Automated hill chart modeling procedure to estimate the performance of double-regulated units

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Abstract

The work presented in this paper details an original procedure developed in order to automatically build on-cam surfaces for double-regulated hydropower units such as Kaplan or bulb turbines. The proposed method allows a sparse exploration of the operating domain to identify cam points of the machine. The automated approach enhance the reliability of performance hill charts obtained from simulation or model testing. The software implementation of the method is described, together with its application to the case of Priest Rapid hydropower plant.

1. Introduction

1.1. Performance hill chart

The performance of hydropower stations have always been characterized by the efficiency it can achieve in converting the hydraulic power into electrical power. Nonetheless, in the current liberalized energy market, modern stations should still reach a high efficiency, but they should also provide an enhanced operational flexibility. An extended operation range is a key to meet electricity market demand. Flexibility in operation also enables high levels of variable renewable energy [1, 2].

Therefore, it is of prime interest to establish a complete mapping of a hydropower unit performance on its entire operating domain. This is usually represented thanks to iso-value curves called hill chart as represented in Figure 1 where the efficiency is plotted as a function of the discharge coefficient Q_{ED} and of the speed coefficient n_{ED}.

On top of plotting the efficiency on the operating domain, the control of hydropower units usually requires models of its behavior, such as the ones reviewed in [3]. It can be generally formulated using the expression given in(1), where the x_i are operation parameters such as the guide vanes opening for instance.

$$\eta = f(x_1, x_2, \ldots, x_n) \tag{1}$$

The graphical representation of Figure 1 and the formulation of (1) are equivalent and relation of the type of (1) are later referred to as *hill chart model*.

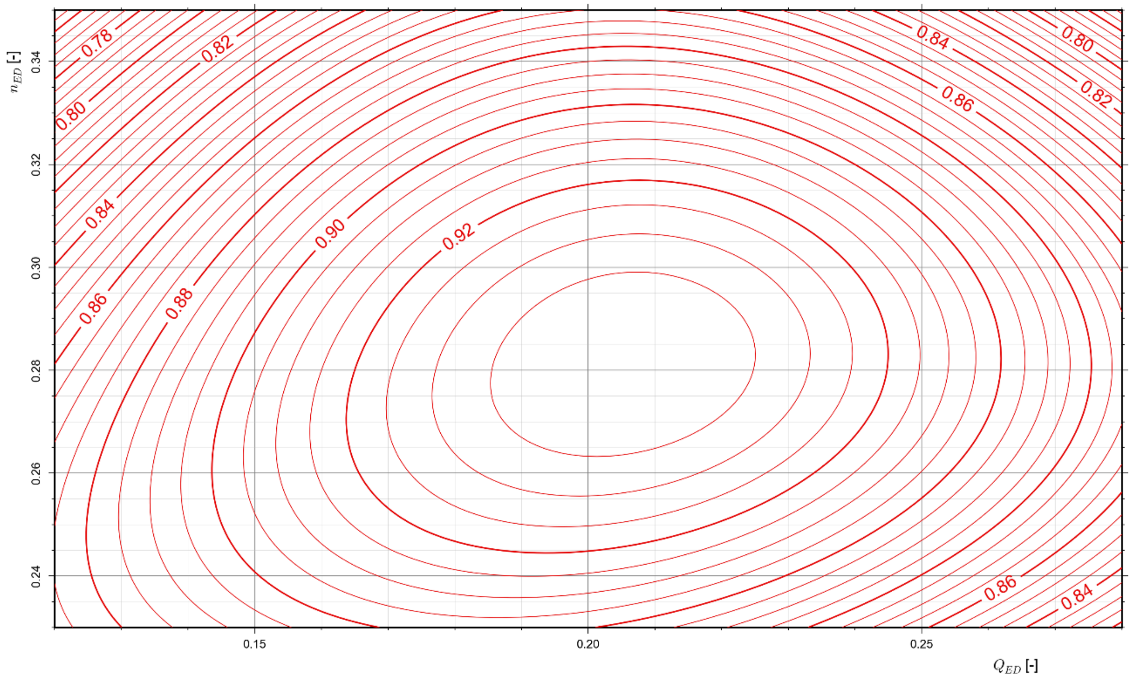

Figure 1: Hill chart of a hydropower unit representing iso-value curves of the efficiency over the operating domain as a function of the IEC discharge factor Q_{ED} and IEC speed factor n_{ED}.

