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# Mitigation of Draft Tube Pressure Pulsations by Radial Protrusion of Solid Bodies into the Flow Field: An Experimental Investigation

Shahab Shiraghaee<sup>1</sup>, Joel Sundström<sup>1</sup>, Mehrdad Raisee<sup>2</sup>, Michel J. Cervantes<sup>1</sup>

<sup>1</sup> Department of Engineering Sciences and Mathematics, Luleå University of Technology, Luleå, Sweden

<sup>2</sup> Hydraulic Machinery Research Institute, School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran

shahab.shiraghaee@ltu.se

**Abstract.** An experimental investigation of frequential protrusion of four solid rods into the draft tube of a propeller turbine operating under partial discharge has been undertaken. The effectiveness of mitigating the pressure fluctuations associated with the rotating vortex rope (RVR) has been quantified using pressure measurements on the wall of the draft tube cone. Three azimuthal configurations of the phase difference between the rods, and four protrusion lengths were investigated. It is shown that the rotating component of the RVR decreases, irrespective of the azimuthal configuration and protrusion length, with imposed phase differences in the same direction as the runner rotation being the most effective, reducing the amplitude of the rotating component by a maximum of 62%. However, for each azimuthal configuration, the plunging mode of the RVR is amplified for large protrusion lengths, with the smallest amplification occurring for the case of 180 degrees phase difference between protrusions. Therefore, to quantify the most efficient configuration in mitigating the harmful effects of the RVR, an overall assessment of its effects on the entire turbine must be made before a conclusion can be drawn.

**Keywords:** hydraulic turbines, part load, rotating vortex rope, pressure pulsations, RVR mitigation, solid-body protrusion

## 1. Introduction

The increasing implementation of intermittent energy sources for electricity production -such as solar and wind- along with their inherent inability in adapting to the variable electricity demands have drawn attention over the last few years [1]. One solution to this growing concern is to employ hydropower in order to stabilize grid network due to their flexibility and quick response [2]. This dictates an increasing operation of hydraulic turbines at off-design conditions including part load. During part load operation, the decelerated swirl inside the draft tube of hydraulic turbines leads to vortex breakdown, and the consequent precessing vortex otherwise known as rotating vortex rope (RVR) induces pressure fluctuations which can cause efficiency losses and acoustic resonance [1-3]. The RVR forms around a stagnant region resulting from the interactions between the latter and the swirling flow present on its periphery. It rotates at a frequency of 0.2 to 0.4 that of the runner [4].



Although investigations carried out in characterizing this phenomenon are quite abundant, attempts made to mitigate the effects of the RVR are comparatively fewer. These mitigation techniques can be generally categorized into active -where energy is required in the application of control- and passive - where no external energy source is required- control methods [5]. Active methods include air or water injections along with the eventual implementation of a feedback system, whereas passive methods include geometrical modifications, baffles, and installation of fins or plates inside the draft tube.

The effect of fins on pressure fluctuations caused by draft tube surge of a Francis turbine was investigated experimentally by Nishi et al. [6]. They observed a decrease in the amplitude of the pressure oscillations while the frequency of the rotating vortex slightly increased. Their results also showed that the installation of fins does not always lead to mitigation of pressure fluctuations. In some cases, it even intensified the resonance between the frequency of the cavitating vortex rope and the natural frequency of the draft tube vibration system which is stated to be the source of these pressure oscillations. In a combined numerical and experimental study, Zhou et al. [7] investigated installation of baffles in two, three, and four-baffle arrangements. The results indicated the ability of this method in alleviating draft tube pressure pulsations at part load with the four-baffle arrangement being the most effective. When using the baffles, they observed a notable shrinkage of the dead-water stagnation zone along with an increase in the axial component of the velocity along the baffles. The mitigating effect of the baffles was attributed to the reduction of tangential velocity, hence preventing the development of a strong swirling flow. Tanasa et al. [8] introduced a novel passive technique that adjusts the circular cross section area at the outlet of a conical diffuser by means of a diaphragm mechanism. They succeeded to mitigate the rotating component of the pressure fluctuations associated with the RVR, whereas the plunging mode slightly increased in their experiments after applying the flow control. In addition, the installation of a diaphragm improved the pressure recovery along the wall of the conical diffuser. At higher diaphragm shutter area ratios, the RVR transforms into bubble form which is considered to be less harmful [9].

