Model testing beyond the scope of international standards: An outlook

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During the past decades, the original role of energy generation of hydropower plant (HPP) has been supplemented with the provision of ancillary services to the grid. The increasing need for integration of non-dispatchable renewable energy sources to the grid in the coming years is expected to foster this trend.

The new missions accomplished by HPP also brought new technological challenges to ensure reliable, efficient and long lasting operation. Some of the innovations proposed by hydro mechanical equipment manufacturers to overcome these challenges rely on the implementation of digital solutions to support the HPP operation and monitoring.

Reduced scale physical model testing of hydraulic machines is a well established and standardised activity, especially when it comes to experimentally validate the hydraulic performances of the machines subject of contractual guarantees between the manufacturer and the electrical utility. But model testing also provides a valuable opportunity to accurately gather information and to build digital models of the machine behaviour that are of critical importance to fuel the transition of hydropower into the digital era.

This work presents a short review of selected recent research and development projects involving non-standard model testing activities and techniques. These studies address the characterization of the stability of the units, their transient behaviours and the machine condition within various operating modes and regimes. A reflection is also conducted about the foreseeable needs for model testing in the coming years, the gap with the existing state of the art and the envisioned paths to close it.

1. Reduced scale physical model testing of hydraulic machines

1.1 Scope of model test as described in IEC60193

The International Standard IEC60193 [1] is the most commonly applied standard for the performance of model acceptance tests of hydraulic turbines, storage pumps and pump-turbines. It is also widely applied for the performance of research and development model testing campaign, without contractual guarantees to be checked.

It details procedures to measure the *main hydraulic performances* [1] of the machines based on the measurement and determination of the following quantities in quasi-static conditions:

- the discharge Q;
- the specific energy E and the net positive suction energy $NPSE$;
- the mechanical torque T_m transmitted by the runner to the shaft;
- the rotational speed n of the runner.

This leads to the determination of the hydraulic characteristic of the machine, possibly in the four quadrants of operation, together with the investigation of the cavitation conditions in the machine. The transposition of the results obtained at model scale to the prototype scale is also detailed.

The measurement or determination of further quantities, referred to as *additional performance data* in [1], is also detailed. It covers the measurement and determination of the following quantities in quasi-static conditions:

- pressure fluctuations;
- shaft torque fluctuations;
- axial and radial thrust;
- hydraulic loads on control components, such as guide vanes or blades when applicable.

Concerning the additional performance data, guidelines for the transposition to the prototype scale are also provided. Nonetheless, assessing the homology of the investigated phenomenon between the model and the prototype scale is not straightforward and the uncertainty in the transposition is larger than for the main hydraulic performances, reaching typical level of +/- 10 to 20% of the maximum mean value [1].

As an example, the transposition of pressure fluctuations measurement from model to prototype in the case of Francis turbine is the object of dedicated efforts from the International Electrotechnical Commission [2] to tighten the gap between existing documentation and current and future needs. Similar efforts for other topics could help addressing the needs for more detailed models and data describing the hydropower units and its digital avatar.