1.2. Performance of double-regulated units

In the case of double regulated hydraulic machines such as Kaplan turbines depicted in Figure 2, one operating point with a given discharge at a given head can be reached with several combinations of guide vanes opening angle α and blade pitch angle β. The conjugated, or on cam – point is the one for which output mechanical power – and the efficiency – is maximum.

The usual strategies to identify the conjugation law of a unit requires a broad experimental investigation through model testing in order to manually identify on cam points or interpolate cam curves [4,5]. Finally, an interpolation must be performed to estimate the efficiency hill chart of the machine on its entire operating domain.

1.3. Proposed methodology

This paper describes a mathematical procedure to automatically identify the cam curves out of the result of an experimental campaign. It includes guidelines for an optimal definition of the experimental points. The efficiency hill chart of the machine is directly built on its entire operating range. It provides both the ability to estimate the machine performance for various operation scenarios and the conjugation map between the guide vanes opening angle and the blade pitch angle over the operating range.

The developed procedure is applied to a 200 MW Kaplan unit from a world-class hydropower station. Efficiency hill chart models are built for the original unit and from the one installed during the rehabilitation. The expected increase of energy production after the rehabilitation is estimated thanks to the modelled hill charts.

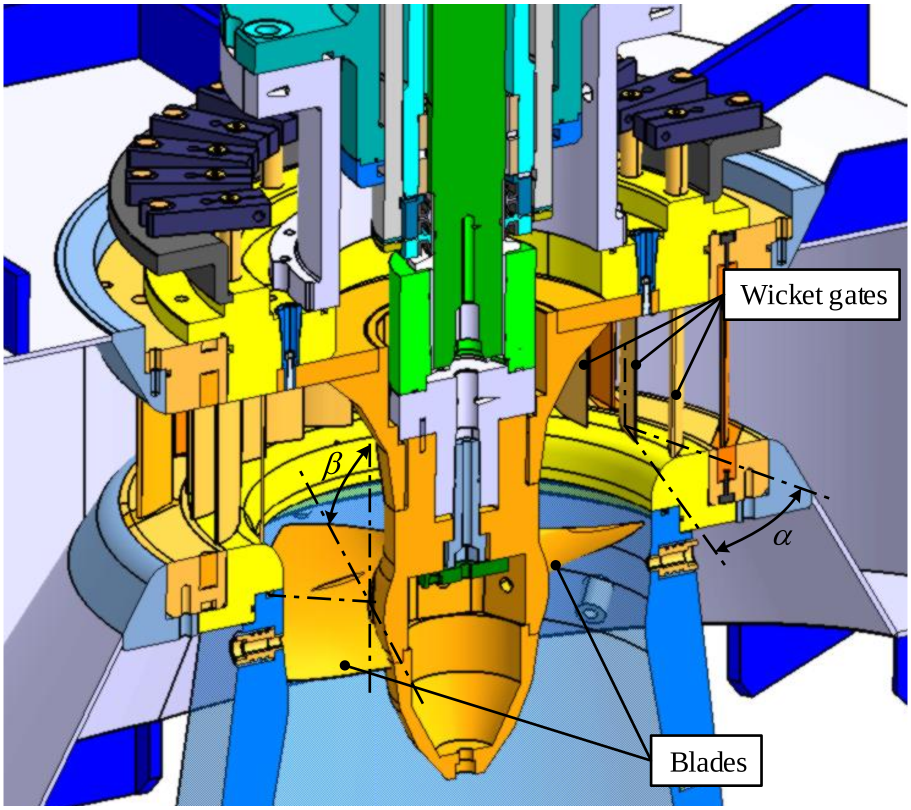

Figure 2: Half-view of a Kaplan turbine with the controllable guide vanes opening angle α and blade pitch angle β .

