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Design and Control of a New Hydraulic Test Rig for Small-Power Turbomachines

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Abstract

The University of Applied Sciences and Arts Western Switzerland – Sion (HES-SO Valais//Wallis) has installed in its hydraulic laboratory a new universal test rig to assess hydraulic performances of different types of small-power axial and radial-axial turbines and/or pumps (up to 10 kW), valves as well as other components of hydraulic systems. The IEC 60193 standard recommendations are implemented. The closed-loop hydraulic circuit is fed by three recirculating multistage centrifugal pumps (with variable speed), connected in parallel, that can deliver a maximum discharge of 45 m³/h and a maximum pressure of 160 mWC. The pressurized reservoir installed downstream the test section allows simulating different implantation levels of the model and therefore recovering the cavitation performances as well. The operation of the test rig is controlled with an automatic system through a customized Labview® interface that allows for real-time measurement and display instantaneous values of pumps speed, flow discharge, testing head, water temperature and Thoma number.

The main contribution of this paper is to introduce a state-of-the-art approach of an automatic regulation for test rigs. The full capabilities of a National Instruments cRIO-9074 are used to develop an autonomous regulation system based on real time measurements in order to keep constant the value of the desired parameters. In addition, a special care is put on the wireless communication architecture between the hydraulic test rig and further measurement/monitoring systems (e.g. testing model control system). Meanwhile, the test rig control system manages a dedicated cloud of variables and makes them available for client systems. Finally, such approach allows for safe data centralization, storage and sharing on model testing.

Keywords: test rig design, hydraulic turbomachines, small-hydro, smart wireless control, cloud of variables

Introduction

When addressing the design and the optimisation of hydraulic turbomachines, numerical simulation can be a relatively fast and cost effective mean to evaluate performances and to explore the flow hydrodynamics. To validate the simulation process, particularly in case of multiphase and unsteady flows, and to complete the final development of turbomachines, model testing in laboratory is still essential. The latest presents the big

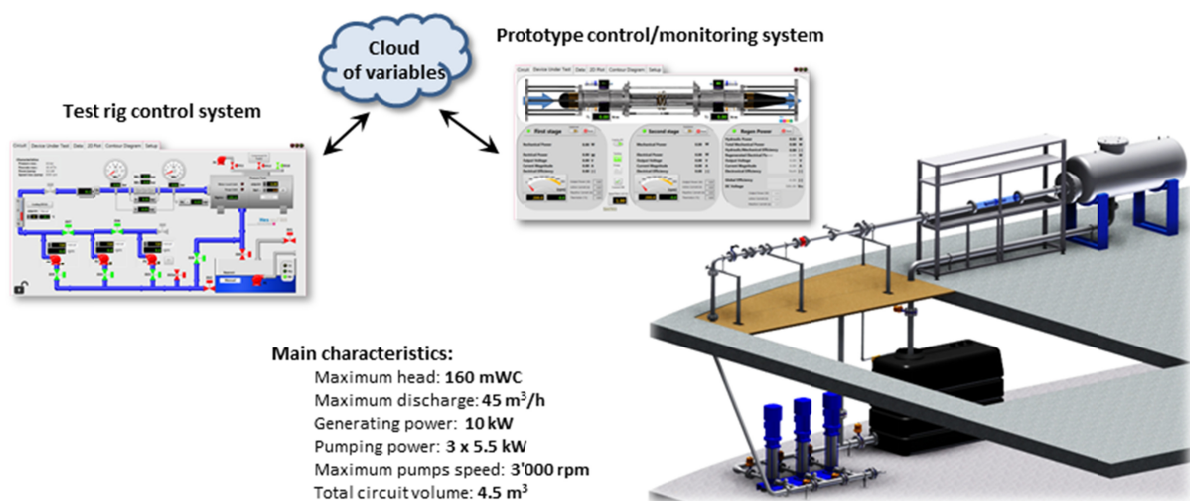


Fig. 1. New hydraulic test rig of the HES-SO Valais // Wallis – Sion, Switzerland.

advantage of allowing for high precision measurements necessary to predict the performances of hydraulic turbomachines in their whole prescribed operating range and beyond. Nevertheless, measurement precision and repeatability are capital.

As a proof of model testing importance, one may be stated that, on the one hand, all the main large-hydro manufacturers in the world detain hydraulic test rigs, dedicated to either action or to reaction machines (turbines and/or pumps), and actively maintain and update them. On the other hand, there are several academic laboratories dedicated to neutral certified performance testing and advanced experimental investigation, such as the testing hydraulic infrastructure of the Laboratory for Hydraulic Machines of the École Polytechnique Fédérale de Lausanne, Switzerland (Bovet and Henry [2]), or the one of the Institute of Fluid Mechanics and Hydraulic Machinery from the University of Stuttgart, Germany (Kirschner et al. [3]). Focusing on small-hydro energy production technologies (e.g. less than 50 MW power), the range of hydraulic turbine types goes often beyond the three classical shapes: Kaplan, Francis and Pelton. In this way, examples such as Deriaz diagonal turbine, swirl turbine, very low head (VLH) turbine, or even the Archimedean screw may be mentioned. Among these test rigs dedicated to small-hydro technologies, one may list here the MHyLab's (Switzerland) test rig, adapted for Pelton and diagonal turbines (Denis [4]), the test rigs of the Hydraulic Machinery Laboratory of Laval University, Canada, adapted for VLH turbines (Fraser et al. [5]) or for micro-turbines (Deschênes [6]). Moreover, test rigs adapted for performance measurements of specific hydraulic components of turbomachines, as the one built in the Hydraulic Machinery Department from the University "Polytechnica" of Timisoara, Romania, to investigate the flow development in draft tube cones of Francis turbines (Bosioc et al. [7]) comes to complete this various list.