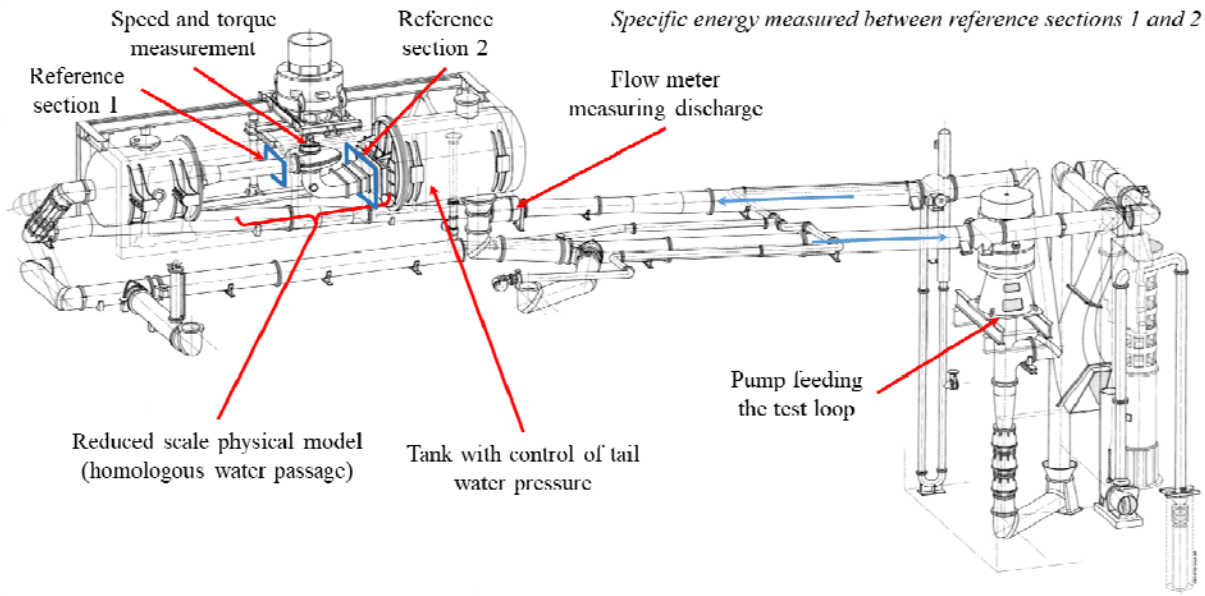

Fig. 1. Layout of a universal test rig designed for measuring the main hydraulic performances on a reduced scale physical model of hydraulic machine.

1.2 Further need for model testing

The mission of hydropower plants includes more and more the fulfilment of the need for ancillary services to the grid. The hydropower units are globally experiencing more operating time at off-design conditions, i.e. at part load or full load, outside of the operating range for which they are optimally designed. The number of start & stop cycles experienced by the units is also increasing dramatically in many power plants.

The operation at off design condition and the transient phases in operation are sources of high dynamic solicitations that can potentially reduce the lifetime of the components of the turbine, and especially the runner [3]. As it involves complex hydraulic phenomenon and plays and important role along the lifetime of the units, it also deserves in depth investigation. Other parameters such as the actual mileage covered by the control components – guide vanes or runner blades for example – during the operation of the power plant with the governor acting to stabilize the grid, could have a major impact on the residual life of the units and of its components but lacks experimental investigations.

The model testing phase is one opportunity for experimental investigation and validation not only of the sole hydraulic machine design, but also of the entire hydraulic unit as whole system. Even if many quantities of interest, such as mechanical stress on components or the hydraulic behaviour of the unit during transient phases, are beyond the scope of the applicable standards [1], some experimental set-ups and methods have been successfully implemented and described in the literature. The following sections provide some highlights of outcomes from

model testing campaigns addressing these topics together with indications of their maturity level and required efforts for their performance.

2. Achievable outcomes from model testing campaigns

2.1 Model test results obtained without specific equipment

The available operating parameters of a hydraulic unit are usually limited to:

- the difference of elevation between the head water reservoir level and the tail water reservoir level, referred to as the gross head;
- the output electrical power;
- the stroke of the servomotors controlling the guide vanes opening and the blade pitch angle if any;
- the unit rotating speed.

The margin with respect to the unit operating domain limit cannot be estimated in a straightforward manner with only this set of quantities in hand. The main difficulty for on-site estimation of the hydraulic operating conditions is related to the determination of the discharge in the unit. In [4], Gomes Pereira Junior *et al.* detailed a procedure to build an explicit model of a Francis turbine hill chart allowing the live monitoring of the unit operating conditions – including discharge – based on the data available during power plant operation.

The explicit turbine hill chart is built directly from the measurement results gathered during a typical model testing campaign. The method has been tested during an experimental campaign on the prototype machine [4] with a relevant prediction of the transition area between stable operating conditions and the onset of full load instabilities.