Active flow control has also been investigated through the years. Resiga et al. [10] injected water from the tip of runner crown to mitigate part load pressure fluctuations. Recognizing vortex breakdown as the main source of draft tube pressure fluctuations at part load, they suggested that this source should be the focus of mitigation methods, hence injecting the water into the vortex region. Doing so, they alleviated the severe pressure fluctuations in their simulations by at least one order of magnitude. Bosioc et al. [11] conducted experiments on axial water injection through runner crown and analyzed the results based on collecting pressure signals at different locations in the draft tube. They concluded from pressure measurements that injecting axial water from runner crown leads to an improved pressure recovery and reduced pressure fluctuations at part load operation. In a numerical investigation, Javadi and Nilsson [12] studied the mitigating effects of slot jet injection from different locations and with different angles on runner crown. Given the influence of the runner on the formation of the separation region and ultimately the vortex rope, they assumed that a proper mitigation strategy ought to address the problem at locations more upstream in order to prevent vortex breakdown. They concluded that the jet opposite to the rotating direction of the vortex rope is the most effective. The tangential component of the slot jet was found more important in mitigating the pressure pulsations compared to the axial component. Another widely investigated active method to tackle the problems associated with the RVR is the introduction of air into the draft tube [13-16]. Aeration can take place either through the runner cone, or the discharge ring ultimately leading to the alleviation of pressure fluctuations inside the draft tube [17]. Aeration from the runner crown causes an increase of vortex core pressure and a change of RVR structure in some cases [18].

In the present study, mitigation of part load RVR is experimentally investigated on a down-scaled model propeller turbine through radial protrusion of solid bodies into the flow field. The basic idea is to manipulate the shear layer at the interface between the stagnant region and outer swirling flow with sinks and sources. Four rods placed perpendicular to the draft tube and 90 degrees separated from one another are protruded periodically at four different lengths and three different azimuthal modes. The aim is to assess the mitigating effects of the disturbances introduced by the rods and their periodic motion on the swirling flow region, the stagnant region, and the interface between them. The

subsequent effects are compared by means of transient pressure measurements that are conducted at two locations 180 degrees apart on the periphery of the draft tube.

## 2. Material and method

The measurements were carried out on a down-scaled model propeller turbine with a runner outlet diameter  $D=88$  mm. The distributor in the spiral casing comprises 6 guide vanes that direct the flow to a runner composed of four fixed blades. At the runner outlet, a square aluminium block with an 88 mm circular hole in its center was installed to carry the reciprocating motion of the rods and facilitate the RVR mitigation. Four LinMot ps01-23x80 linear motors were installed on the sides of the aluminium block as schematically displayed in Fig.1.

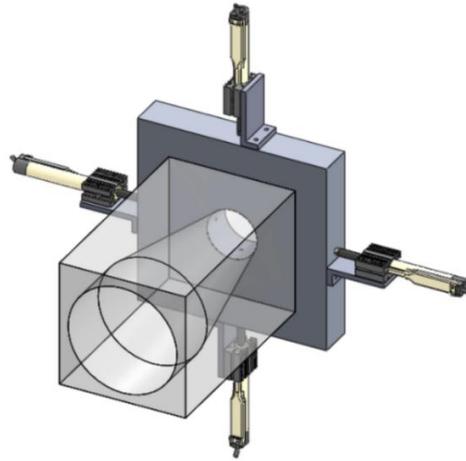


Figure 1 Schematic view of the aluminum block mounted on the draft tube cone with the linear motors.