2. Proposed automated procedure

2.1. Description of the procedure

While operating, the net head H available to the hydropower unit cannot be freely controlled by the operator. Only the guide vanes opening angle α and the blade pitch angle β can be regulated to adapt the discharge Q in the turbine to reach a targeted converted mechanical power P_m . During the experimental campaign, measurements are conducted at several fixed head levels for which the cam curves are identified. These cam curves at constant head are finally used to build global performance model and an associated cam surface on the unit operating domain, as summarized in Figure 3.

The method proposed to automatically identify a set of on-cam points at each constant head level rely on a functional modeling method explained in subsection 2.2. The actual search for on-cam point is detailed in subsection 2.3. Then, a global model of the performance of the machine using the same functional modeling technique is explained in subsection 0.

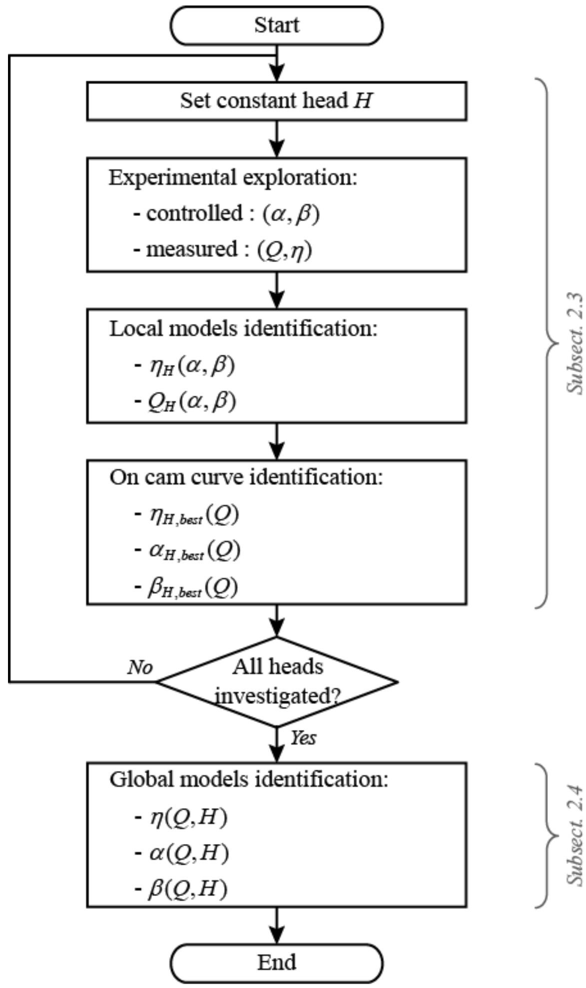

Figure 3: Flowchart of the proposed procedure

2.2. Functional modelling

A model testing campaign is assumed to be achieved in order to gather measurements of the performance p of the unit at N operating points for which the operation parameters $x_1, x_2, \ldots, x_n$ are recorded.

The method proposed in this work rely on a global functional modeling approach that yields a model p^* of the unit performance as a function of the operation parameters. The model p^* is a Hermite polynomials interpolation [6] that minimizes the distance ε from (2).

$$\varepsilon = \sum_{i=1}^{N}\left(p^*\left({}^i x_1, \ldots, {}^i x_n\right) - {}^i p\right)^2 \tag{2}$$

2.3. Cam curve search at constant head level

For every given head H level to be investigated, the controllable parameters α and β are independently explored as illustrated in Figure 4. Then, models Q_H and η_H of the discharge and of the efficiency respectively are identified as functions of β and α, using the functional modelling approach described in the previous subsection. The iso-discharge curves in Figure 4 are also iso-hydraulic power curves, according to the definition of the hydraulic power P_h given in (3).