The main parameters necessary to retrieve the hydraulic performance of a turbomachine are the specific energy E , the discharge Q , the rotational speed of the runner/impeller n , the main torque at the runner shaft T_m and the pressure at the low side of the machine. With these measured parameters, the E - Q operating range along with the corresponding hydraulic efficiency and the cavitation behaviour are calculated. In addition, measurements of the runaway characteristic, different loading forces (either on the runner or on the guide vanes), pressure fluctuations and observations on the draft tube vortex rope development come to complete a typical set of tests (Jacob [8]). Finally, the dimensionless characteristics (e.g. using the discharge-energy coefficients ϕ - ψ , or the speed-discharge factors n_{ED} - Q_{ED} , etc.) retrieved on the reduced-scale model present the advantage of being valid for the target prototype as well, with the condition of respecting both the geometric and hydraulic similitude laws. When dealing with micro-power turbomachines, the testing may be often performed directly at prototype scale.

The present work comes first with a detailed description of the hydraulic circuit and its main capabilities. The electrical circuit is addressed as well. The instrumentation and the specific working philosophy of the automatic regulation system are then introduced. Finally, a short description of a fully-equipped laboratory prototype, consisting of a new axial counter-rotating turbine to recover the energy lost in release valves of water supply, already installed and tested on the hydraulic test rig, is provided along with its resulting characteristic curves.

1. Main characteristics of the test rig

1.1 The hydraulic circuit

Built on two floors of the HES-SO Valais/Wallis hydraulic laboratory (see Fig. 1), the closed-loop hydraulic circuit, schematically illustrated in Fig. 2, is supplied with fresh water from a main reservoir R_1 of 3 m³. The latest is fed from the drinking water system, whilst an immersed centrifugal pump P_4 ensures its drain. Its volume has been selected as 2 times the total volume of the closed-loop circuit (including the R_2 reservoir). Then, 3 recirculating multistage centrifugal pumps $P_{1,2,3}$ (with variable speed and a power of 5.5 kW each), connected in parallel, supply the circuit with hydraulic power. The pumps can deliver a maximum discharge of 3x15 m³/h and a maximum pressure of 160 mWC. The testing variable-speed model T/P, with a power of maximum 10 kW, is installed in an accessible position (in terms of instrumentation, operation and observations) in the upper part of the circuit. Finally, the pressurized reservoir R_2 placed downstream the test section allows simulating different (positive and negative) implantation levels of the model and therefore determining the cavitation performances as well. This free-surface reservoir has been designed to support both vacuum and high pressure (up to 8 bars), whereas its volume of 1 m³ has been chosen as 2 times the volume of the remaining closed-loop circuit.

To complete, more solenoid valves $EV_{2..9}$ (of butterfly type) are used to control the hydraulic circuit configuration. Several other valves, either solenoid or manual, are used for filling, cooling, spillway, control, security and operation of the test rig. In addition, the installed honeycomb sections ensure a uniform axial flow upstream the flowmeter and the testing model. The rest of uncounted additional components may be retrieved in the full list of main hydraulic components and their functionalities in Table 1.