The rods with a diameter of 6 mm attached to the linear motors protruded into the flow in a periodic motion through holes that had been drilled on the sides of the aluminium block  $1.25D$  downstream of the runner. Three azimuthal configurations of the rod protrusion were investigated in these experiments;  $M=-1$  in which each rod moves with a phase difference of 90 degrees with its neighboring rod in the same direction as the runner,  $M=1$  in which the rods acts with a phase difference of 90 degrees with its neighboring rod in a direction opposite to the rotation of the runner, and  $M=2$  in which the rods acts with a phase difference of 180 degrees to their neighboring rods. These configurations are displayed schematically in Fig.2. Four different protrusion lengths were investigated for each azimuthal configuration:  $L=10$  mm,  $L=20$  mm,  $L=30$  mm, and  $L=40$  mm. The largest protrusion length corresponds to the case when the rods meet almost in the center of the draft tube cone.

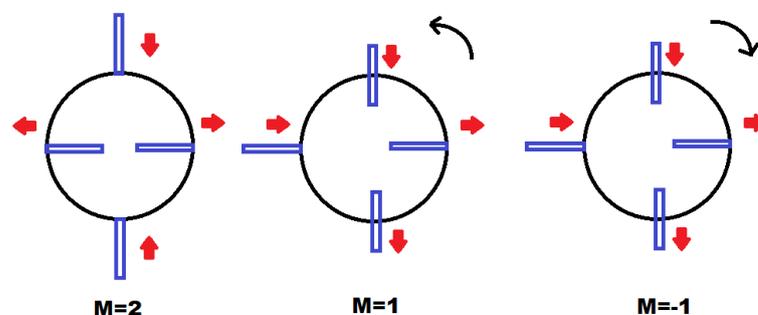


Figure 2 Different azimuthal configurations.

Upon exiting the aluminum section, the flow enters an elbow-type conical draft tube that has an expansion angle of 11 degrees. A pump installed in the open circuit provides a flowrate of up to 6 l/s.

A Bull Electric MD90/130LDH generator was used to control the load and rotational speed on the turbine.

### 2.1. Instrumentation and data reduction

The effectiveness of using rod protrusion for RVR mitigation was quantified by pressure measurements in the draft tube cone in the presence and absence of the flow control. Two PCB 113B28 piezoelectric pressure transducers were flush mounted at approximately  $2D$  downstream of the runner facing one another on the draft tube wall. Such installation allows the decomposition of the pressure signals into a plunging and rotating mode as proposed by Bosioc et al. [11] based on the following equations:

$$\frac{A_1 + A_2}{2} = P_S \quad (1)$$

$$\frac{A_1 - A_2}{2} = P_A \quad (2)$$

where  $A_1$  and  $A_2$  are the pressure amplitudes collected by the two transducers.  $P_S$  and  $P_A$  are the synchronous and asynchronous modes of the pressure signals associated with the plunging and rotating component of the RVR, respectively. The above equations yield the rotating and plunging components of the RVR that are attributed to the presence of RVR and the draft tube elbow, respectively.

A Fischer DE28 differential pressure transducer was used to observe the pressure difference across the turbine, and a Coriolis flow meter was employed to measure the discharge in the circuit. To measure the rotational velocity and the torque of the runner, an optical revolution sensor along with a Honeywell FSG15N1 load cell were utilized, respectively.

The signals were recorded using a National Instruments (NI) PXI-4472 analog to digital converter (ADC) with a resolution of 24 bits, at a sampling frequency of 2 kHz. The operating condition chosen for the experiments was a flowrate of  $4.5 \text{ l/s}$  at a guide vane opening angle of 19 degrees. This operating point was found to be the most repeatable in terms of pressure fluctuation amplitudes and frequency of the RVR. At this operating condition, the runner rotated at a frequency of 24.9 Hz with a corresponding RVR dimensionless frequency of 0.35, i.e., within the limit stated by Nishi et al. [4].