$$P_h(\beta,\alpha) = \rho \cdot g \cdot H \cdot Q_H(\beta,\alpha) \tag{3}$$

Thus, for any given discharge, the associated best cam point is obtained by searching the conjugated values of guide vanes opening and blade pitch angle that maximizes the converted mechanical power P_m, or as an equivalent the efficiency $\eta_H(\beta,\alpha)$.

$$P_m = \rho \cdot g \cdot H \cdot Q_H(\beta,\alpha) \cdot \eta_H(\beta,\alpha) \tag{4}$$

The best cam curve of Figure 5 and the associated blade pitch angle and guide vane opening angle result from solving the collection of optimization problem defined by (5) with Q_t varying in the range of discharge experienced at this head.

$$\left(\beta_{H,\text{best}}, \alpha_{H,\text{best}}\right) = \underset{Q_H(\beta,\alpha)=Q_t}{\arg\max} \quad \eta_H(\beta,\alpha) \tag{5}$$

The resolution of such a collection of optimization problem is straightforward with gradient-based methods thanks to the Hermite polynomials framework applied to model Q_H and η_H.

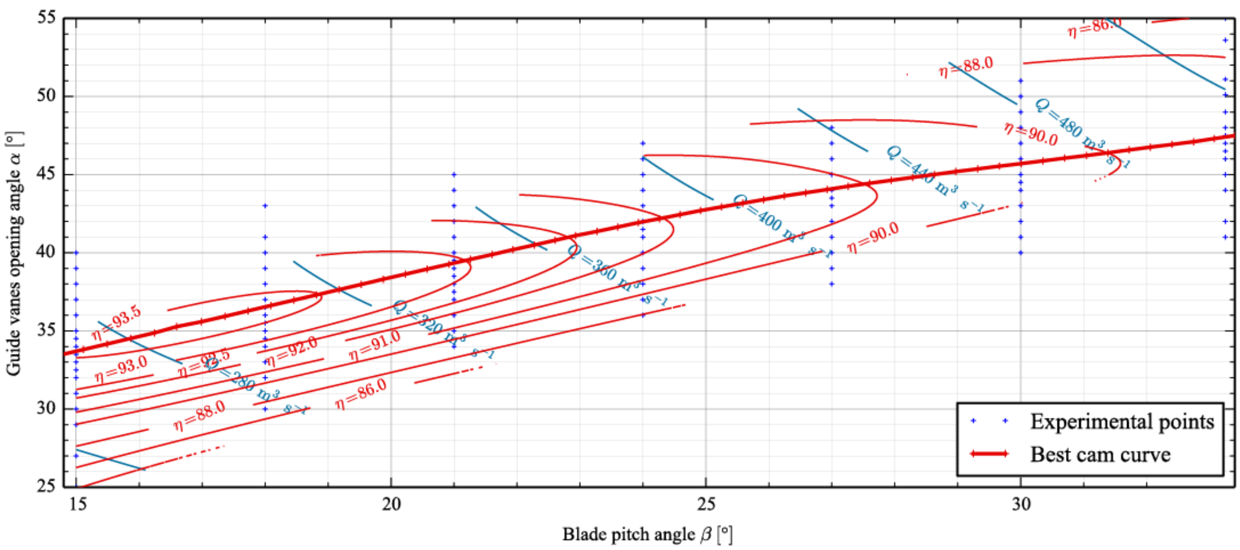

Figure 4: Best cam curve identified on efficiency η_H and discharge Q_H models at constant head as functions of blade pitch angle β and guide vane opening angle α.

One advantage of the proposed methods sits in the ability to build models of the discharge Q_H and efficiency η_H at an early stage of an experimental campaign with only a sparse sampling of the operating domain. The early search for a rough cam curve can be a guide for the area of interest where to focus in order to refine measurements. The strategy can also be applied with data obtained thanks to numerical simulation to reduce the number of runs required to capture the best cam curve location.

