Conference on Modelling Fluid Flow (CMFF'22)
The 18th International Conference on Fluid Flow Technologies
Budapest, Hungary, August 30 -September 2, 2022

NUMERICAL ANALYSIS OF THE FLOW BY USING A FREE RUNNER DOWNSTREAM THE FRANCIS TURBINE

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ABSTRACT

Current requirements of the industrialized countries impose to use as much renewable energy as possible. One meaningful problem of renewable energy is that the produced power is fluctuating. Currently, the only available method for energy compensation in the shortest time is given by hydroelectric power plants. Instead, the hydroelectric power plants (especially the plants equipped with hydraulic turbines with fixed blades) are designed to operate in the vicinity of the optimum operating point with a maximum ±10% deviation. The energy market requires that hydraulic turbines operate in an increasingly wide area between -35 - 20% from the optimum operating point. Operation of hydraulic turbines far from the optimum operating point involves the appearing downstream from the turbine of a decelerated swirling flow with hydraulic instabilities (known in the literature as the vortex rope).

The main purpose of the paper is to investigate numerically a new concept by using a free runner downstream on the main hydraulic runner turbine more precisely in the draft tube cone. The free runner concept supposes that rotates at the runaway speed with vanishing mechanical torque. The main purpose is to redistribute between the shaft and the periphery the total pressure and the moment. Moreover, the free runner does not modify the operating point of the main hydraulic turbine runner.

Keywords: Free Runner Concept, Hydraulic Turbines, Numerical Simulation, LDA

NOMENCLATURE

V_m	[m/sec]	meridional velocity
V_u	[m/sec]	circumferential velocity
V_{ref}	[m/sec]	reference velocity

1. INTRODUCTION

In last decades, the market policy was focused on renewable energy development. The renewable energy (solar and wind) introduces a large fluctuating component in the electrical grid. As consequence, many hydroelectric power plants are operated at for flattening wind and solar power fluctuation [1]. While operated at off-design condition for grid services (part load and high load), hydraulic turbines with fixed blades experience an abrupt decrease in terms of efficiency [4]. An excess of residual swirl is ingested by the draft tube, downstream the turbine runner. The residual swirl that occurs at off-design conditions is a consequence of the mismatch between the flow generated by the wicked gates and the angular momentum extracted by the turbine runner [5]. The most harmful phenomena developed in the draft tube of hydraulic turbine are those at part-load operating conditions. At these regimes, the residual swirl ingested by de conical diffuser of the draft-tube leads to development of so-called vortex rope [6-10]. Vortex rope is a self-induced hydrodynamic instability which can be characterized by a well-defined predominant fundamental frequency. In general, the vortex ropes fundamental frequency varies 0.2 – 0.4 times of the turbine runner rotational frequency, Ciocan et al. [11]. The vortex rope leads to harsh pressure fluctuations that interrupts the safe operation of the hydraulic turbine [12-14]. Many approaches have been considered for mitigation the undesirable effect of the vortex rope or to deeply understand the flow behaviour. Both passive (not require auxiliary power) and active (require auxiliary power and control loop) technics were studied. One of the earlier passive techniques was proposed back in 80`s by Thicke [15]. Later, many other passive technics as J-grooves mounted on the cone wall [16], fins [17], runner cone extensions [18], diaphragm mounted downstream the conical diffuser [19], radial protrusion of solid bodies [20], flow-feedback method [21] and stator mounted downstream the runner [22] were investigated. Active control technics as air or water injections through various zones of the hydraulic turbine [23-27] and magneto-rheological control technique [28, 29] were also investigated. However, both passive and active control technics have some advantages and drawbacks as presented by Kougias et al. [1]. Together with these control technics various measuring and observing systems were used to quantify the control technics impact on hydrodynamic phenomena developed in the conical diffuser. The most common type of investigations on the hydrodynamic flow filed generated at part load conditions are the pressure measurements at the wall of the conical diffuser and the 2D Laser Doppler Velocimetry (LDV) measurements. Besides these, high speed camera observations and 2D or 3D particle image velocimetry (PIV) were used. The 2D LDV systems is a non-invasive method that allow measuring the velocity profiles in the conical diffusers offering a wide image of the entire flow fields. In contrast, the tools used for measuring the pressure are hard to fit inside the flow and for this reason are often used at the wall of the conical diffuser [23, 30-32]. As consequence, the 2D LDV velocity profile together with the pressure measurements at the wall of the conical diffuser complete each other strengthen a solid base for a deeply understanding of hydrodynamic field in conical diffuser of hydraulic turbines operation at part-load condition. Hence, the two measuring systems are suitable to also investigate the impact of an approached control technique on the vortex rope and its effects.