The procedure for each measurement consisted of two consecutive 30 s periods where in the first period, the flow control system was inactive, and the rod tips were flush mounted on the inner surface of the draft tube cone. In the following 30 s period, the linear motors were activated, protruding into the flow field at a frequency equal to that of the undisturbed RVR and the defined length and azimuthal configuration. The measurements were repeated up to 10 times to make sure of the repeatability of the results, and the spread achieved for the amplitude reduction of the RVR-related pressure fluctuations were below 15%.

## 3. Results

The results of the experiments performed are presented in the following based on each of the azimuthal protrusion configurations.

### 3.1. Configuration $M=-1$

The Fourier spectra for one repetition of the measurements with and without protrusion are displayed in Fig.3 and Fig.4 for rotating and plunging components, respectively. The results feature the amplitude of pressure fluctuations (in Pa) against the frequency  $f^*$  made dimensionless with respect to runner rotational frequency  $f_n$ .

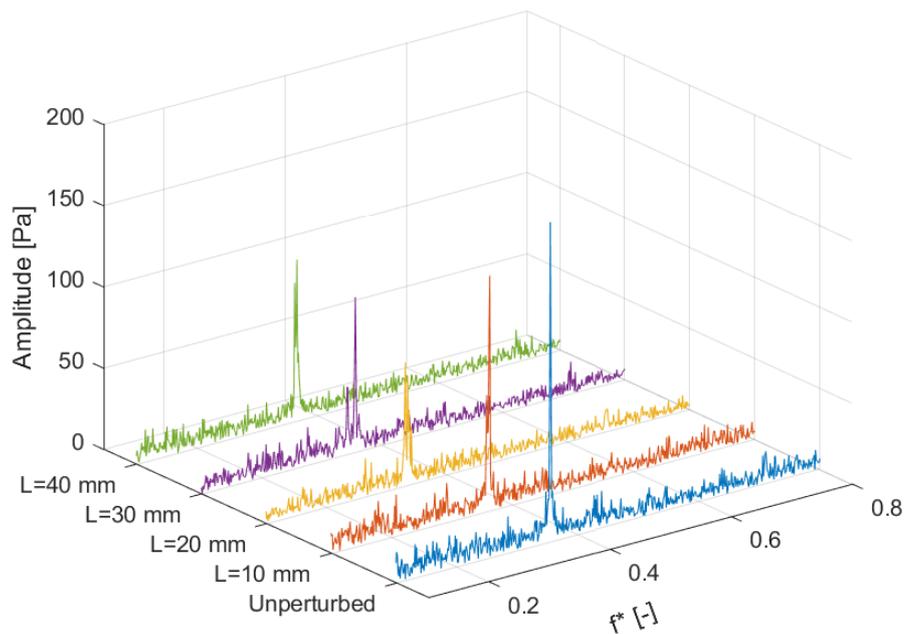


Figure 3 Fourier spectra of the rotating component of pressure signals without rod protrusion and with rod protrusion at different lengths for  $M=-1$ .