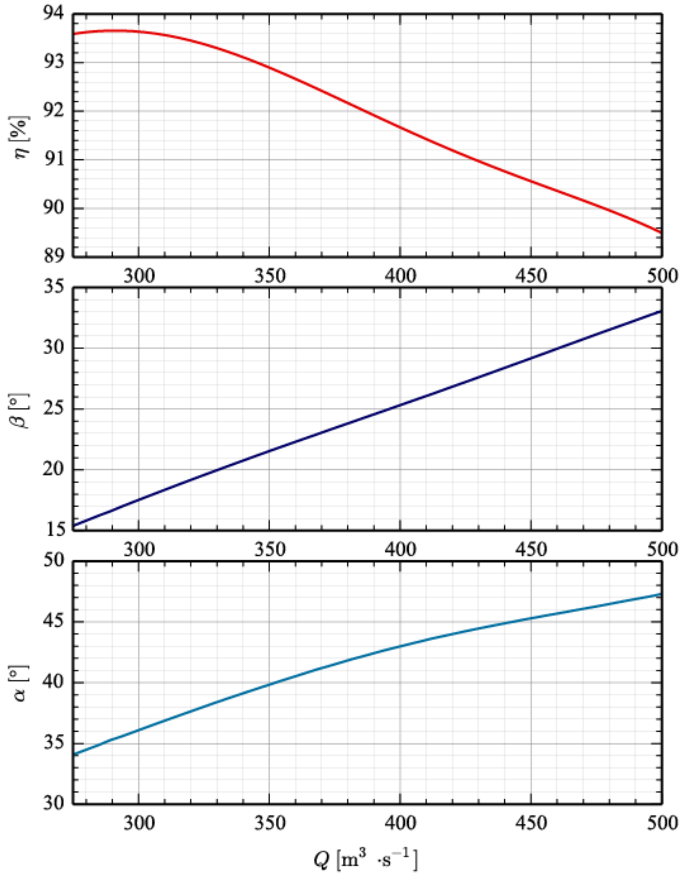

Figure 5: Efficiency along the best cam curve and associated blade pitch angle β and guide vane opening angle α for a constant head.

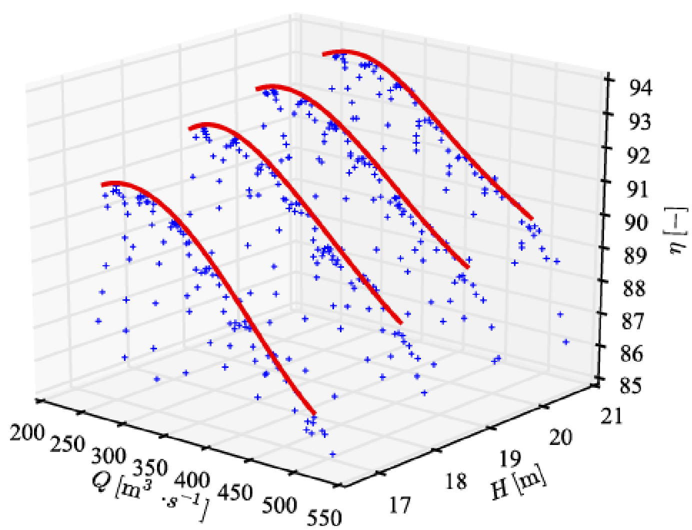

Figure 6: Collection of best cam curves forming envelopes of the experimental point for different head values

2.4. Hill chart modelling on identified on-cam points

Once the cam curves have been identified at every investigated head levels, they form envelopes of the experimentally explored points, as illustrated in Figure 6. Functional models of the efficiency η and the associated conjugated values of guide vanes opening angle α and blade pitch angle β can finally be built as functions of the discharge Q and of the head H.

Hence, during the unit operation, the efficiency model $\eta(Q,H)$ leads to the identification of the appropriate discharge to reach a targeted output power with the available head and the models $\alpha(Q,H)$ and $\beta(Q,H)$ provides the values of the parameters to reach it.

3. Software implementation

3.1. Programing framework

The developed methodology has been programmed using Python language [7]. To ensure quick and exact computation, most of the implementation rely on symbolic mathematics. The functional modeling described in subsection 2.2 is based on OpenTURNS library [8]. The search for cam points following (5) is achieved using the Python library for symbolic mathematics SymPy [9].