The analysis combined with the numerical simulation is able to provide a full image of the flow from the hydraulic machinery. Accordingly, the paper presents and analyses the flow in the conical diffuser by combining the experimental investigation and the numerical simulation. The experimental investigations performed in this paper consist by measurements of velocity profiles with Laser Doppler Velocimetry (LDV) and pressure pulsations respectively. The numerical simulation performed in the paper, first is validated from the numerical simulation, and second the vortex rope is extracted for the investigated cases. From the experimental and numerical analysis, the new concept of the free runner mounted downstream the main runner is analysed.

2. EXPERIMENTAL SETUP

In order to analyse the decelerated swirling flow from the conical diffusers of the hydraulic turbines, can be used model turbines or surrogate model turbines. In our case, we have chosen a surrogate model – a swirl generator – capable to offer at the inlet in the conical diffuser a decelerated swirling flow similar with the flow outlet of a real hydraulic turbine, [26].

The swirl apparatus is mounted on an experimental test rig developed in the laboratory, which serves by investigating different control methods of diminishing the flow instabilities associated with the vortex rope. The swirl apparatus which is mounted on the main hydraulic circuit on the test rig has two main components: the swirl generator and the test section. The swirl generator has three components: the ogive, the stator and the main runner, which are mounted on a cylindrical Plexiglas section at an interior diameter of 0,150 m, as presented in Figure 1. The stator and the main runner generate at the inlet in the conical diffuser a rotating flow similar with the flow downstream of a Francis runner operated at 70% discharge from the nominal flow rate, [11].

Downstream the main runner, on the experimental test rig was mounted the free runner concept, see Figure 1 (right). The free runner concept supposes that rotates at the runaway speed with vanishing mechanical torque. The main purpose is to redistribute between the shaft and the periphery the total pressure and the momentum such that the flux of total pressure and the momentum are not altered. Moreover, the free runner does not modify the operating point of the main hydraulic turbine runner. The benefits of the free runner downstream the main runner turbine approach is:

i. reducing the pressure pulsations (synchronous or asynchronous) from the draft tube cone,

ii. optimal configuration for the swirling flow ingested by the draft tube cone,

iii. minimum draft tube losses and maximum pressure recovery.

The concept has been presented by Susan - Resiga et al. [5] by using a Francis turbine with tandem runners. Similar approach can be found at Gokhman [22] by using a stay apparatus downstream the Francis runner. The free runner concept (see the sketch in Figure 1) downstream the main turbine will add the required flexibility for the Francis turbine regulation and avoid the deterioration of hydraulic turbine components.

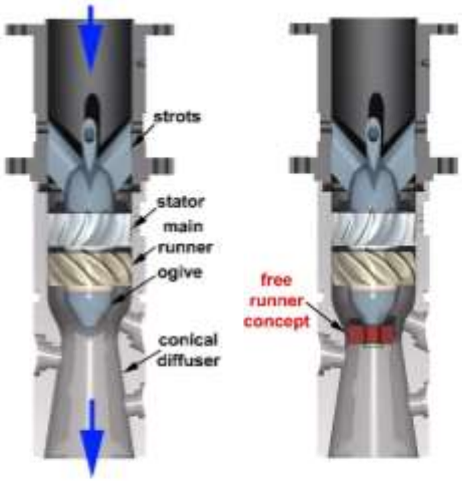


Figure 1. Swirl apparatus and the test section from experimental test rig. The original configuration (left) and the configuration with the free runner concept implemented on the test rig (right).

The main dimensions of the components from the swirl apparatus together with the dimensions of the free runner concept are presented in below table.

Table 1. Hydraulic parameters for the test rig components.