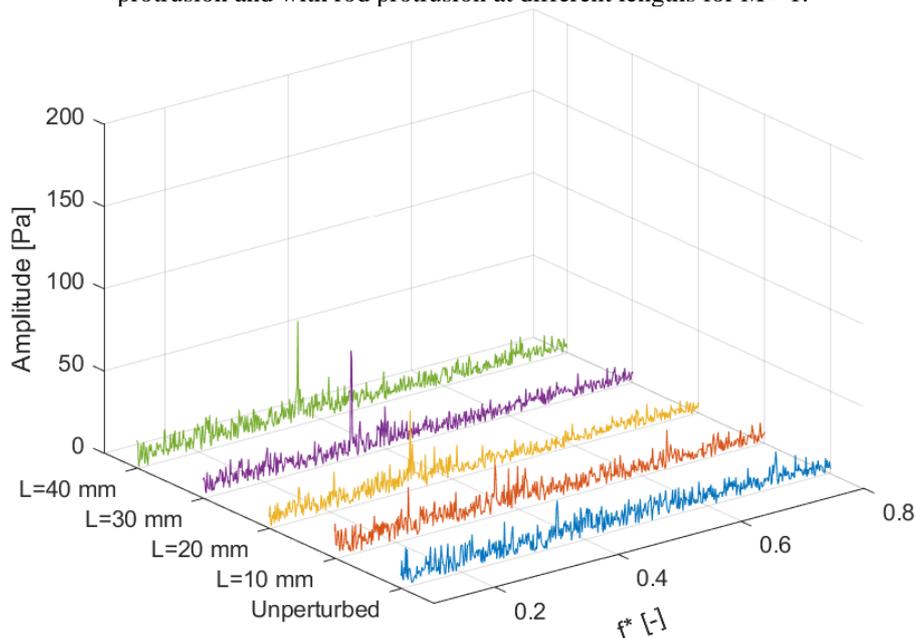


Figure 4 Fourier spectra of the plunging component of pressure signals without rod protrusion and with rod protrusion at different lengths for  $M=-1$ .

A notable characteristic of the undisturbed RVR is the dominance of the rotating mode over the plunging mode, with the amplitude of the former being an order of magnitude larger than the latter. The effectiveness by which the rotating component can be mitigated displays a clear dependence on the protrusion length, which does not follow a linear pattern. The amplitude of the rotating component of the RVR decreases by 26% for a rod protrusion of  $L=10$  mm while the plunging component does not change significantly. At  $L=20$  mm, the rotating component drops by 62%, the highest mitigation in this arrangement, while the plunging mode begins to amplify. Further increase of the protrusion length leads to slight amplification of the plunging mode whereas the amplitude of the rotating component decreases for  $L=30$  mm and  $L=40$  mm by 52% and 50%, respectively.

### 3.2. Configuration $M=1$

The corresponding Fourier spectra for each case with and without the flow control application are represented in Fig.5 and Fig.6 for rotating and plunging component, respectively.

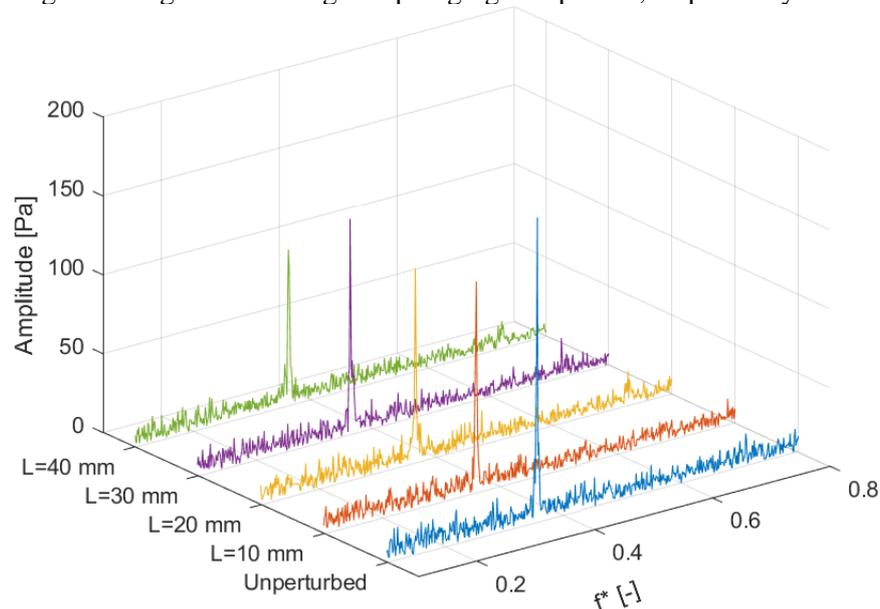


Figure 5 Fourier spectra of the rotating component of pressure signals without rod protrusion and with rod protrusion at different lengths for  $M=1$ .

