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DEVELOPMENT A NEW TEST RIG FOR ANALYSIS AND CONTROL OF SWIRLING FLOWS

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The paper presents the main steps in order to develop an experimental test rig for analysis and control the swirling flows in draft tube cone of the Francis turbine. The main goal of test rig and experimental methodology developed will be focuses on the vortex rope generated in Francis turbines' draft tube. This is a very important matter in Francis turbine operation, because at partial load a cavitational vortex rope is developed. Consequently, strong vibrations and output power pulsations are generated. So, the contribution of hydropower plants equipped with Francis turbines at stability of energetic system is limited. A new solution is developed in order to mitigate the vortex rope using a new technique: based on injecting an axial water jet in draft tube. In order to investigate these phenomena a special swirl generator was designed based on numerical analysis. In the paper are presented the main aspects of hydraulic and mechanical design. Some experimental results concerning test rig operation domain a qualitative results of rope vortex development and mitigation, are also presented.

Keywords: draft tube, swirling flow, experimental analysis, jet control.

1. Introduction

Advanced knowledge and control of swirling flow in turbomachines are the essence of real improving of turbomachines operation both at the best point but also in a large range of flow rates. A turbomachine with fixed blades runner (such as Francis turbine) is traditionally designed for operating in the best point, at the highest value of efficiency. Presently, the market requests impose Francis turbine operation range to be extended to one half of the nominal flow rate. In these conditions, appearance of a breakdown vortex in the draft tube of the turbine is certain. The breakdown vortex produces pressure pulsations of high amplitude, which lead to decreasing of energetical and cavitational turbine's performances,

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and strong vibrations causing blades breaks and damaging of other parts of turbine. It may be considered that around the world are in operation hundreds or thousands Francis turbines facing the problem of vortex rope effects.

Upper considerations are motives to develop new techniques to control swirling flows in hydraulic turbines with fixed runner blades, in order to operate safety in a large range of flow rate. Because experimental studies on a turbine model implies a lot of supplementary difficulties, it was decide to realize a special test rig configuration, including a swirling flows generator operating in similar conditions like in a draft tube of a Francis turbine. Flow visualization is one of the main goals of test rig, so vortex rope developing domain was made of acrylic glass. In order to provide further analysis of flow structure by laser techniques clear water is strictly necessary. So, the closed - loop and all test rigs parts touched by water must be of stainless steel made.

2. Aspects of hydraulic design

First of all, establishing suitable dimensions of test section in order to have convenient flow development and correct reproduction of real phenomena, needs to respect hydrodynamic similarity. In order to realize this goal, it is necessary that Reynolds number (*Re*), to be finding in range of $10^5 \ldots 10^6$.

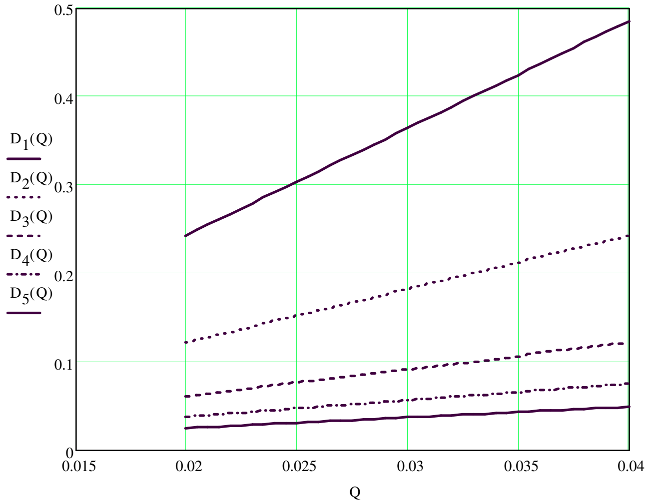

Fig. 1. Pipe diameter D_i [m] versus flow rate [m^3/s].