Parameter	Value	Unit
Nominal discharge Qn	0,03	[m^3/s]
Main runner - rotational speed n	940	[rpm]
Main runner - tip diameter D_t	0,150	[m]
Main runner - hub diameter D_h	0,06	[m]
Main runner - blade number z	10	[-]
Free runner - rotational speed n_{fr}	850	[rpm]
Free runner - tip diameter $D_{t\ \text{-fr}}$	0,100	[m]
Free runner - hub diameter $D_{h\text{-fr}}$	0,03	[m]
Free runner - blade number z_{fr}	3	[-]

During the measurements, the nominal discharge in the main hydraulic circuit was 0,03 m^3/s. The speed for the main runner was measured with the acquisition system existed in the laboratory, while the speed for the free runner was established with the help of the stroboscope.

3. NUMERICAL SETUP

The numerical domain was represented full 3D and consists of 5.8 million mixed cells. First the numerical results were obtained without taking into account the presence of the free runner, and after the vortex rope was developed, the free runner with three blades was activated.

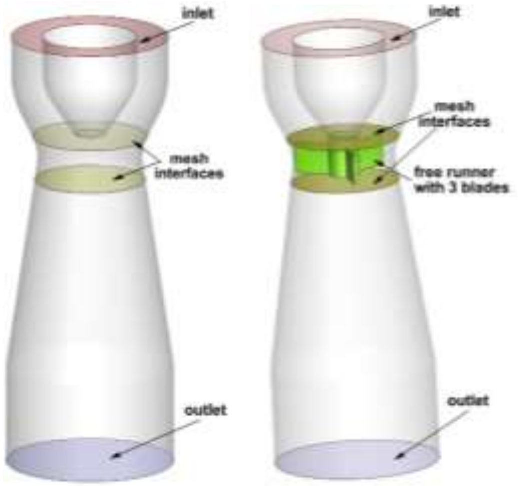


Figure 2. Full 3D domain: without free runner (left), with free runner (right)

The numerical simulation was performed with the help of ANSYS Fluent 2021R1. The unsteady solver was employed, together with the Generalised k-ω (GEKO) model for modelling the turbulence parameters. The velocity components together with the turbulence parameters, from the exit section of the swirl generator, obtained from experimental measurements, were imposed on the inlet boundary of the domain. On the outlet boundary the outflow condition was imposed. For all the wall boundary conditions the default set-up of the Fluent was retained, with No slip shear condition and standard roughness model, [33-34].

In order to compute the interaction between the rotating domain, containing the free runner with 3 blades, and the static domain, the sliding mesh technique was employed, and two mesh interfaces were defined with the matching option activated, upstream and downstream of the free runner. The rotational speed imposed on the rotating domain was 850 rpm, corresponds to the free movement of the runner and was experimentally determined.

To generate the vortex rope, first the presence of the free runner was “hidden” by defining the boundary condition on the blades as interior, and the volume was set as water. After the vortex rope was generated, the free runner was activated by imposing the wall boundary condition on the blades, and the volume was set as solid.

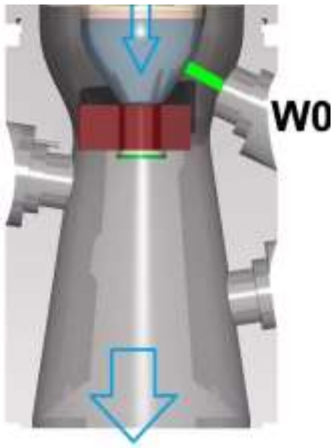
As solution methods, the scheme of SIMPLEC was employed for computing the pressure-velocity coupling. The spatial discretization was set to Second Order Upwind for pressure, momentum and turbulence parameters and to Least Squares Cell Based for the gradient. The transient formulation was set to Bounded Second Order Implicit.

The time step was set as 0.001 seconds, corresponding to a movement of the free runner of approximately 5°, and 15 iterations were considered for each time step. The numerical simulation was carried out for a flow time of 4.458 seconds for the case without the free runner and for a flow time of 2.505 seconds for the case with the free runner.

4. VALIDATION OF THE RESULTS

A first step in the analysis of the new concept is the validation of the velocity profiles obtained from the 3D numerical simulation against the experimental results. The measurements have been validated in the convergent part of the test section on survey axis W0.