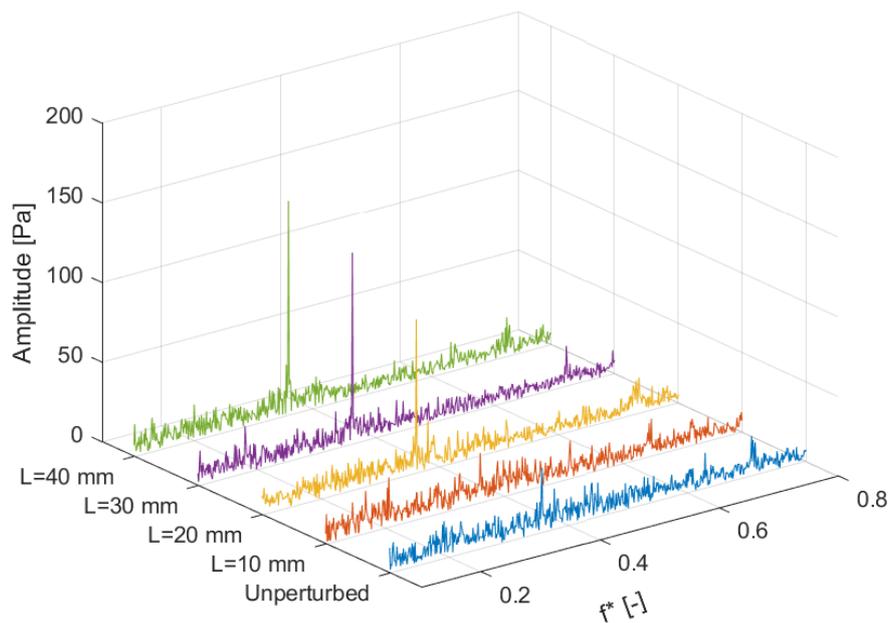


Figure 6 Fourier spectra of the plunging component of pressure signals without rod protrusion and with rod protrusion at different lengths for  $M=1$ .

This configuration led to results like those occurring for  $M=-1$ . The pressure fluctuations associated with the plunging component of the RVR are not affected at a protrusion length of  $L=10$  mm, but start to intensify for  $L=20$  mm, and subsequently display a monotonic increase with further increase of the protrusion. The amplitude of the rotating component also follows a pattern similar to  $M=-1$  configuration, with an initial increase in mitigation from  $L=10$  mm protrusion to  $L=20$  mm protrusion, followed by a subsequent decrease in the percentage of mitigation from  $L=20$  mm to  $L=30$  mm. At  $L=40$  mm, however, the mitigation increases to its relative maximum for this configuration in contrast to previous case where the maximum mitigation was observed at  $L=20$  mm. The respective mitigation

percentages of rotating component achieved for the protrusion lengths from 10 mm to 40 mm in this case were 30%, 41%, 37%, and 51%.

### 3.3. Configuration $M=2$

The frequency spectra of the pressure signals measured for different protrusion lengths in this configuration are displayed in Fig.7 and Fig.8 for rotating and plunging components, respectively.

