cavitation $\eta - \sigma$ curves) in order to determine standard σ;
- location of the zones where extrados and intrados cavitation, whirl and lowload vortices appear;
- measurement of the pressure and torque fluctuation in order to determine their frequencies and amplitudes. These measurements are taken so that resonance phenomena between the machine and the penstock can be avoided and to prevent vibrations and excessive noise in the prototype. The effect of air injection on the pressure and torque fluctuation is also very often measured. This also means that the injected air flow and the pressure must be measured to calculate the prototype values; *figure 4* shows typical results of pressure fluctuations measured at the wall of the draft-tube cone. Pressure is measured at different flows at constant head and results are given on the form of a Fourier analysis;
- measurement of the mechanical values such as axial and radial thrust and guide-vane torque. It is very important to know the axial and radial thrust, both static and fluctuating, in order to check the dimensions of the axial thrust bearing and the bearings of the machine. If the guide-vane torque in both the synchronized and desynchronized configuration is known, the actuating device can be checked with the distributor in any position and strains on the adjacent blades can be predicted in case of rupture of the safety device of one of the guide-vanes.

4. Similitude problems

4.1 Efficiency

Calculation of prototype efficiency based on model efficiency is at present relatively accurate in the case of a model and a prototype which are hydraulically smooth.

Working Group 5 of the IAHR (International Association for Hydraulic Research) has established a generel formula: [3], [4]

$$\Delta\eta = V(1-\eta_m)\left[1-\left(\frac{Re_m}{Re_p}\right)^{0.16}\right]$$

$\Delta\eta$ prototype/model efficiency difference
η_m model efficiency
Re_m, Re_p model and prototype Reynolds number
V ratio between friction loss and singular losses

IAHR Group 5 has shown that for Francis turbines V is about 0.7 (range between 0.5 and 0.8) and for Kaplan turbines V is about 0.8. The value of V is the main uncertainty. Taking into account the accuracy of model efficiency measurement and the uncertainty about step-up formulas, the overall accuracy of prototype efficiency prediction from model tests is often greater than direct field measurement, mainly for low head installations.

A good comparison of model and prototype efficiency was made for the *La Grande 2* power plant in Canada [7], [8]. *Figure 5* shows the results. The prototype measurement was made using the thermodynamic method. The model efficiency is stepped up using the formula of paragraph 4.1 with $V = 0.7$.

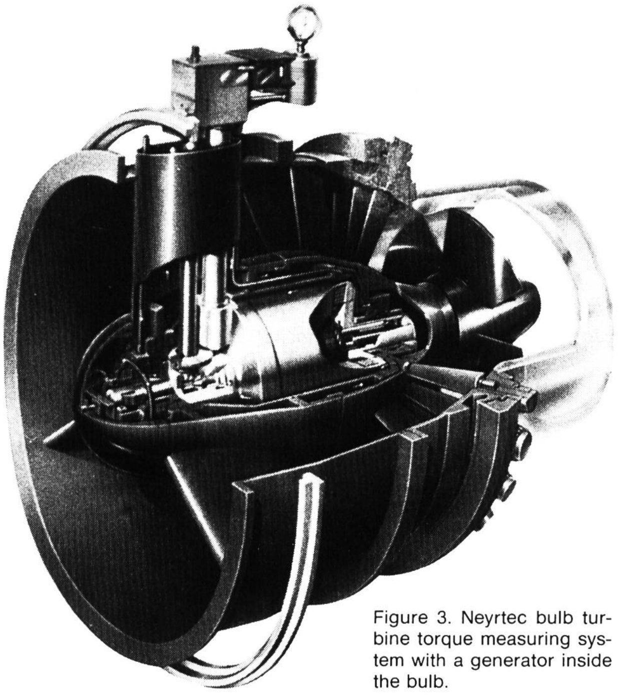


Figure 3. Neyrtec bulb turbine torque measuring system with a generator inside the bulb.