The comparison between the experimental analysis and the 3D numerical simulation, shows that the numerical results are in very good agreement with the experimental values. The comparison was focused on two velocity components: the meridional velocity and the circumferential velocity. Note that the experimental velocity components were used to validate the results from numerical simulations, not as boundary conditions



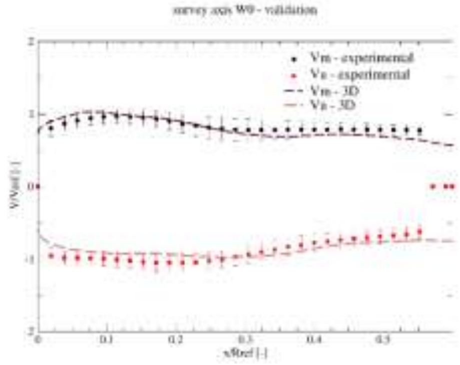
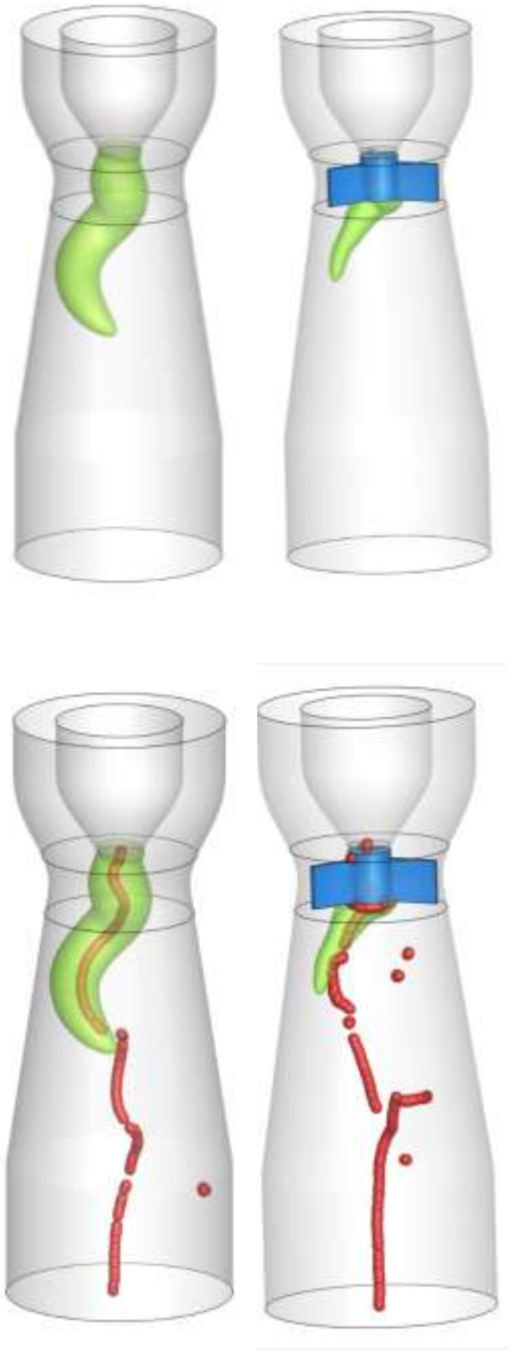


Figure 3. Validation of the velocities measured experimentally with the LDV on survey axis W0 with the velocity profiles obtained from the 3D numerical simulation

5. RESULTS AND ANALYSIS

Taking into account the good validation of the numerical investigation, a next step is the analysis of the flow and of the pressure from the numerical simulation for the investigated cases: without and with free runner. Figure 4 present the flow evaluation in the conical diffuser for both cases, by analysing the formation of the vortex rope. To visualize the vortex rope, a constant pressure iso-surface was plotted, with green colour, and the vortex cores of the flow filed were calculated and plotted, the red coloured spheres. The pictures show that the vortex rope is present in the conical diffuser in the case without free runner (left part of the images). Is forming close to the ogive and continues 2/3 from the length of the conical diffuser. When the free runner is inserted in the extension of the ogive, the vortex rope starts to diminish in length and thickness. Is forming at the end of the shaft of the free runner and continues approximately 1/3 from the length of the conical diffuser.



Formation of the vortex rope in the conical diffuser without free runner

Formation of the vortex rope in the conical diffuser with the free runner

Figure 4. Visualisation of the vortex rope for the case: without and with free runner.