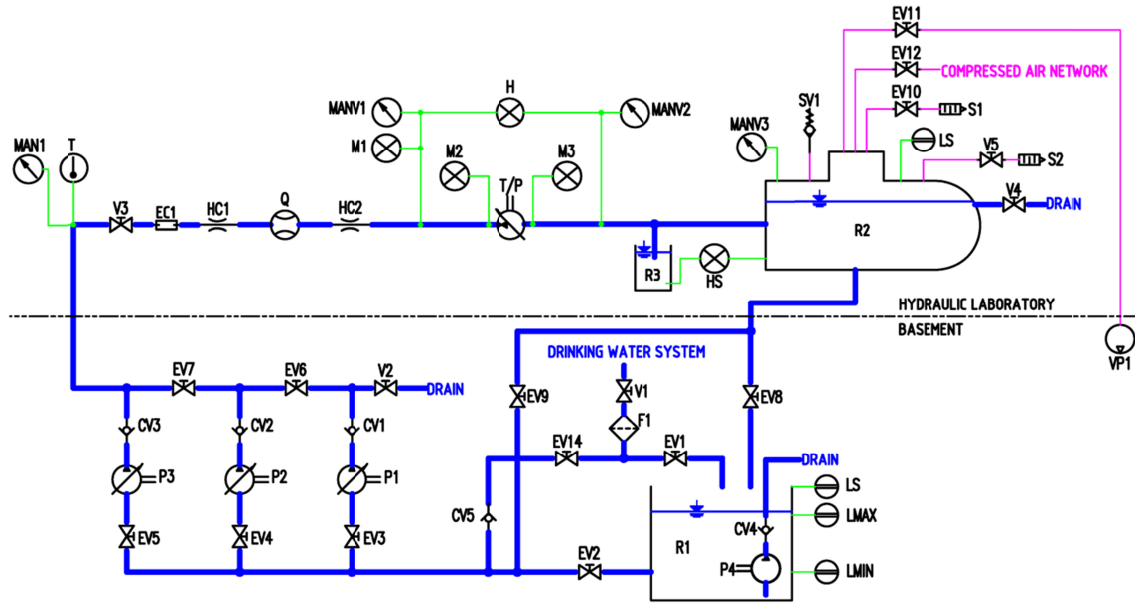


Fig. 2. Schematic representation of the hydraulic circuit.

Table 1. Main hydraulic components of the test rig and their functionalities.

Acronym	Component	Functionality
R ₁	Main reservoir	Supply the test rig with water
F ₁	Filter	Water filter
EV ₁	Solenoid valve	Control the water supply from the drinking water system
P ₄	Centrifugal pump	Drain the main reservoir
CV ₄	Check valve	Ensures unidirectional flow toward drain
P _{1,2,3}	Centrifugal pumps	Supply the circuit with hydraulic power
CV _{1,2,3}	Check valves	Ensure unidirectional flow in turbine mode operation
T/P	Turbine/Pump	Variable speed reduced-scale testing model
EV _{2,3...9}	Solenoid valves	Control the hydraulic circuit configuration
EV ₁₄	Solenoid valve	Control the fresh water supply for cooling
CV ₅	Check valve	Ensures unidirectional flow during cooling
EC ₁	Expansion compensator	Ensures axial direction flexibility for the testing model assembly
HC _{1,2}	Honeycomb sections	Ensures uniform flow upstream the flowmeter and the testing model
R ₂	Pressurised reservoir	Allows simulating different positive or negative implantation levels
EV _{10,11,12}	Solenoid valves	Control the air pressure into the pressurised reservoir
VP ₁	Vacuum pump	Supply the pressurised reservoir with vacuum
SV ₁	Safety valve	Protect the pressurised reservoir from excessive pressure
S _{1,2}	Silencers	Silencers for pressurised air drain
R ₃	Level reservoir	Water reservoir for the zero implantation level of the testing model
V _{1,2,...}	Manual valves	Security and control for filling, spillway and operation of the test rig

1.2 The electrical circuit

The schematic representation of the associated electrical circuit of the test rig is provided in Fig. 3. The electrical control cabinet along with its front panel are illustrated as well. The electrical box is supplied with 3x400 VAC. Then, the supply of the test rig components is split in 3 types: 3x400 VAC used to power the driving electrical motors of the P_{1,2,3} recirculation pumps; 1x230 VAC used to power the drain pump P₄, the vacuum pump VP₁ as well as the solenoid valves; 24 VDC used to power the small solenoid valves and particularly the automatic regulation system and the measurement instruments. On the one hand, the front panel is split in four main regions dedicated to: manual control of the hydraulic circuit configuration through the solenoid valves state (green); manual recirculating pumps power on (yellow); manual drain pump power on (cyan); manual vacuum pump power on (purple). On the other hand, the electrical box is organised in 5 main regions including the safety electrical devices, the relays, the 24 VDC supply, the NI Compact RIO automatic regulator and the terminals.