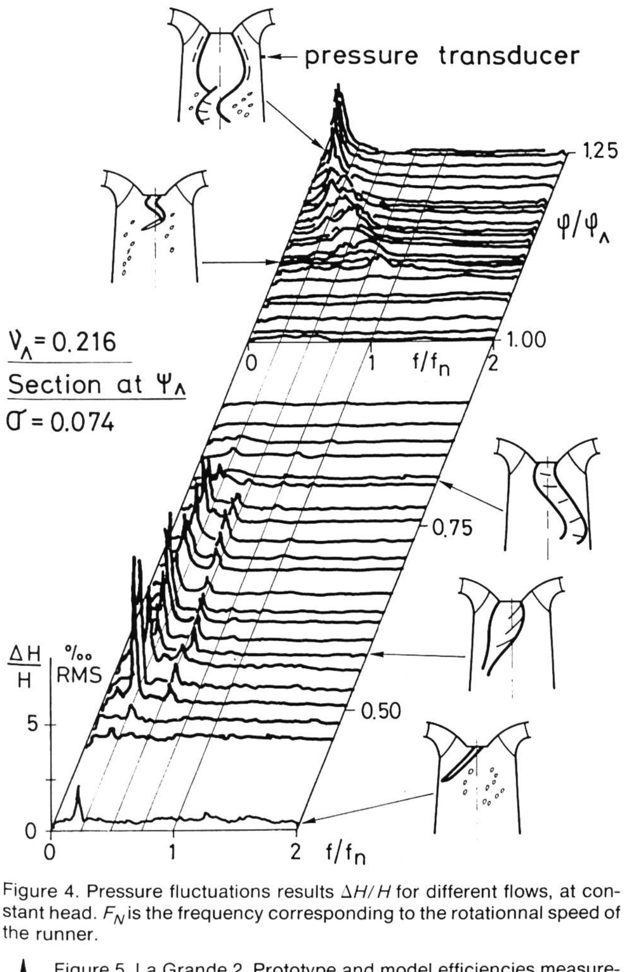
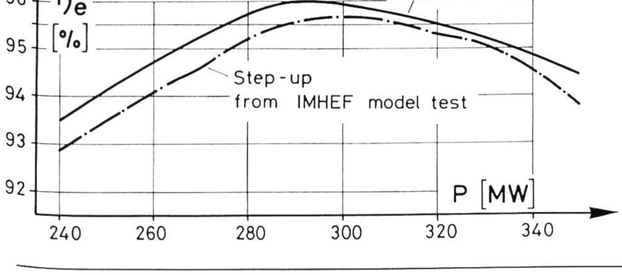


Figure 4. Pressure fluctuations results $\Delta H/H$ for different flows, at constant head. F_N is the frequency corresponding to the rotationnal speed of the runner.

Figure 5. La Grande 2. Prototype and model efficiencies measurements.



4.2 Similitude in cavitation

Cavitation tests on a model are very important. They are the only way of ensuring the smooth running of the prototype as far as the risk of erosion and of pressure and power fluctuations are concerned.
The problem of transposing the results of the model tests to the prototype is worthy of particular attention.
In fact, the similitude criterion universally used in cavitation is Thoma's σ.

$$\sigma = \frac{H_B - H_V - H_S}{H}$$

H_B representative level of the atmospheric pressure
H_V representative level of the vapour pressure
H_S suction head of the machine
H net head

This criterion is valid only for incipient cavitation. It is theoretically not valid when cavitation is developed. The quality of the water is also very important for cavitation tests. Travelling cavitation is greatly influenced by the presence of nuclei in the water used for the test. The nuclei are very small diameter microbubbles (0 to 50 μm). Since cavitation is caused by a sudden increase in the diameter of these nuclei, the extent of the cavitation is considerably affected by the nuclei density in the water used for the test.
The test head also has an important influence on cavitation test results [6], [9], [10]. With a high head, smaller nuclei have an explosive growth and as the amount of small nuclei is much more numerous in normal test water, the cavitation will be more developed.