Favrel *et al.* presented an approach for the determination of the dynamics of the cavitating vortex rope in the draft tube cone f a Francis turbine based on the swirl number [5]. It allows the fine prediction of the stability limits for the prototype operation according to model testing results. The swirl number can be obtained according to the determination of swirl-free operating conditions on the model. This is technically achievable without dedicated equipment on the model except visual access to the runner outlet. Nonetheless, a flow velocimetry survey in the draft tube cone allows an enhanced determination of the swirl number value over the entire operating domain of the machine [5].

2.2 Velocimetry survey

The investigation of the flow velocimetry provides a valuable overview of the flow structure that helps explaining various phenomenon regarding for instance energy conversion or unit stability [7]. While Pitot probes has been intensively used for such application, this measuring technique is penalized by the disturbance generated by the probe itself in the area of interest. Laser based flow survey methods such as Laser Doppler Velocimetry (LDV) or Particle Image Velocimetry (PIV) have also long been used for studying the flow in hydraulic machines. It has been extensively used in the framework of research projects aiming at investigating the behaviour of hydraulic machines at off-design conditions [6].

Apart from the dedicated measuring equipment, such as the compact LDV system depicted in Fig. 3, the requirement on the model design and manufacturing are limited to ensuring a proper optical access. An example of the model modification performed and of the procedure for a flow survey in a Francis turbine draft tube cone is proposed in [8].

With the price, size and complexity of the necessary equipment for such experiments noticeably decreasing during the past decades, the technical and economic feasibility of flow velocimetry surveys is nowadays accessible to a wider range of projects [8, 9], with manifold merits, ranging from local validation of numerical simulation results to the investigation of the global unit stability.

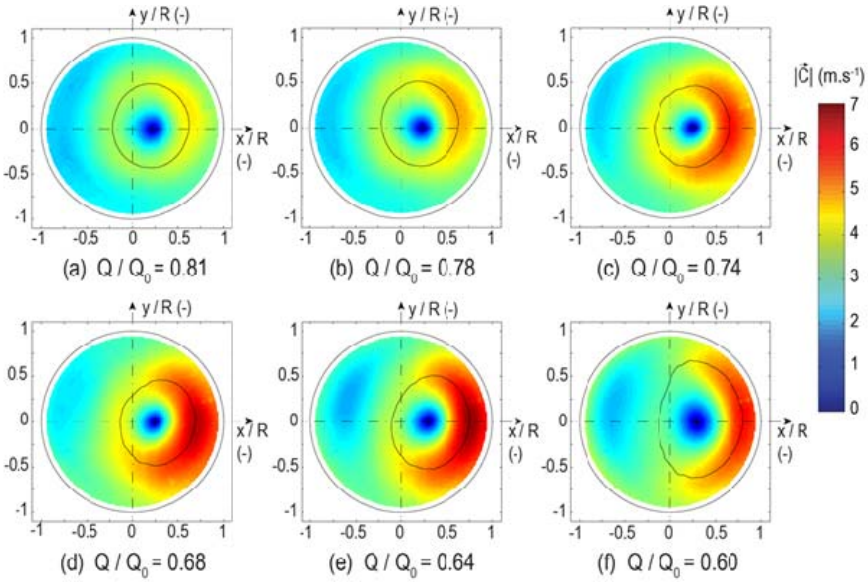

Fig. 2. Identification of the vortex rope parameters at the outlet of a Francis turbine runner operating at part load, from [7].