The methodology can either be used in Python scripts to fit to custom needs or be applied through the graphical user interfaces described in the following subsections.

3.2. LMH Cam Curves Finder

The Graphical User Interface (GUI) dedicated to the cam curve search, see Figure 7, implementing the method described in subsection 2.3 lets the user select a Microsoft Excel file containing the raw measurement data (or alternatively the raw simulation results) and pick the appropriate quantities read in the input file headers. As the search is a collection of independent optimization problems, its implementation is multithreaded. Each run can benefit from a parallel execution on several cores.

3.3. LMH Hill Chart

The second application developed is dedicated to the identification of hill chart models. The GUI visible in Figure 8 reads data contained in an input Microsoft Excel file and allows the user to specify the models he identifies. The application can output the identified models under various usable formats such as MS Excel-ready Visual Basic macros, on top of being directly useable within Python scripts. Custom plots such as the example of Figure 9 can also be generated within minutes.

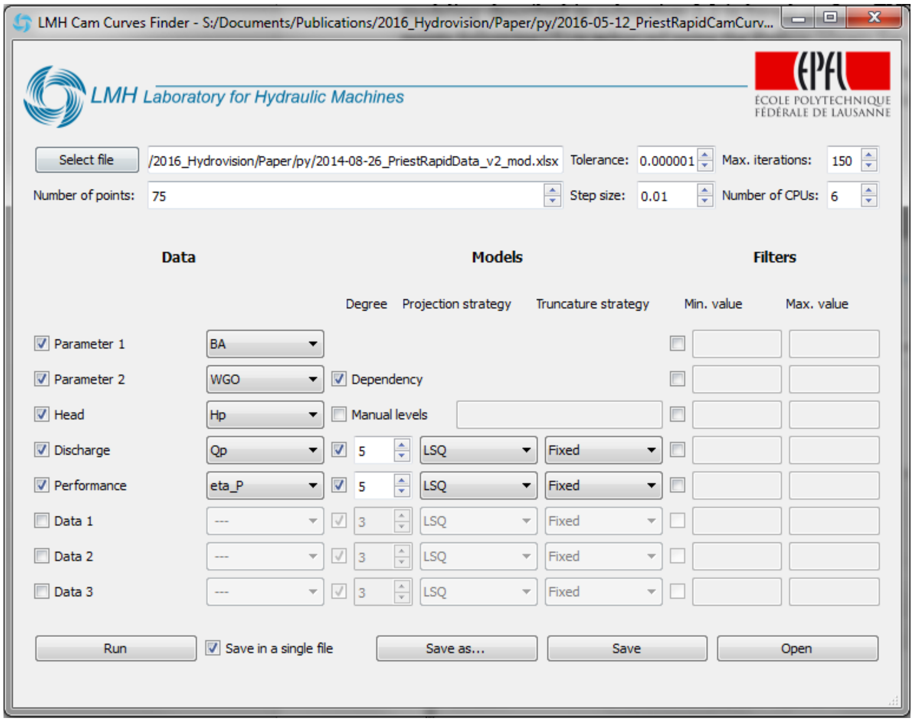

Figure 7: Screenshot of LMH Cam Curves Finder GUI.