Considering relations between *Re*, flow rate *Q*, average fluid speed *v*, pipe diameter *D* and cinematic viscosity, there are:

$$Re = \frac{4Q}{\pi \nu D} \tag{1}$$

It result dependence between D and flow rate such as:

$$D(Q) = \frac{4Q}{\pi \nu \, Re} \tag{2}$$

Choosing five Reynolds values, such as: Re_1=1. 10^5, Re_2= 2.10^5, Re_3= 4.10^5, Re_4=6,5.10^5, and Re_5=10^6, it results graphic dependences, like in Fig.1.

It can be observed that a suitable dimension of pipe diameter is D=100 mm, for $\mathrm{Re}_3 = 4 \cdot 10^5$. For these values necessary flow rate Q_0 and average fluid velocity v_0 can be determinate: Q_0= 0.0033 m^3/s, or Q_0= 118.75 m^3/h, and v_0= 4.20 m/s

A schematic diagram of the test rig is presented in Fig. 2.

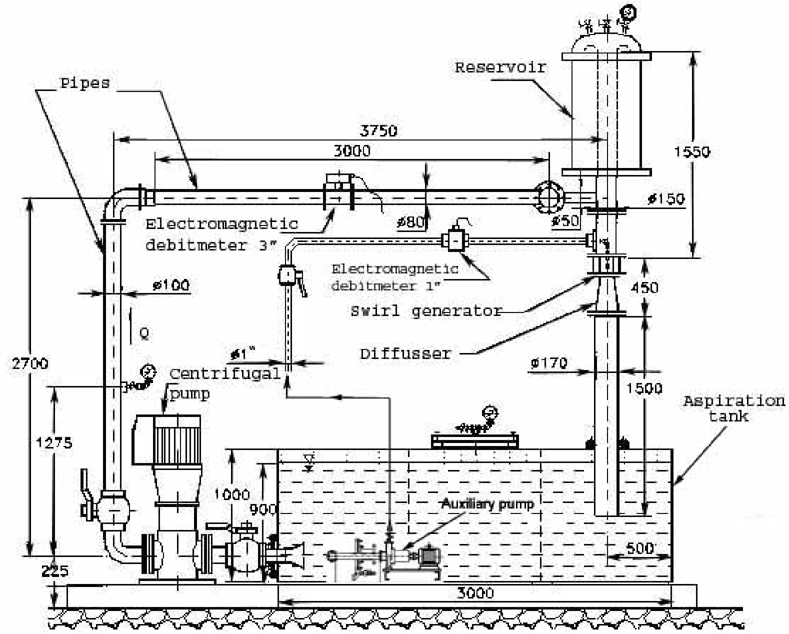

Fig. 2. Schematic diagram of the test rig.

The test rig consist of an 4 m^3 aspiration tank, a centrifugal pump, two ball valves, an auxiliary upper reservoir for turbulence decreasing, an electromagnetic flow meter, and of 100mm and 80mm- pipes diameter for closing the hydraulic loop. It is necessary a large aspiration tank because hydraulic losses should not increase water temperature more than 2°…3°C in about 3 hours of operation.

The variable speed GRUNFOS CRNE 90-2 pump can provide a flowrate up to 33 liter/sec, the discharge being measured with a 3” electromagnetic flowmeter of 0.2% accuracy. The main pump supplies decreasing turbulence reservoir, which provides a well controlled uniform flow through ø150 mm pipe to the test section. Downstream the test section, ø160 mm pipe returns the discharge to the aspiration tank. This closed-loop test rig can be pressurized or de-pressurized in order to examine the cavitating vortex rope as well. An auxiliary variable speed centrifugal WILLO pump can provide the jet flowrate up to 4 liter/sec, with a 1'' turbine flowmeter of 0.1% accuracy.

In order to investigate the decelerated swirling flow in a conical diffuser, one must provide a swirl generator upstream the cone inlet (Fig. 3). For Francis turbines, the runner itself provides the swirling flow at the draft tube inlet.