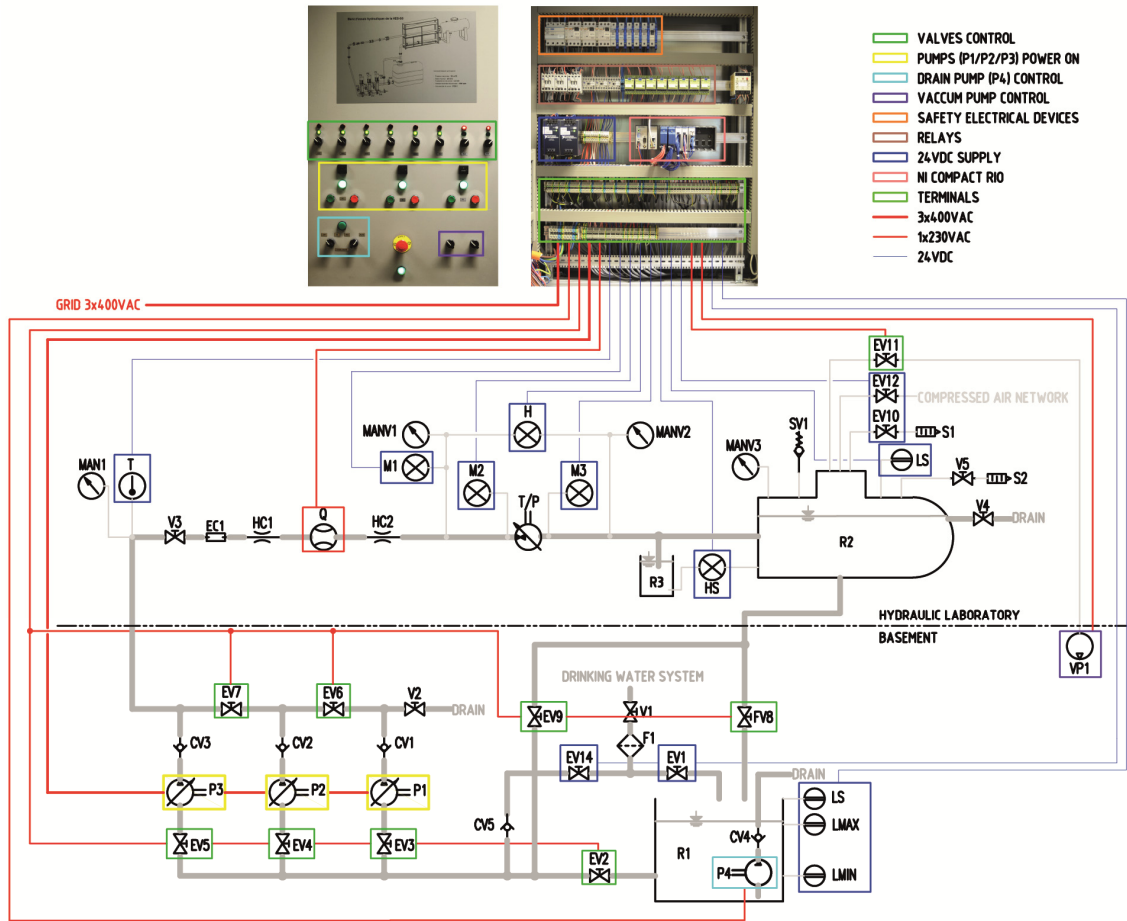


Fig. 3. Schematic representation of the electrical circuit.

2. Instrumentation

The test rig is equipped with several measurement instruments with the aim of recovering the full testing conditions and particularly the hydraulic power of the testing model. The characteristics of the main measurement instruments that equip the test rig are provided in Table 2, including the output signal type, measurement range and absolute error. Their position on the hydraulic circuit may be observed in Fig. 2. The discharge Q is measured with the help of an electromagnetic flowmeter. The head H and the implantation level H_s are measured with differential pressure transducers, whilst the static pressure at the wall $M_{1,2,3}$ is measured with capacitive absolute pressure transducers. The temperature T is retrieved with the help of a PT100 transducer. Then, the rotational speed of the recirculating pumps $n_{\text{pump}1, 2, 3}$ is measured using optical tachometers, and vibrating tuning fork detectors are used for the minimum, maximum and security water level $L_{\text{min, max, s}}$ measurements. Finally, the manometers and the manovacuumeters are used as visual indicators for the test rig operator.

In Fig. 4, the measured calibration curves and the absolute error for the two differential pressure transducers, dedicated to acquire the head H and the model implantation level H_s (necessary for the calculation of the Thoma

Table 2. Characteristics of main measurement instruments.

Acronym	Measured/displayed quantity	Output signal	Range	Precision
Q	Discharge	4..20 [mA]	0..50 [m ³ /h]	± 0.5 [%]
H	Head	4..20 [mA]	0..16 [bar]	± 0.1 [%]
H_s	Implantation level	4..20 [mA]	0..5 [bar]	± 0.2 [%]
$M_{1,2,3}$	Absolute static pressure	4..20 [mA]	0..10/20 [bar]	± 0.05 [%]
T	Temperature	4..20 [mA]	0..100 [°C]	± 0.1 [%]
$n_{\text{pump}1, 2, 3}$	Rotational speed	24 [V] pulse	0..1000 [Hz]	-
$L_{\text{min, max, s}}$	Min, max & security levels	24 [V]	on/off	-
Man_1	Relative static pressure	-	0..16 [bar]	± 1 [%]
$MV_{1,2,3}$	Absolute static pressure	-	-1..9/15 [bar]	± 1 [%]

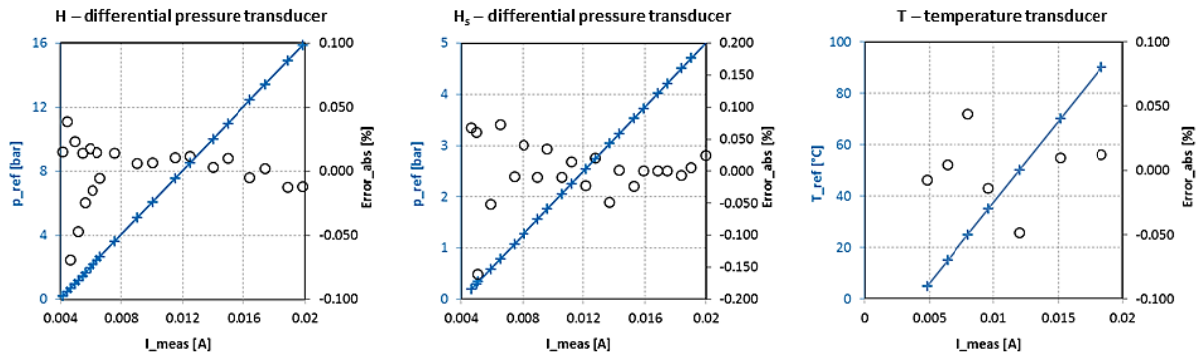


Fig. 4. Measured calibration curves and the absolute error for the two differential pressure transducers (H and H_s) and the temperature transducer (T).

