Innovative research on flow instabilities in hydropower turbines for the integration of new renewable energy

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１． 研究課題

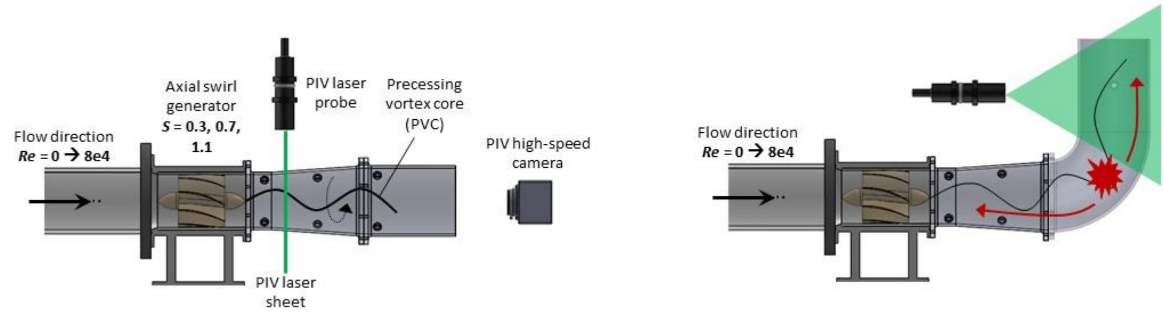
In the context of increasing electricity production by intermittent New and Renewable Energy (NRE) sources such as wind and solar, hydropower will play a crucial role in the power network by providing grid frequency control and balancing between electricity production and consumption. This, however, requires flexible operations of the hydropower units, notably the extension of their operating range to off-design conditions, where they are subject to dramatic flow instabilities putting at risk the system stability.

This research proposes to reach a better understanding of the physical mechanisms involved in draft tube flow instabilities and, in turn, to implement new optimized draft tube designs and flow control methods. An approach based on both fundamental and applied research is proposed. The fundamental physics of the turbine flow is investigated on simplified test-cases and the new gathered methodologies for the optimization of turbine design and flow controls will be finally applied to an actual Francis turbine model and then to industrial projects in collaboration with Japanese hydro equipment manufacturers and hydropower utilities. This might represent an important milestone towards the safe operating range extension and flexible operation of hydropower units to fulfill with the new requirements of the electrical power network.

２． 主な研究成果

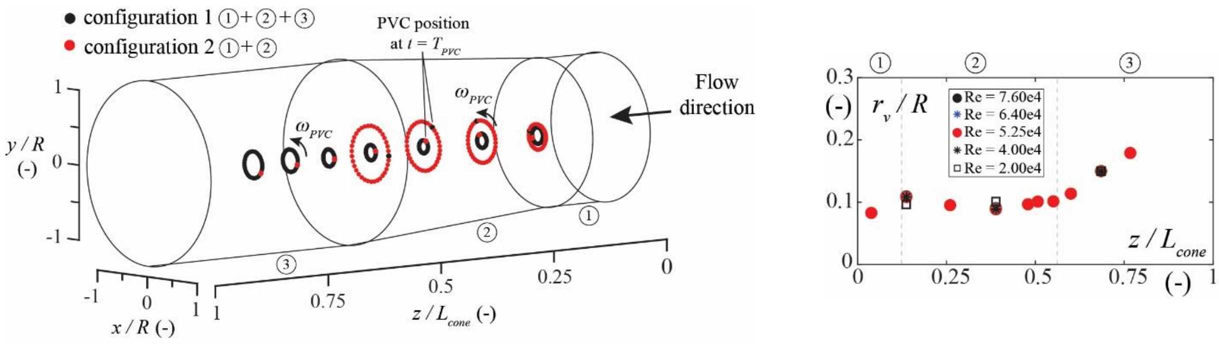
(1) Dynamics of the part-load vortex rope investigated on a simplified test apparatus