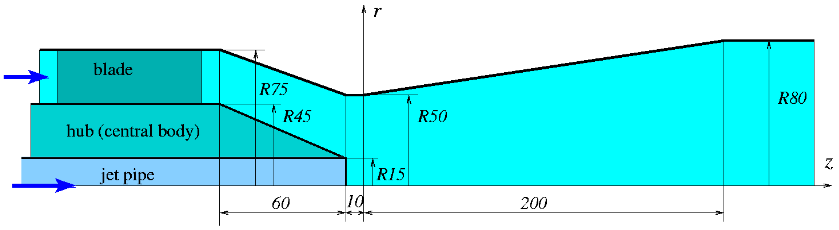

Fig. 3. Meridian cross section of swirling flow generator. Dimensions in *mm*.

The convergent swirling flow upstream the diffuser throat is closer to the Francis turbine configuration, and could produce a swirling flow similar to the one downstream the Francis runner.

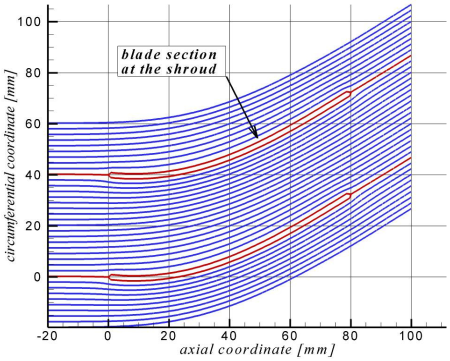

Fig. 4. Blade cascade at the shroud.

Angular deviation realized by blade cascade (Fig. 4) is about 30^o, approximating rotating component of the flow in Francis turbine draft tube, operating at flow rate values under nominal value.

In order to select the suitable pump, it is necessary hydraulic loss calculus along test rig and determination of external characteristic $h_p(Q)$. By using well known formulas of distributed and local hydraulic losses from fluid mechanics:

$$h_p = h_{plong} + h_{ploc} = h_p(Q) \tag{4}$$

$$h_{plong} = \lambda \frac{\sum l_i}{d_i} \frac{v_i^2}{2g}; \quad h_{ploc} = \sum \zeta_i \frac{v_i^2}{2g} \tag{5a,b}$$

it is possible to obtain functional characteristic of test rig, $h_{p=}f(Q_x)$ like in Fig.5, where is also represented choose centrifugal pump characteristic $H= f(Q)$.

It can be observed that at operating point, flow rate value is about Q=135 m^3/h, enough to realized necessary Reynolds number.

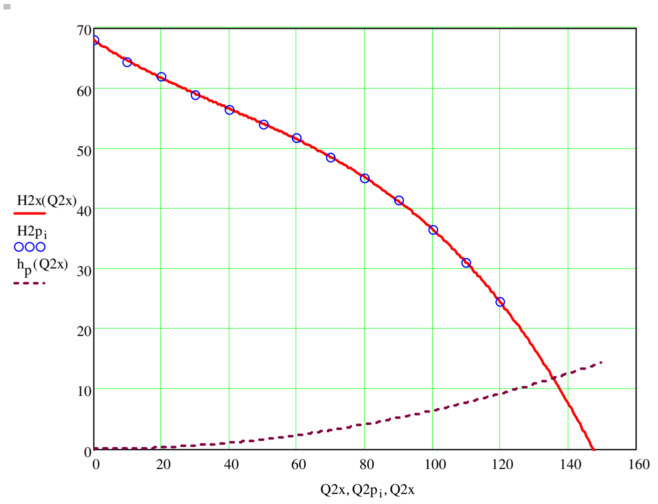

Fig. 5. Functional characteristics of test rig and centrifugal pump.

3. Aspects concerning mechanical design

The main problem of hydraulic part of the test rig is mechanical resistance of the aspiration tank, realized of stainless steel of 3mm thickness. So, dimensioning and verifying calculus were made. Considering operating conditions like maximum water capacity $V\cong$ 4m^3 and pressure range p=±0.5bar, verifying calculus shows maximum stress and deformation near the admissible limits.