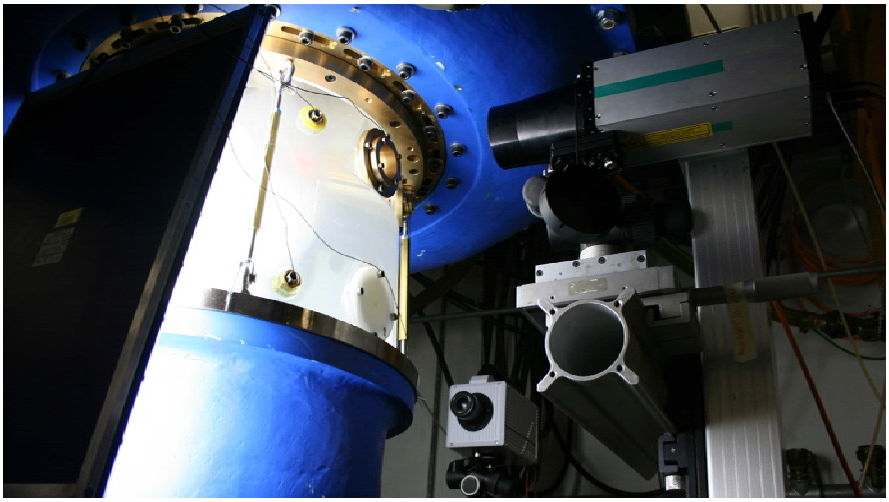

Fig. 3. Compact LDV system and associated traversing system installed to perform a flow velocimetry survey in a Francis turbine draft tube cone during [6].

2.3 Instrumented runners and measurement in the rotating frame

Together with a flow velocimetry survey, the performance of measurement in the rotating frame attached to the runner provides valuable information to validate the hydraulic design and the mechanical design of an hydraulic machine.

Current existing techniques have been developed for the measurement of dynamic pressure fluctuations [10] and of the dynamic stress [11] at various location on the model runner. This allows a better understanding of the dynamic load experienced by the runner while operating at off-design condition and possibly under transient operation.

From the practical point of view, the performance of measurement in the rotating frame requires a dedicated design and manufacturing for the model runner, as illustrated in Fig. 4 in the case of a Francis turbine runner. The synchronous recording of the signals from the transducers installed on the runner and of the other fixed transducers installed on the model also requires the use of an appropriate telemetry system. The development of a standard telemetry system embedded in the test rig bearing, as illustrated in Fig. 5, allows to limit the specific development for a model testing campaign.

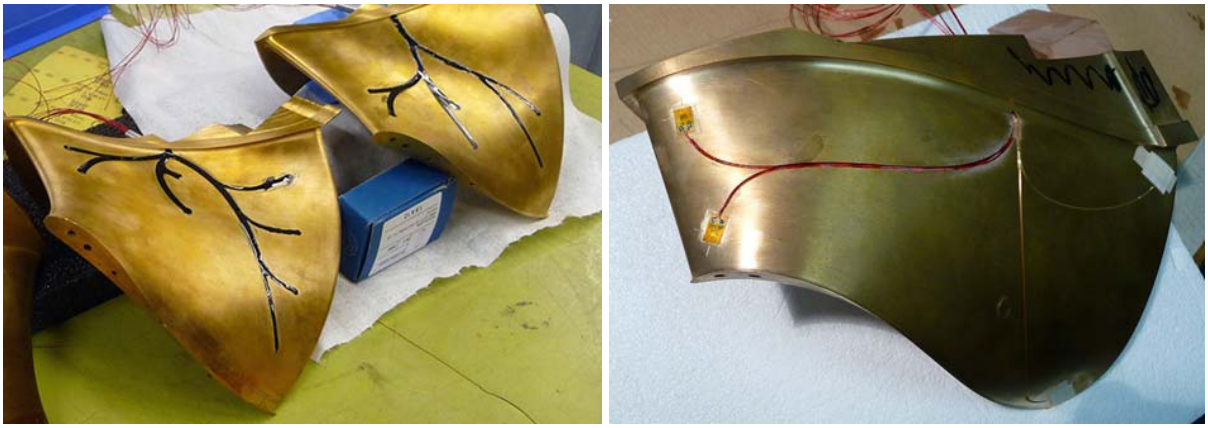

Fig 4. Instrumented Francis turbine runner blades with embedded pressure sensors (left) and strain gauges (right).