number), and for the temperature transducer are provided. The reference values are obtained with a high precision deadweight reference pressure sensor, HAENNI M 1900/2, and respectively a high precision reference temperature sensor, Jofra D 55 SE. At the end, the sensors constant calculation (in [Engineering Units / mA]) has been done using a linear regression fit (see Hasmatuchi [9]).

3. Automation and control

3.1 The controller

The full capabilities of a National Instruments cRIO-9074 (see Fig. 5) are used to develop an autonomous regulation system based on real time measurements in order to keep constant the value of the desired parameters (e.g. testing head, discharge, pumps speed, Thoma number, etc). The latest is actually an integrated system that combines a 400 MHz industrial real-time processor and a 2M gate, 8-slot, Reconfigurable Field-Programmable Gate Array (FPGA) within the same chassis. Equipped with two Ethernet ports, it allows for programmatic communication over the network.



Fig. 5. NI cRIO-9074 [10] automatic controller and the managed test rig I/O variables.

Five modules are selected to fit the deployed sensors and relays:

- NI 9425, a 32-Channel Digital Input Module employed to retrieve the state of the level sensors, leakage detection, solenoid valves and emergency stop buttons.
- NI 9477, a 32-Channel Digital Output Module used to set the state of the recirculating pumps, drain pump, vacuum pump, solenoid valves for water supply, cooling and pneumatic control of the pressurised reservoir, etc.
- NI 9203, a 8-Channel Analog Current Input Module used to acquire signals from the flowmeter, pressure and temperature sensors.
- NI 9265, a 4-Channel Analog Current Output Module used to control the rotating speed of the recirculating pumps.
- NI 9411, a 6-Channel Digital Input Module suited for high-speed pulse counting, used to measure the rotating speed of the recirculating pumps.

3.2 The system architecture

A special care is put on the wireless communication architecture (see Fig. 6) between the hydraulic test rig and further measurement/monitoring systems (e.g. testing model control system). The implemented specific network architecture is based on LabVIEW™ 2013. The main goal behind this architecture is to provide robustness and modularity to the automatic regulation system. The Shared Variable Engine (SVE) running in the controller collects values from different acquisition systems and makes them available to every local or remote client. Such approach allows for safe data centralization, storage and sharing. The networking implementation is actually entirely handled by two network-published variables: cRIO-R, dedicated to monitoring issues and written only by the controller and read by the client; cRIO-W, dedicated to control issues and written by the client and read by the controller. Furthermore, an implemented specific looping-structure enhances the system performance and reduces the network traffic.

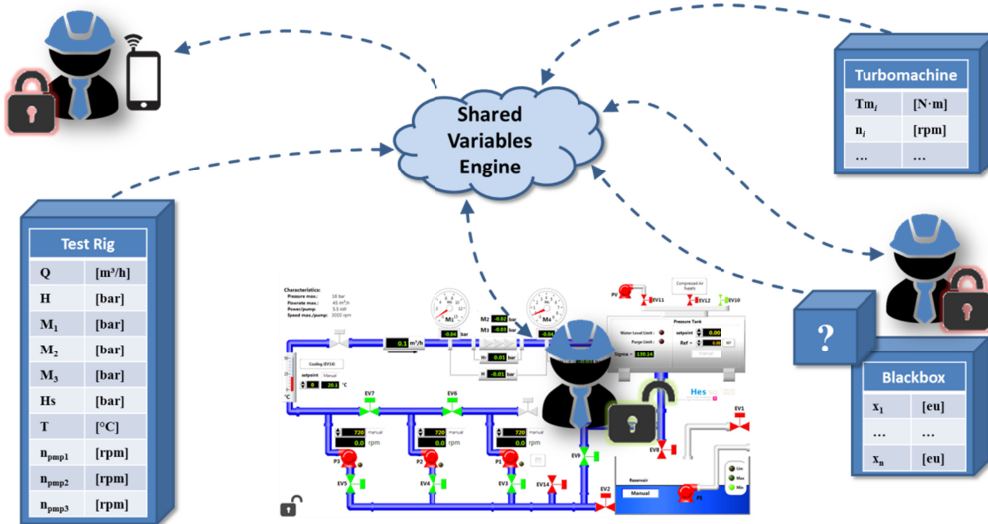


Fig. 6. Schematic representation of the test rig multi-user control system architecture.