4.3 Similitude in pressure and torque oscillations

Low-frequency hydraulic oscillations in the plant and resulting power swings can be an important problem, and attention must be given to this in model tests. Similitude laws are not yet fully understood in dealing with the dynamic behaviour of hydraulic turbines, but the measurement of pressure and torque fluctuations with the associated frequencies is well-established.
Provided that operating conditions – flow, head, rotation speed and cavitation – are in similitude, the relative frequencies F/F_N of model test oscillations seem to be transposable to the prototype.
Fourier analysis of the measured signals gives a fairly good idea of the prototype hydraulic system's excitation sources. Dynamic parameters of the model – inertance, resistance, cavitation compliance – may be identified using an adequate test procedure. In the near future, acceptable mathematical models for the oscillatory behaviour of the prototype turbine should thus be produced from model tests to obtain a prediction of hydraulic fluctuations and power swings.

5. Conclusions

The installations for model testing now make it possible to achieve a high degree of accuracy in predicting the prototype performance (efficiency, power). Considerable progress has also been made in the transposition to the proto-

type of results obtained with the model. Under these conditions, the results of a model test transposed to the prototype will very often be considerably more accurate than a field test on a prototype.
Other tests such as those for cavitation, runaway, mechanical efforts are also very accurate and, in spite of the transposition difficulties, the results of these tests are also very reliable.
It is clear that all these tests require a rigorous geometric similitude. Special attention must therefore be paid to checking the dimensions of the model and the prototype to ensure homology.

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EAWAG

Swiss Federal Institute for Water Resources and Water Pollution Control

Eidg. Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz

Institut fédéral pour l'aménagement, l'épuration et la protection des eaux

The EAWAG, founded in 1936, is Switzerland's principal institute of water protection research (figure 1). *Associated with the Swiss Federal Institutes of Technology it has a status similar to a university institute. The mandate comprises the research, teaching and consulting in the field of water resources, water pollution control and waste management. The advisory services are provided to the government, to communities and to industry. The EAWAG has no regulatory functions.*
Some 170 staff collaborate in the several departments of EAWAG. Approximately half are academically qualified chemists, biologists, physicists, geologists, computer scientists, and civil, environmental, chemical and mechanical engineers. Additionally, there are 20 to 30 doctoral students and several visiting scientists. Some 80 percent of the finances stem from governmental funding and 10 percent each from research foundations and contractual work.

Objectives

The main role of the EAWAG is to act as an interface between science and the implementation of environmental protection. Its primary objective is to serve as a research and educational centre for developing improved concepts for environmental protection, water resources and waste management. In doing so, EAWAG is oriented by the objectives of the Federal laws on water protection and on environmental protection.
Establishing effective environmental protection policies demands a comprehensive understanding of natural processes and ecological relationships. Thus, primary research areas concern
- the physical, chemical and biological processes that occur in both natural systems and engineered systems for waste, water and sewage treatment and
- the material cycles connecting water, soil and air which are increasingly influenced by man.

EAWAG maintains extensive contacts to foreign research institutes and its own research activities are strongly motivated by the findings of international basic research.

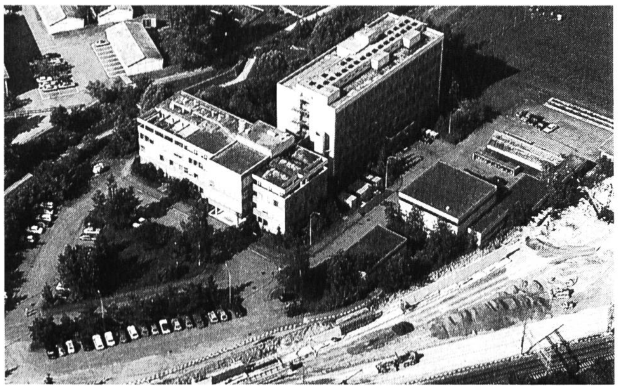

Figure 1. Main facilities of EAWAG in Dübendorf.
Bild 1. EAWAG-Hauptgebäude in Dübendorf.
Figure 1. Vue générale des bâtiments de l'EAWAG.
(Foto: Militärflugdienst Dübendorf)