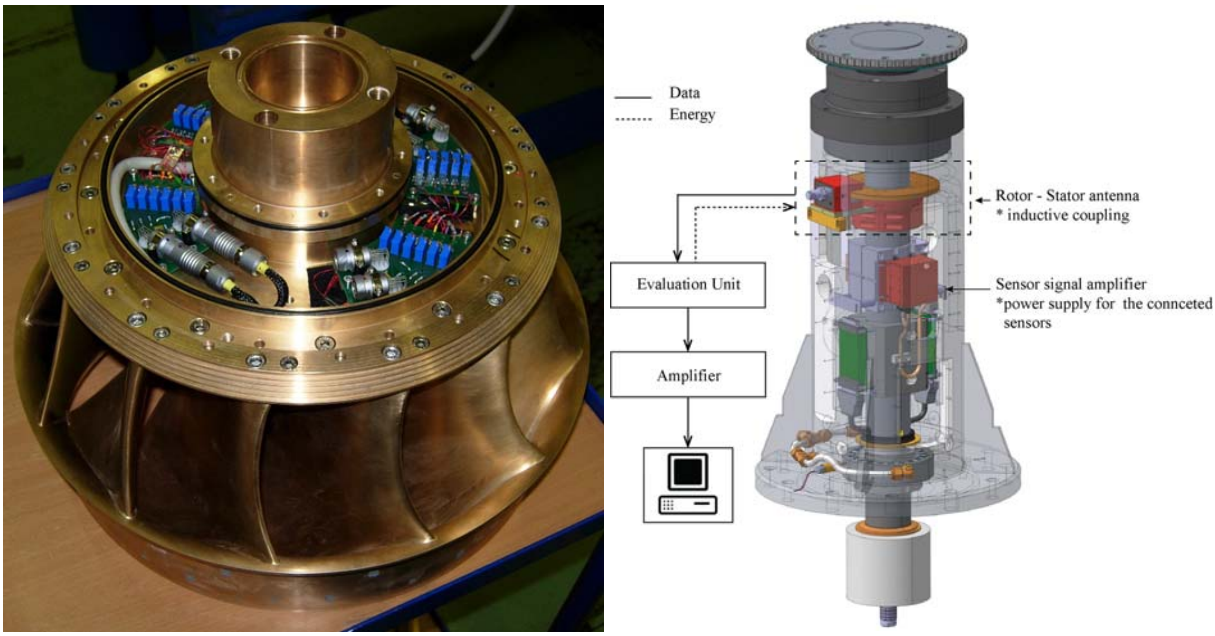

Fig 5. Instrumented Francis turbine runner with embedded pressure sensors and signal conditioners (left) adapted to the telemetry system embedded in the test rig bearing (right).

2.4 Transient tests requiring dedicated test rig instrumentation

One of the challenge to transpose fluctuating quantities measured at model scale to the prototype scale lies in the limitation of the geometrical homology to the hydraulic machine, while the hydraulic system of the test rig is not fully representative of the ones of the hydro power plant. Nonetheless, the model testing phase offers the opportunity to identify hydro acoustic parameters intrinsic to the tested model allowing the simulation of the prototype operation. Landry *et al.* [12] developed an excitation system dedicated to the measurement of the dynamic response of the hydraulic system and the decoupling of separate influence of the test rig and of the tested model.

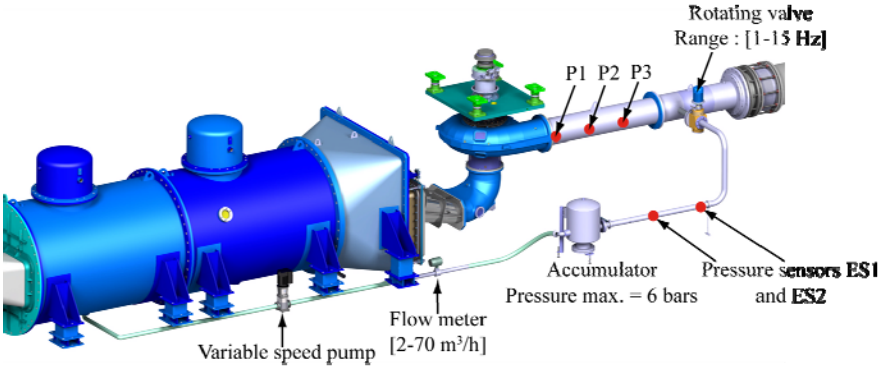

Fig. 6. CAD view of the developed excitation system and associated dynamic pressure sensors from [12].