3.3 The software structure

The control and monitoring software is created through a standard LabVIEW project. The latest consists of two main blocks: one for the controller (NI cRIO-9074) and other for the remote device (client). The structure of the project is based on a 3-level architecture in which software applications of different levels are responsible for assigned tasks and run on their corresponding hardware targets. The 1st level application is the high-level interface with the client, i.e. the Human-Machine Interface (HMI). It performs tasks such as setting control parameters, editing configuration values, monitoring the sensors and managing the performance tests. This module runs on the host PC. The 2nd level application manages in real-time the reservoir and the vacuum tank controls and adjusts the signal to drive the recirculating pumps using Proportional-Integrate-Derivative (PID) algorithms. This module runs on the real-time controller at CPU level. The 3rd level application is delegated to the Scan Interface, being responsible for data buffer and data I/O with the NI C Series I/O modules. The latest runs on the FPGA chip.

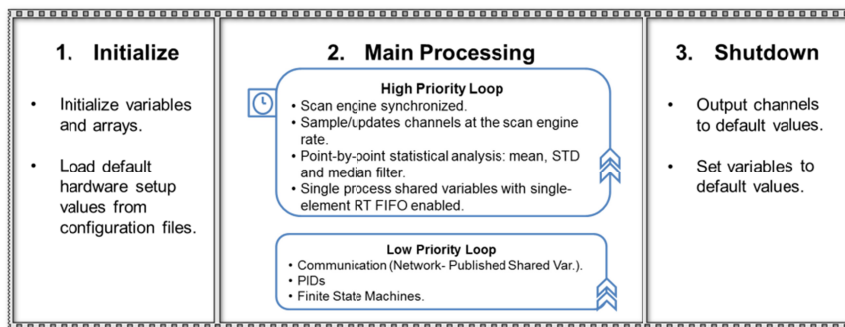


Fig. 7. Main sequences of a real-time application.

Focusing again on the 2nd level application (the most important in the project), its design must be robust, simple, reliable and scalable. It is therefore developed in a three steps conventional sequence model (see Fig. 7) including: Initialization, Main Processing and Shutdown. During the first step, any component of the application that should have a precise state before operation is initialized with a default safety value. The default hardware setup is imported from a configuration file. The Network-Published Shared Variables (NPSV) are initialized as well. The Main Processing step consists of two while loops: High Priority (timed loop – synchronised to the scan engine running at the FPGA level) and Low Priority. Both of them start at the same time. The High Priority loop consists of reading from the input channels, performing basic statistical data conditioning (e.g. mean, STD, median filter) and writing to the output channels. The input-analysis-output process takes place continuously, in real time. The Low priority loop, slower than the High Priority one, can be adjusted according to the growing needs of the application. Its main duty is to handle network communication with the HMI and drive the Finite State Machines (FSM) dedicated to the automatic filling of the main reservoir, regulation of pressure level in the pressurized tank and regulation of the water temperature in the closed-loop hydraulic circuit. The control of the PIDs is also ensured. Finally, during Shutdown, every output channel is reset to the respective default safe value.

As already mentioned, the regulation of the recirculating pumps rotating speed has been implemented using a multi-loop PID control. Three different parameters are allowed to fix their set point: rotating speed, head and discharge. Specific conditions are considered for bumpless transitions among parameters and between manual and automatic driving. PID gains can be further adjusted, depending on the desired system response speed and, not in the end, on the system stability. The maximum and minimum values for the controlled variable and hysteresis tolerance defining an inactive interval are considered as well. Finally, the initial calibration of the PID coefficients, for each pump, is performed using the step response Ziegler-Nichols method [11].

3.4 The Human-Machine Interface (HMI)

The full client application (1st level) is conceived to be executed from a remote device. It is developed in the same three steps conventional sequence model. In this case, the Initialization consists of several functions: initialization of variables, data arrays, SVE communication and table, and preparation of 2D and 3D plots. The default software and hardware setup is loaded from a configuration file. The Main Processing step includes two while loops: a general event based loop and the testing model dedicated loop. The two loops start in the same time but are not synchronised. The events are mainly used to manage the HMI (see Fig. 8), to manipulate data and to handle the communication with the controller (through the NPSVs). Moreover, a NI cDAQ-9174 system, physically connected to one of the remote clients, is used to control and monitor specific parameters of the testing model. Finally, during Shutdown, the output channels are set to a safe value, in particular those related to the testing model.