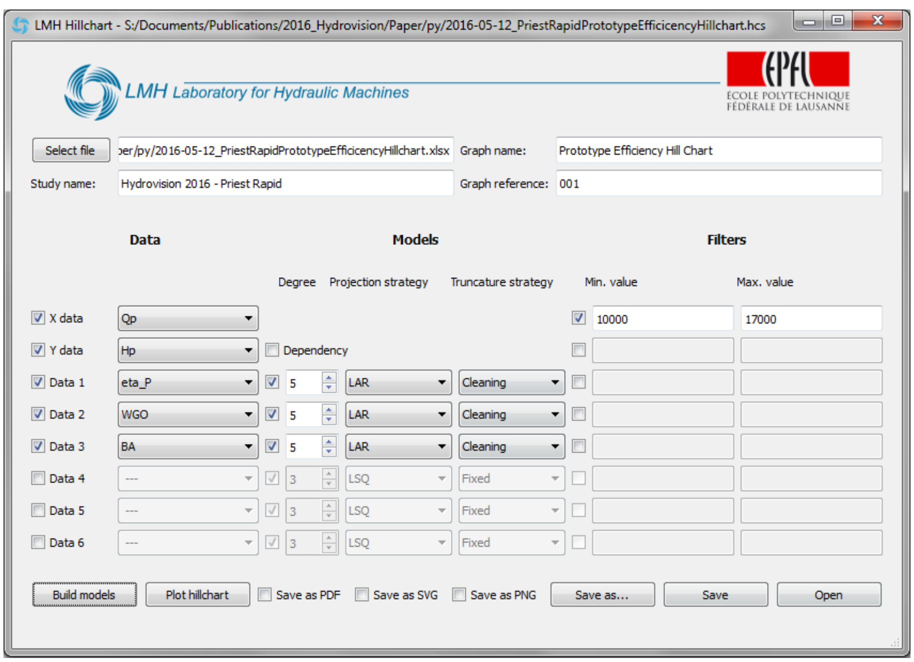

Figure 8: Screenshot of LMH Hillchart GUI

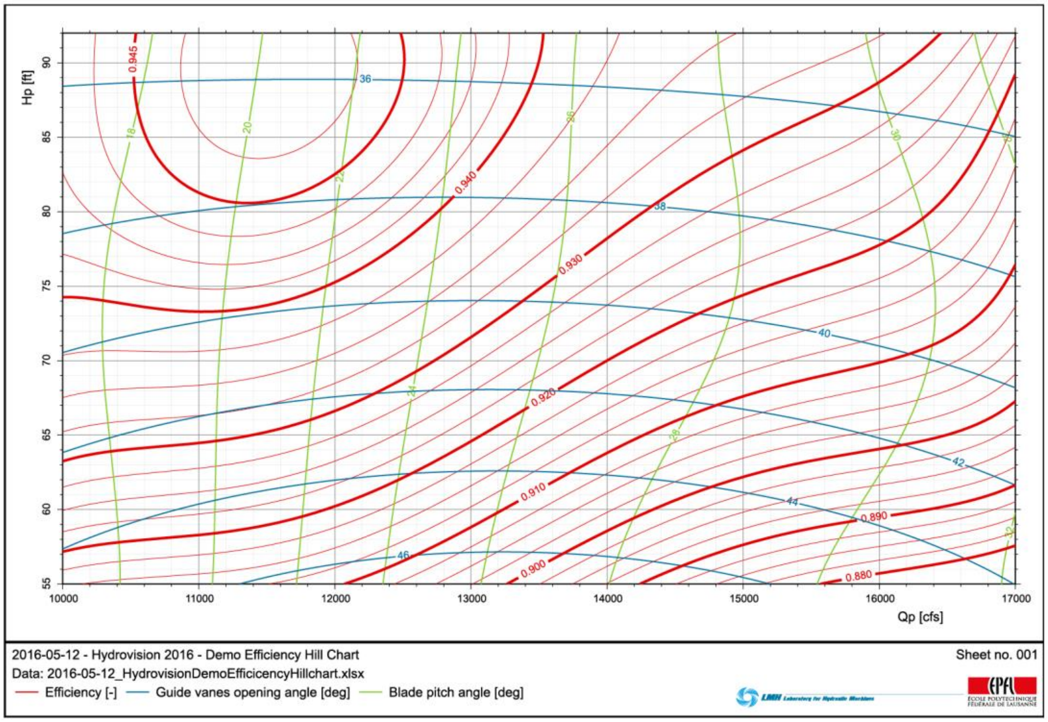

Figure 9: Customized hill chart diagram generated with LMH Hill Chart application.