The universal test rigs, as described in [IEC60193], are designed for the performance of test in steady state conditions. Meanwhile, the experimental investigation and the validation of quantities such as mechanical loads and pressure fluctuations in the hydraulic circuit under fast transient is likely to become of importance with respect to the demanding operating conditions experienced in hydropower plants. It is particularly the case for hydropower project with challenging ancillary services missions such as pumped-storage power plant with frequent and fast transition between pumping mode and generating mode.

The performance of such tests requires the control of timed trajectories for the machine operating parameters, such as guide vanes opening or rotating speed, while maintaining the external operating conditions of the test rig, such as the head, at targeted values representing the prototype operation. The measuring system shall also allow time recording of the signals. Therefore, evolutions of the test rig actuators, control system and data acquisition system are necessary. The work presented by Braun and Ruchonnet [13] illustrates the state-of-the-art capacities for reduced scale physical model transient tests.

3. Summary

3.1 Inventory of testing activities and their technological maturity

The activities described in the previous sections of this paper are summarized in the tab. 1. Activities beyond the usual scope of model testing campaigns as described in [1] require some dedicated features on the model or some specific equipment of the test rig, which are also detailed in the table. Finally, the technology readiness level (TRL) for each activity is estimated based on current state-of-the-art practices. Studies documented in the literature are proposed to the reader for further information.

Tab. 1. Summary of activities beyond the scope of international standards

Activities	Required model or test rig feature	TRL	References
Explicit hydraulic characteristic modelling	None	7	[4]
Prediction of stability based on swirl number	None or Optical access	5	[5]
Flow velocimetry survey with LDV	Optical access	8	[7, 8, 9]
Dynamic pressure measurement on runner blade	Instrumented blade and telemetry system	7	[10]
Mechanical load measurement on runner blade	Instrumented blade and telemetry system	7	[11]
Dynamic response investigation	External excitation system	6	[12]
Transient investigation, e.g. operating mode change	Advanced test rig actuators, control system and data acquisition system	5	[13]

3.2 Main limitations

In most of the cases, the measurement of the quantities of interest at model scale are technically and economically feasible. One of the main hurdle lies in the transposition of model quantities at the prototype scale. It is mostly related to:

- the sparsity of cases with available and published data at model scale and at prototype scale, allowing assessment of the transposition method;
- the difficulty to engineer and operate reduced scale physical models ensuring homology of the behaviour with respect to the prototype scale.

Collaborative research projects with public funding and published results are a great opportunity for the collection of comprehensive data and many of the works cited in this paper have been completed within the framework of such projects.

4. Conclusion

In many hydropower projects, the completion of the model acceptance test campaign lies on the critical path of the project and adding supplementary testing activities within the scope of guarantees verification would lead to operational constraints and delays not compatible with the objectives of the parties at stake. But after that milestone is reached, lower scheduling constraints and the availability of the reduced scale physical model leaves the opportunity to perform series of supplementary tests to feed the digital representations of the unit to be implemented to support its optimized operation.

This paper provides an overview of possible supplementary model test activities not covered by existing international standard. The value of the results to be provided through these supplementary tests has noticeably increased within the digital era for the operation of hydropower plants requiring in-depth knowledge of the unit behaviour. Nonetheless, the current state of the art shows that most of the presented activities forms a set of mature technological building bricks that still requires research and development activities to be associated to address the transition towards the digital turbine.

The active collaborations of all the actors of the hydropower world, including equipment manufacturers, electrical utilities and universities, through several past and future collaborative research project, is a promise of breakthrough enhancing the hydropower plant capacity to provide ancillary services, thus allowing higher penetration of renewable sources in the energy mix.

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