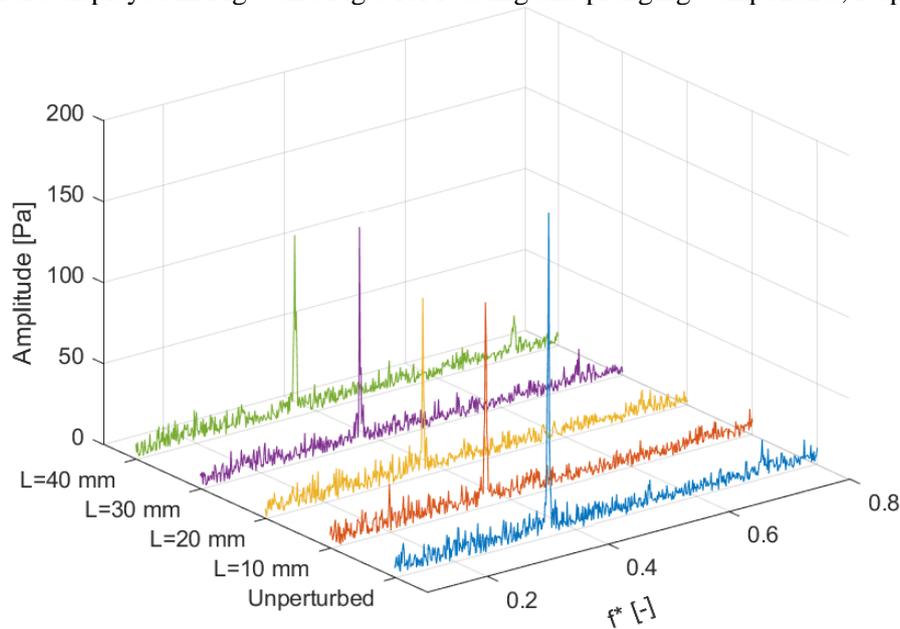


Figure 7 Fourier spectra of the plunging component of pressure signals without rod protrusion and with rod protrusion at different lengths for  $M=2$ .

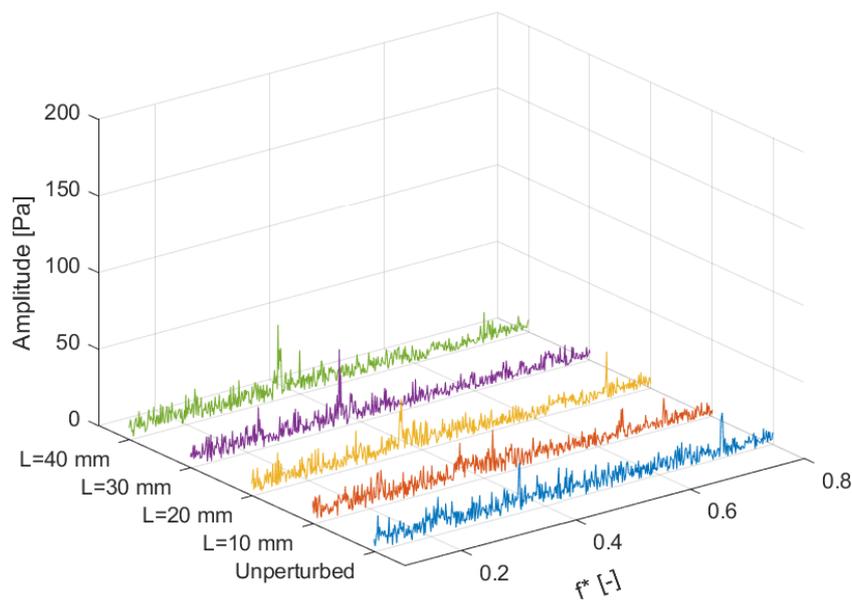


Figure 8 Fourier spectra of the plunging component of pressure signals without rod protrusion and with rod protrusion at different lengths for  $M=2$ .

As can be inferred from the figures, an increase of the plunging amplitude did not occur with the onset of pulsating rod protrusion in this case. Even after performing rod protrusion at the maximum length of  $L=40$  mm with this configuration, the plunging mode remained inferior to the dominant rotating component. As for the rotating component, the mitigating effects demonstrated are generally in agreement with the previous configurations. The amplitude of pressure fluctuations attributed to the

rotating component of the RVR after mitigation dropped by 37%, 44%, 31% and 44% for  $L=10$  mm,  $L=20$  mm,  $L=30$  mm, and  $L=40$  mm, respectively.

#### 4. Discussion

A summary of the results displayed previously is presented in Table 1 where the percentage of the changes in pressure fluctuation amplitudes in both components are displayed for each configuration and protrusion length.