The swirling flow and associated unsteady flow structures observed in the draft tube of hydraulic turbines operating in part-load conditions, i.e. with $Q < Q_{design}$, are reproduced in a simple test apparatus using air as working fluid. The swirling flow is generated by axial swirl generators with fixed blades. The dynamics and coherent structure of the precessing vortex core (PVC) is investigated at several flow conditions, including variation of Reynolds and swirl numbers, in different pipe configurations by means of Particle Image Velocimetry (PIV), see Figure 1. The influence of the configuration of the pipes in the axisymmetric case (Figure 1a) on the structure of the PVC was first investigated. It is demonstrated that the Reynolds number does not influence the coherent structure and the stochastic behavior of the PVC at constant swirl number (Figure 2b) whereas an increase in the value of the swirl number induces an enlargement of the PVC trajectory and an increase of the helical vortex pitch. In addition, the pipe arrangement strongly influences the PVC trajectory and associated unsteadiness, as shown in Figure 2b. A shortening of the distance between the swirl device outlet and the pipe exit destabilizes the swirling flow and enhances the precession of the vortex core [3].



(a) Straight diffuser (b) Elbow pipe

Figure 1 Experimental set-up for PIV measurements downstream of a swirl generator in two pipe configurations



(a) Vortex trajectory in configurations 1 and 2 at S = 1.1 and Re = 5.25e4

(b) Influence of the Reynolds number on the vortex trajectory in the configuration 1 at S = 1.1

Figure 2 Influence of the pipe configuration and Reynolds number on the PVC trajectory

In a second configuration including an elbow (Figure 1b), the occurrence of a pressure-excitation source inducing synchronous pressure pulsations in the complete test rig has been highlighted, as observed in actual Francis turbines. The unsteady flow in the elbow is investigated by means of PIV to reveal the physical mechanisms responsible for the occurrence of this pressure excitation source. Two contributions might be involved: an unsteady force induced by the precession of the helical PVC in the elbow and unsteady pressure losses induced by a fluctuating flow separation at the elbow inner wall.

(2) **Prediction of hydropower unit stability by reduced scale model tests**

A collaboration between EPFL Laboratory for Hydraulic Machines (Switzerland) and Waseda University has been established for the prediction of hydropower stability. It aims at developing and validating the advanced modelling techniques for cavitation flows in the draft tube of hydraulic turbines at off-design operating conditions, enabling the prediction of hydropower units stability across a wide operating range independently of their layout.

A first experimental campaign on the reduced scale model of a Francis turbine installed in EPFL LMH was achieved in June 2019, including the hydroacoustic characterization and modelling of the cavitation flow over a wide range of operating conditions by means of modal analysis and high-speed visualizations. The experimental set-up and complete methodology are described in Figure 3. In particular, the dynamic behavior of a stable full-load cavitation vortex when excited at its first and second eigenfrequencies was investigated by means of high-speed visualizations. It is shown that the pulsations of the cavitation volume and associated pressure fluctuations reach a limit cycle beyond a certain value of excitation [2]. The results open promising development for the understanding and the modelling of full-load cavitation surge.