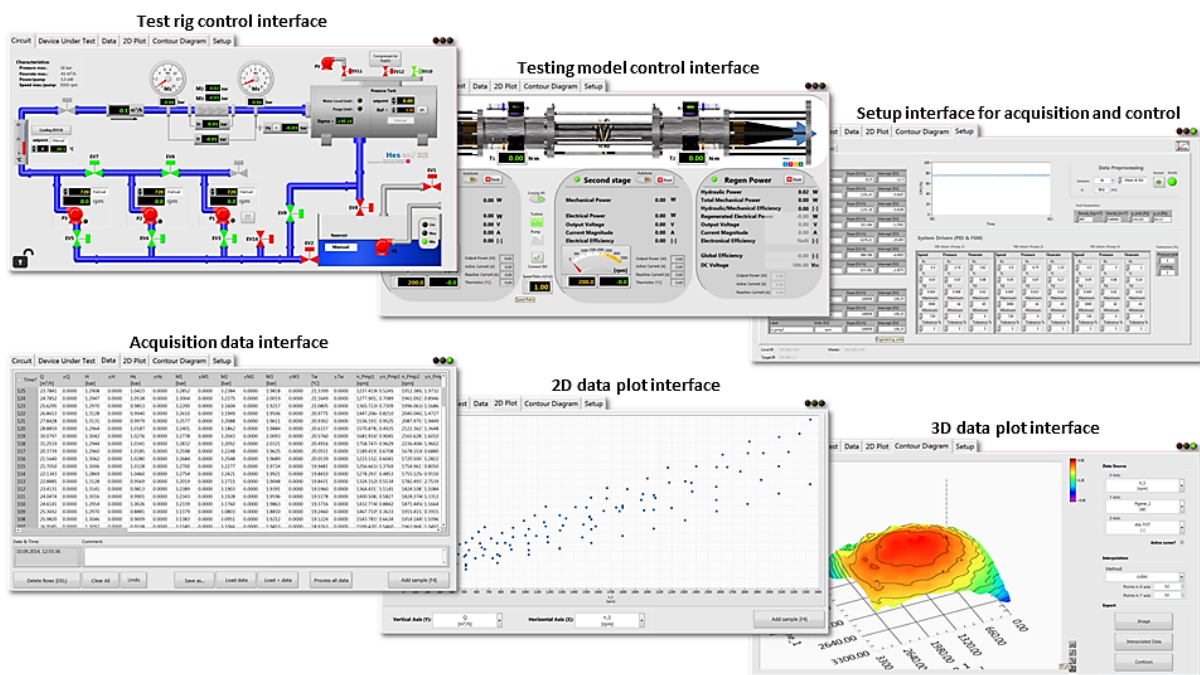


Fig. 8. Human-Machine Interface for the control of the test rig and the testing model.

4. Example of measured characteristics

In the framework of the Hydro VS applied research project, in collaboration with the Laboratory for Hydraulic Machines from École Polytechnique Fédérale de Lausanne - Switzerland, a new axial counter-rotating turbine for small-hydro applications has been developed to recover the energy lost in release valves of water supply networks (Münch-Alligné et al. [12], Hasmatuchi et al. [13]). A fully instrumented laboratory prototype of the in-line bulb version microturbine has been installed in the test rig (see Fig. 9). This prototype version presents the advantage of visual access for flow visualizations and even velocity measurements. The main drawback comes from its complex mechanical system and sealing, including the magnetic mechanical coupling and the ceramic hydrodynamic bearings.

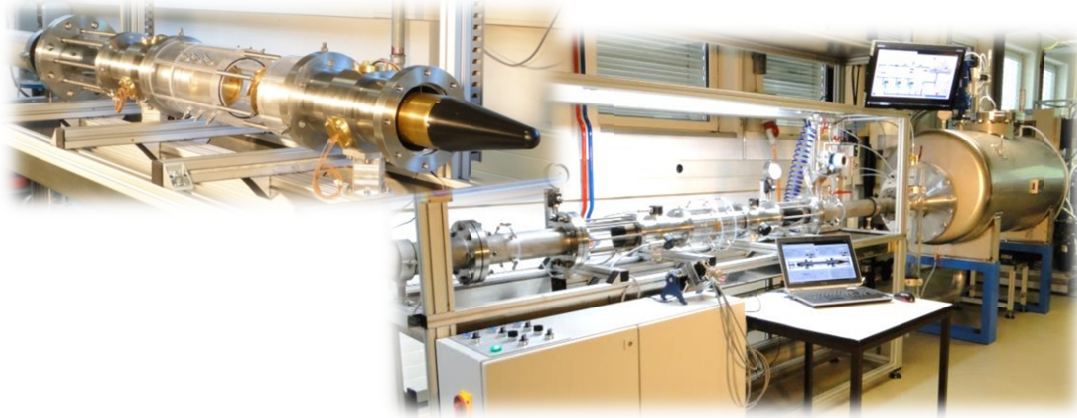


Fig. 9. Axial counter-rotating micro-hydro turbine installed in the test rig.

The one-stage variable speed turbine is composed by one upstream 5-blade runner followed by one counter-rotating downstream 7-blade runner. The turbine inner diameter is 80 mm, whereas the outer diameter is 100 mm. The total length of the prototype is 1.5 m. The turbine is designed to provide about 2.65 kW for a discharge of 37.5 m³/h and a head of 29.9 m. A best efficiency of 85% is reached by numerical simulation for a ratio $\alpha = 1$ between the runners absolute rotational speed. The regulation of the turbine beyond the best efficiency point is ensured by changing the relative rotational speed between the two runners.

In addition to the measurement instrumentation already contained on the test rig (necessary for the hydraulic power) each of the two runners of the microturbine prototype is equipped with an angular encoder and a torquemeter necessary for the driving of the electrical generators (Melly et al. [14]) and, of course, for the computation of the mechanical power. The NI cDAQ-9174 system, attached to the remote client service, ensures the communication of the desired rotational speed values to the additional driving system and allows for mechanical power measurements.