**Table 1.** Summary of protrusion effects on RVR plunging and rotating components for different configurations.

$L$ (mm)	$M=-1$		$M=1$		$M=2$	
	Rotating (%)	Plunging (%)	Rotating (%)	Plunging (%)	Rotating (%)	Plunging (%)
10	-26	+11	-30	-22	-37	-15
20	-62	+63	-41	+107	-44	-4
30	-52	+68	-37	+216	-31	+42
40	-50	+79	-56	+305	-44	+44

A common observation for all cases is that at  $L=20$  mm, the mitigation of the rotating component is either maximum or close to its maximum. In addition, at  $L=30$  mm, a significant decrease in mitigation of the rotating mode is observed compared to  $L=20$  mm. The pulsating movement of the rods can have two effects; one being the momentum they bring into the flow field through their travelling movement, and the other being the interaction of the fluid flow with the solid body both at the tip and over the length of the rods. The interaction of the swirling flow over the tip of the rod is speculated to cause rolling up of the shear layer resulting in formation of small vortices when the tip of the rod is located within the high-tangential velocity region surrounding the stagnation zone. The transverse motion of these vortices can cause flux of momentum into the interface between the high-tangential velocity region and the stagnation zone causing the shrinkage of the latter, and this shrinkage is known to contribute to the mitigation of the RVR-related pressure pulsations [7]. With that in mind, the closer the tip of the rod is placed to the stagnation/rotating interface, the higher the mitigation of the rotating component. Thus, it can be deduced that the stagnation zone in the current investigation has a radius of approximately 20 mm, which is the reason behind the discrepancy between the mitigation of the rotating component at  $L=20$  mm and both  $L=10$  mm and  $L=30$  mm.

Furthermore, the interaction between the solid bodies and the swirling flow reduces the tangential velocity on the periphery of the stagnation zone [7]. This may explain the mitigation for all protrusion lengths.

Based on the above discussions, the mitigation should not change significantly when the rods exceed the interface of the stagnation zone. However, the results indicate a notable increase in mitigation at  $L=40$  mm compared to  $L=30$  mm for all configurations except  $M=-1$ . This can be explained through the momentum that the rods transfer into the flow field -especially into the stagnation zone- with their pulsating movement, playing yet another role in addition to the other two discussed.

When comparing the effects between the configurations, the employment of  $M=-1$  configuration clearly results in a better mitigation of the rotating mode.  $M=1$  triggers the largest plunging mode increases.  $M=2$  configuration has the least effect on the plunging component. Obviously, further investigations are required in this sense to clarify the exact behavior of each configuration.

## 5. Conclusion

An experimental study was conducted on a down-scaled propeller turbine operating at part load condition to investigate the effects of frequential solid body protrusion into the swirling cross flow of the draft tube cone on mitigation of the pressure fluctuations induced by the RVR. Four rods separated by 90 degrees were periodically protruded into the flow field at four different lengths and with three different configurations. The phase difference between the rods for these configurations was 90 degrees in clockwise direction, 90 degrees in counter-clockwise direction, and 180 degrees, designated by  $M=-1$ ,  $M=1$ , and  $M=2$ , respectively. Time-dependent pressure measurements were performed at two points in the draft tube and Fourier spectra was obtained for the pressure signals decomposed into rotating and plunging modes.

The results indicated that  $M=-1$  was the most effecting configuration in mitigating the rotating component of the RVR. However, protrusion of the rods aggravated the plunging mode with  $M=2$  triggering the least effect and  $M=1$  inducing the most severe increase in the plunging mode.

It was proposed that frequential protrusion of the rods interacts with the RVR and the swirling flow of the draft tube through three mechanisms that consequently lead to the mitigation of the rotating component: i) reduction of the swirl in the high-tangential velocity region ii) flux of momentum into the interface of the stagnation zone -at the core of the swirling flow- through formation of transverse shedding vortices at the tip of the rods (when rod tips are located in the high-tangential velocity region), thus shrinking the stagnation zone iii) injection of momentum to into the stagnation zone by motion of the rods.

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