A metallic construction supports the hydraulic loop, and resistance calculus was also made. In Fig. 6 is shown final form of complete test rig, and in Fig.7 is a picture of real test rig.

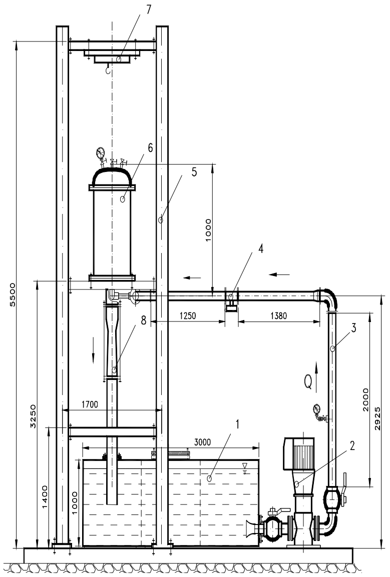

Fig. 6. Schematic diagram of the test rig.

Fig. 7. Picture of the test rig from Hydraulic Machinery Laboratory.

4. Preliminary tests

In order to verify operation domain regarding flow rate and pressure ranges, the first step is to use a 160 mm – pipe diameter instead swirl generator and attached diffuser. Following operations will be made:

- Checking of existence of all parts of the test rig, correctly mounted
- Filling with water at maximum capacity
- Verifying not to exist water leaks all over hydraulic circuit
- Verifying pump operation in all range of rotational speed, computer controlled
- Determining of centrifugal pump operation characteristic using thermodynamic method with a real time acquisition data system
- Determining of hydraulic loop operating characteristic using thermodynamic method with a real time acquisition data system
- Establishing operating points for a number of flow rate values in connection with necessary flow rates for swirling flows.

Using thermodinamic method for turbomachinery performance determining, it was possible to obtain both pump and test rig operation characteristics and so operating domain of the test rig, like in Fig.8. It can be observed that needed Reynolds numbers will be reached.

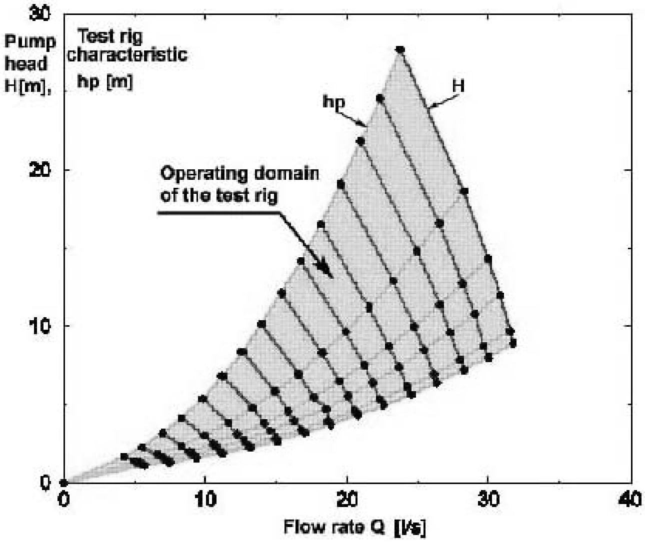

Fig. 8. Operating domain of the test rig.

Fig. 9. Test section.

Fig. 10. Vortex rope I.

Fig. 11. Vortex rope II.

In Fig. 9 is presented real test section with swirl generator an acrylic glass cover. Fig. 10 and Fig.11 shows vortex rope in two development cases.

5. Conclusions

Test rig conception and realization are in perfect connections with swirling flows experimental analyses established, and create proper conditions to observe the effects of central jet in instability correction of the vortex.

Preliminary experiments also confirm correct initial suppositions and a good real design.

Both hydraulic part and support structure offer possibilities to versatile experiments, including investigation on turbine operation parameters.

A future implementation of computer control and real time data acquisition system is also a guarantee for high-class experiments.

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