4. Test case

Apart from being used for adjusting the output power, the potential of the proposed approach also lies in the comparison of the energy production of several machines. It has been applied to the case of the Kaplan units from the Priest Rapid power plant located on the Columbia River (Washington, USA). After around 50 years of operation, the original runners are to be replaced during the rehabilitation of the power plant. Efficiency hill charts have been built for the original runner and for the Voith Hydro runner that are currently being installed.

The hill charts have been build according to data obtained during two experimental campaigns carried out on models reduced at a 1:20 scale of the original unit and of the new Kaplan unit. They were conducted on a test rig that complies with the IEC 60193 standards [10]. The proposed method proved effective to compare the performance of the two geometries due to the absence of manual selection of cam points. The exact same data processing scheme is applied for the two campaigns.

The weighted efficiency $\overline{\eta}$ and the weighted mechanical power $\overline{P_m}$ before and after the rehabilitation of the power plant are computed using (6) and (7) respectively, according to the weighted operating points provided by the operator and summarized in Table 1.

$$\overline{\eta} = \sum_{Q_u} \sum_{H_v} w_{uv} \cdot \eta(Q_u, H_v) \tag{6}$$

$$W = \rho \cdot g \cdot \sum_{Q_u} \sum_{H_v} w_{uv} \cdot \eta(Q_u, H_v) \cdot Q_u \cdot H_v \tag{7}$$

Table 1: Weighting factors applied to compute the weighted performance of the Kaplan units.

Net head H_v [feet]	Discharge Q_u [cfs] 10.10^3	13.10^3	16.10^3	18.10^3
80	0.169	0.08	0.006	0
76	0.056	0.155	0.125	0.033
72	0.021	0.075	0.145	0.135

The weighted efficiency of the machine is evaluated to 91.14% before rehabilitation and to 92.54% after the rehabilitation. The weighted mechanical power of the Kaplan unit is also expected to rise from 80.62 MW to 81.73MW. Assuming an availability rate of 70 for the 10 Kaplan units of the power station, the rehabilitation will yield a 72.4MWh increase of the annual energy production.

5. Conclusion

The method presented in this paper deals with the modelling of the best efficiency achievable with double regulated hydraulic machines such as Kaplan or bulb turbines. It is nonetheless applicable to any other type of double regulated unit. The models obtained can be used for the estimation of the performance. They can also serve the regulation of the machine towards a target operating point as they yields the optimum machine settings together with the best achievable efficiency. Even if the method is originally dedicated to the analysis of model testing campaigns, it can be applied on numerical simulation results without suffering from sparsity. A software implementation makes it easily usable.

The paper exposes several potential applications of the method developed. It is particularly well suited for the estimation of the machine settings to reach a targeted power. The low computational cost to evaluate the identified analytic models also let them be suitable for being implemented in wider optimization schemes such as multiple power plant scheduling or power system operation with a high penetration of intermittent renewable energy. The models built for the Kaplan units of the Priest Rapid power plant have finally been used to estimate the increase of energy generation after the rehabilitation of the power plant, also providing the combination of wicket gate angle and blade angle that will lead to this gain.

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Biographies

Dr. Loïc Andolfatto completed his doctoral studies in 2013 at École Normale Supérieure de Cachan and at the corporate research center Innovation Works of Airbus Group. He joined the EPFL Laboratory for Hydraulic Machines in 2014 as a research associate and works on topics regarding modeling and optimization of hydraulic machine performance, with a focus on profitable harvesting of small hydro potential.

Henri-Pascal Mombelli graduated from EPFL in 1978. After working 2 years as a mechanical engineer in the private sector, he became chief engineer of the hydraulic testing platform within EPFL in 1980. He is currently the head of the model testing group of the EPFL Laboratory for Hydraulic Machines, delivering worldwide renowned expertise in the field of hydraulic machinery.

Prof. François Avellan joined EPFL in 1984. He is director of the EPFL Laboratory for Hydraulic Machines since 1994 and he was appointed Ordinary Professor in 2003. His main research interests are the hydrodynamics of turbines, pumps and pump-turbines, including cavitation, hydro-acoustics, design and evaluation of the performance of hydraulic machines trough both experimental investigations and numerical simulations.