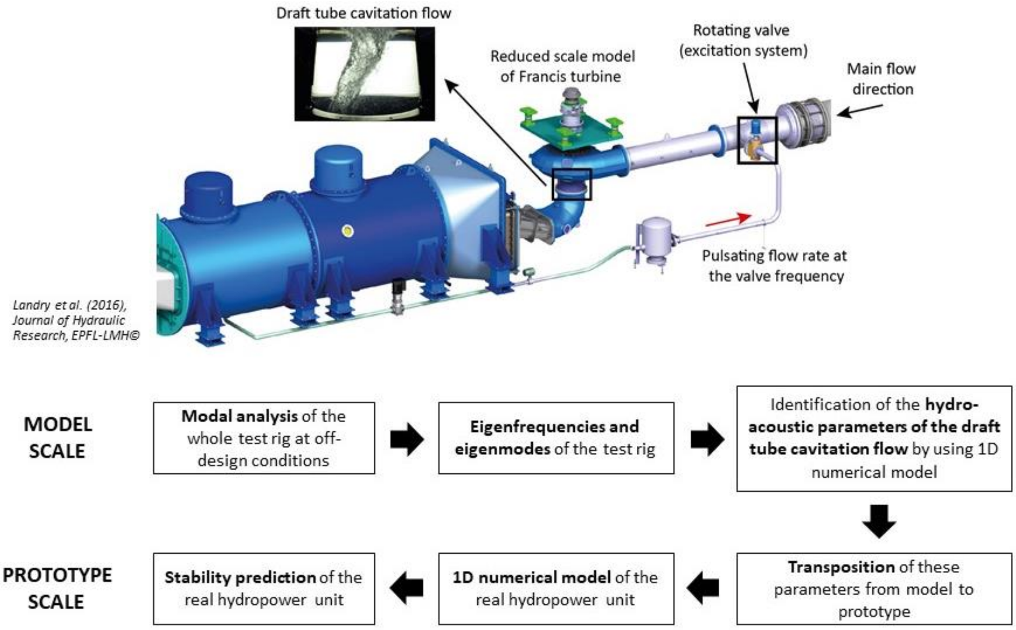


Figure 3 Methodology for the stability prediction of prototype hydropower unit based on reduced scale model tests and 1D modelling of the draft tube cavitation flow and hydraulic components

３． 共同研究者

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４． 研究業績

4.1 学術論文

[1] A. Favrel, Z. Liu, W. Takahashi, T. Irie, M. Kubo and K. Miyagawa (2019), *Visualization of the elliptical form of a cavitation vortex rope and its collapse by means of two cameras*, IOP Conference Series: Earth and Environmental Science, vol. 405 (8th IAHR Meeting of the Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems, Stuttgart, Germany)

[2] A. Favrel, E. Vagnoni, J. Gomes, A. Müller, M. Sakamoto, K. Yamaishi, F. Avellan and K. Miyagawa (2020), *Dynamic behavior of a full-load cavitation vortex in a Francis turbine draft tube excited at its eigenfrequencies*, to be presented at the 30th IAHR Symposium on Hydraulic Machinery and Systems, Lausanne, Switzerland

[3] A. Favrel, Z. Liu and K. Miyagawa (2020), *Influence of the flow conditions and downstream tubes arrangement on the dynamics of confined precessing vortex cores*, submitted to

Experiments in Fluids

4.2 総説・著書

4.3 招待講演

4.4 受賞・表彰

4.5 学会および社会的活動

- Consortium member of High-Performance Computing in Turbomachinery Society of Japan
- Member of the ISROMAC18 organizing and scientific committee
- Guest Editor of the ISROMAC18 Special Issue "Aeroacoustics of turbomachines" (Acoustics, MDPI)

５． 研究活動の課題と展望

In the future, two main aspects will be investigated by using a simple test apparatus reproducing draft tube flow instabilities and the reduced scale model of an actual Francis turbine. The findings and new developed methodologies will be then applied to industrial projects for further deployments at a large industrial scale.

(a) Optimization of draft tube design and active flow control methods

The influence of the geometry of the draft tube, including the diffuser and the elbow, on the vortex development and associated pressure pulsations will be investigated by means of both experiments and numerical simulations. As it would be costly to perform this investigation directly on a reduced scale model of a Francis turbine, the research will be first carried out on the simplified air draft tube test apparatus described in the present report and the final design(s) will be finally validated on a reduced scale model of a Francis turbine. In addition, active flow control methods promoting the stability of air swirling flows will be developed and optimized by using the simplified air draft tube test apparatus and will be then applied to the case of real draft tube flows in Francis turbines.

(b) Final validation of a methodology for the prediction of hydropower unit stability

In the framework of the collaboration between EPFL and Waseda University, a second experimental campaign on the same turbine model will be carried out at EPFL LMH in 2020. It aims at validating, on a different test rig than last year, the methodology of hydroacoustic characterization and the modelling of Francis turbines cavitation flow. It is expected that the results of this collaboration will enable the systematic application of the methodology during development and acceptance tests on a reduced scale model of hydro turbines in industrial projects.