Another analysis consists on the evaluation of the unsteady pressure registered 100 mm downstream from the inlet in the conical diffuser, as shown in Figure 5. The unsteady pressure is registered from the numerical simulation and after was performed the FFT. The analysis of the FFT shows the main frequency of the vortex rope (15.6 Hz). In the case without free runner, the maximum amplitude reaches a value of 2000 Pa. When the free runner is introduced, the maximum amplitude reaches at a value of 1500 Pa, which it means a reduction of 25 %. Nevertheless, is pointed out that in this case is tested a simple free runner with only three straight blades.

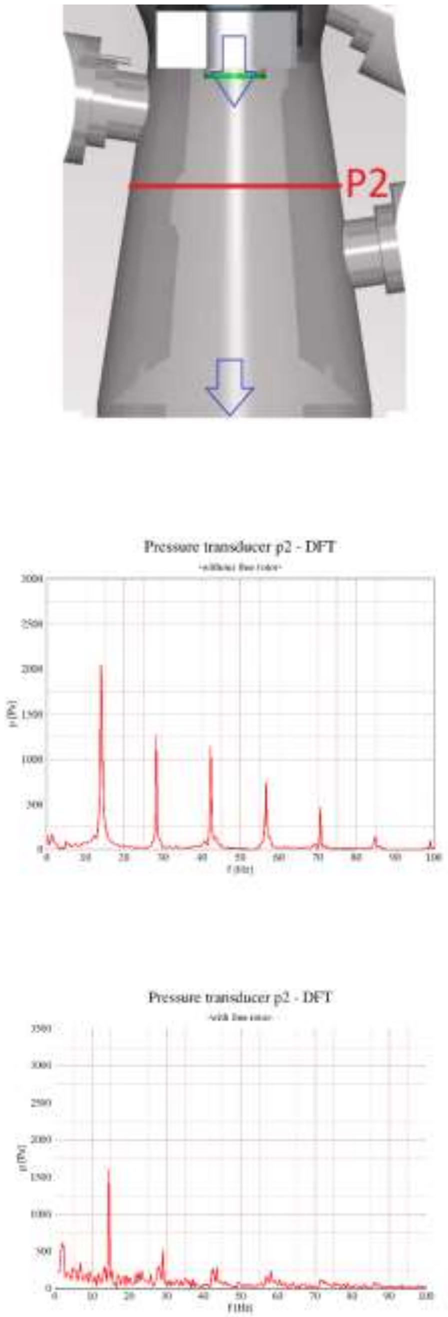


Figure 5. Evaluation of the Fourier transform on the point P2, 100 mm downstream of the inlet in the conical diffuser, for the cases without and with free runner from the numerical simulation.

6. CONCLUSIONS

The paper proposes a new method in order to increase the flexibility in operation for hydraulic turbines by using a free runner mounted downstream the main hydraulic runner. In doing so, on the experimental investigation and numerical simulation, was implemented the new concept. First, was tested a simple free runner, with three straight blades only. The ogive which closes the swirl generator, was modified such that the free runner can be attached and rotated freely with minimum friction. The measurements and the numerical simulation have been performed without and with free runner (at a speed of 850 rpm of the free runner). The vortex rope was evaluated from the 3D numerical simulation for both cases. It was observed clearly that when the free runner is installed, the vortex rope is diminishing in length and thickness. This conclusion can also be supported by the Fourier analysis of the unsteady pressure signals, when the amplitude diminishes with approximately 25% when the free runner is used. Nevertheless, the free runner concept investigated in this paper has used a simple runner with three straight blades only. The further investigations (free runner with more blades and hydrodynamically designed) which are in progress, will confirm that the new concept could reduce the unsteadiness produced by the vortex rope.

ACKNOWLEDGEMENTS

This work was supported by a grant of the Romanian Ministry of Education and Research, CNCS - UEFISCDI, project number PN-III-P1-1.1-TE-2019-1594, within PNCDI III. The second author acknowledge the support of the Romanian Academy – Timişoara Branch thru the research programs of Hydrodynamic, Cavitation and Magnetic Liquid Division from Center for Fundamental and Advanced Technical Research.

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