The resulting operating characteristics of the prototype at constant test head are provided in Fig. 10. The measured 3D hill-chart in n_A - n_B - η_{exp}^* is provided on the left side. The n_A and n_B represents respectively the absolute rotational speed of the first and of the second runner. The efficiency is scaled with the maximum value of measured efficiency. On the right side, the dimensionless efficiency contour is represented along with the speed n_{ED_B} and discharge Q_{ED_B} factors of the second runner (see their definition in IEC [1]). Finally, isolines of constant rotational speed ratio between the two runners shows an optimal efficiency operation for $\alpha = 1/0.85 \div 0.85$.

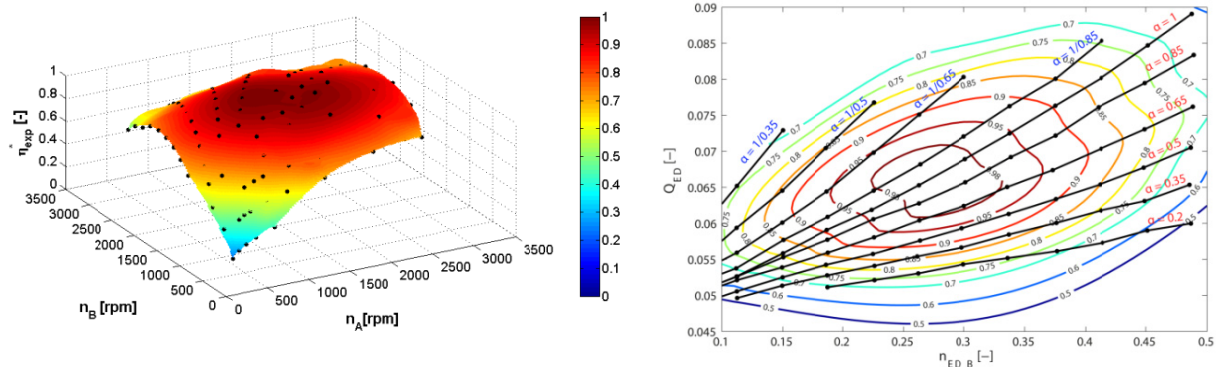


Fig. 10. Measured 3D and 2D hill-charts of the counter-rotating microturbine at constant testing head.

Conclusions

A new universal test rig to assess hydraulic performances of different types of small-power axial and radial-axial turbines and/or pumps (up to 10 kW), valves as well as other components of hydraulic systems has been introduced. The test rig is installed in the hydraulic laboratory of the University of Applied Sciences and Arts Western Switzerland - Sion (HES-SO // Valais-Wallis). It has been designed following the IEC [1] standard recommendations. Built on two floors of the hydraulic laboratory, the closed-loop hydraulic circuit is supplied by three recirculating multistage centrifugal pumps (with variable speed and a power of 5.5 kW each) connected in parallel. The three pumps can deliver a maximum discharge of 45 m³/h and a maximum pressure of 160 mWC. The pressurized reservoir placed downstream the test section allows simulating different implantation levels of the model and therefore recovering the cavitation performances as well. The operation of the test rig is controlled with an automatic system through a customized Labview® interface that allows for real-time measurement and display values of pumps speed, flow discharge, testing head, water temperature and Thoma number.

The present work introduces a state-of-the-art approach of an automatic regulation for test rigs. The full capabilities of a National Instruments cRIO-9074 are used to develop an autonomous regulation system based on real time measurements in order to keep constant the value of the desired parameters (e.g. testing head, discharge, pumps speed, Thoma number, etc). In addition, a special care is put on the wireless communication architecture between the hydraulic test rig and further measurement/monitoring systems (e.g. testing model control system). Meanwhile, the test rig control system manages a dedicated cloud of variables and makes them available for client systems. Such approach allows for safe data centralization and storage on model testing.

Perspectives

Despite the fact that the measurement system of the test rig exhibits acceptable accuracy and repeatability, an improvement of the measurement precision remains always desirable. It has been observed during the measurements on the presented example that the main uncertainties were induced by different interferences caused mainly by the encapsulated bulb generators and their driving system. A median filter has been successfully deployed on the measured signals to cope with this phenomenon. Anyway, the elimination of the interferences in the future would be preferable.

Concerning the data acquisition, the synchronisation of the existing static measuring system with an additional dynamic acquisition system and even with a high-speed visualisation system is scheduled. This operation should allow for advanced hydrodynamic analysis of different phenomena developing in the turbine, including flow separation, tip vortex dynamics and cavitation. Moreover, such a system could also be employed in the optimisation process of the hydraulic profiles of the machine.

In the end, the use of a dynamic measurement method of the testing model characteristics, as the sliding gate method (Abgottspon and Staubli [15]), could be very interesting, compared to the classical static measurement method, especially in terms of time costs. However, the required initial effort necessary to the implementation and the validation of such a dynamic measurement method may be considerable.

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In the end, the authors would like to address a special thank to the Fluid Automation Systems (Switzerland) industrial partner for its donation, consisting in several hydraulic components and measuring instruments used as base for the construction of the current test rig.

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