IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

Evaluation of runner cone extension to dampen pressure pulsations in a Francis model turbine

To cite this article: Peter Joachim Gogstad and Ole Gunnar Dahlhaug 2016 *IOP Conf. Ser.: Earth Environ. Sci.* **49** 082019

Evaluation of runner cone extension to dampen pressure pulsations in a Francis model turbine

Peter Joachim Gogstad and Ole Gunnar Dahlhaug

Waterpower Laboratory, NTNU, 7491 Trondheim, Norway

E-mail: `peter.j.gogstad@ntnu.no`

Abstract. Today's energy market has a high demand of flexibility due to introduction of other intermittent renewables as wind and solar. To ensure a steady power supply, hydro turbines are often forced to operate more at part load conditions. Originally, turbines were built for steady operation around the best efficiency point. The demand of flexibility, combined with old designs has showed an increase in turbines having problems with hydrodynamic instabilities such as pressure pulsations. Different methods have been investigated to mitigate pressure pulsations. Air injection shows a significant reduction of pressure pulsation amplitudes. However, installation of air injection requires extra piping and a compressor. Investigation of other methods such as shaft extension shows promising results for some operational points, but may significantly reduce the efficiency of the turbine at other operational points. The installation of an extension of the runner cone has been investigated at NTNU by Vekve in 2004. This has resulted in a cylindrical extension at Litjfossen Power Plant in Norway, where the bolt suffered mechanical failure. This indicates high amplitude pressure pulsations in the draft tube centre. The high pressure pulsation amplitudes are believed to be related to high tangential velocity in the draft tube. The mentioned runner cone extension has further been developed to a freely rotating extension. The objective is to reduce the tangential velocity in the draft tube and thereby the pressure pulsation amplitudes.

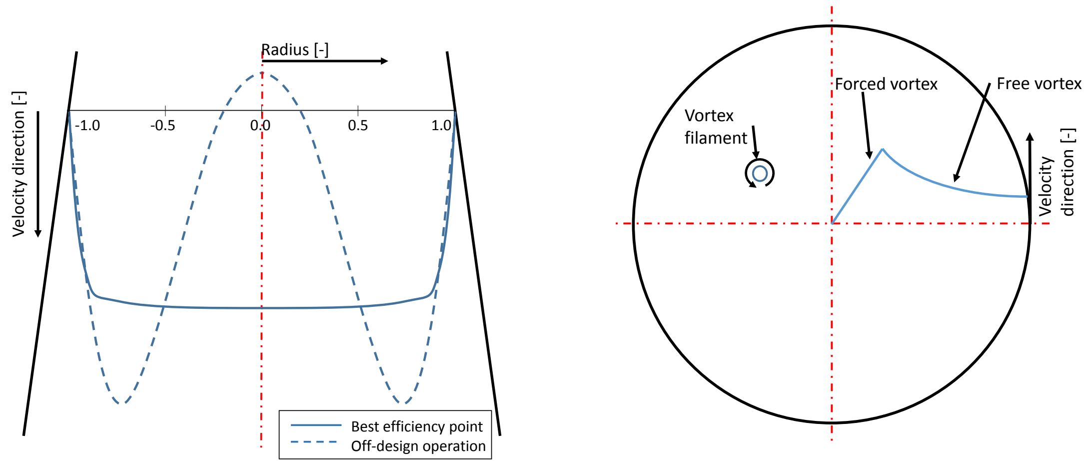
1. Introduction

Hydropower is a renewable energy source with high efficiency. Moreover, its storage capacity and flexibility in power generation makes hydropower an excellent form of energy generation to ensure steady power supply. Increased amount of intermittent energy generation introduced the last years has increased the flexibility demand of the energy market. This has led to increased part load operation of hydro turbines. Originally, turbines were built for steady operation around the best efficiency point. The demand for flexibility, combined with old designs has shown an increase in turbines having problems with hydrodynamic instabilities such as pressure pulsations. Direct consequences of pressure pulsations may be cavitation erosion and fatigue damages.

Mitigation of pressure pulsations is considered an important task to reduce fatigue damages in order to increase the turbine lifetime. There is a strong coupling between the axial and tangential velocity profiles in the draft tube at part load operation [1]. The radial pressure gradient and the presence of vortex rope is influenced by the tangential velocity [2]. To reduce the tangential velocity, experiments with a freely rotating runner cone extension (FRUCE) has been carried out. Introducing a runner cone extension in the draft tube has previously shown promising result with regards to reduce pressure pulsation amplitudes. When the runner cone extension is rotating freely it will only be driven by the free vortex in draft tube and thereby reduce the tangential velocity and pressure pulsation amplitudes.

2. Background

Rotating machinery such as turbines tend to create periodic pressure fluctuations known as pressure pulsations. Vortex breakdown occurring in the draft tube is recognized as the primary cause of severe flow instabilities and pressure pulsations [3]. Cassidy and Falvey [4] discovered that a helical vortex could form downstream of the vortex breakdown. This phenomenon is often referred to as the rotating vortex rope (RVR) in the hydropower literature [5]. One of the strongest pressure pulsation amplitudes is often related to the RVR. For fixed blade runners, such as Francis, a vortex rope tends to occur in the draft tube at part load operation.



(a) Axial velocity profile (b) Tangential velociy profile with vortex filament

Figure 1. Theoretical velocity profiles in a turbine draft tube

For Francis runners, performance is influenced by the design of the runner, guide vanes and draft tube. The flow regime in the draft tube is normally described by two velocity components: axial and tangential as illustrated in Figure 1. The tangential velocity is known to be the driving force of the RVR. The tangential velocity profile is generally assumed to be a Rankine vortex, i.e. a combination of a forced and free vortex, as shown in Figure 1b. It illustrates an ideal Rankine vortex which is referred to in the present work. In a typical Francis turbine, the profile of the trailing edge will define the tangential velocity profile at the inlet of the draft tube. The tangential velocity component is also known as the swirl component, as it is the component describing the swirl. The definition of swirl number is as follows;

$$S = \frac{\int_{R_i}^{R_0} v \cdot w \cdot r^2 \cdot dr}{\int_{R_i}^{R_0} v^2 \cdot r \cdot dr} \tag{1}$$

Where w is the tangential velocity component and v is the axial velocity component. For swirl numbers larger than 0.10, a Rankine vortex is present [6][7]. The vortex filament within swirl flow was described analytically by Hardin [8] and Alekseenko and Kuibin [9]. If the swirl is sufficiently strong, the vortex filaments may easily roll up into a single vortex core [10]. This type of filament is also found in draft tubes, where it is observed as a helix or spiral rotating around the draft tube center [10][11]. In the field of hydropower, the spiral vortex filament is known as a vortex rope. If the pressure is low enough, the vortex rope is visible due to vapor core.

The remaining hydraulic energy in the draft tube is divided between pressure and kinetic energy. The kinetic energy is again divided into three velocity components, where the tangential and axial velocity are dominating. Due to the strong coupling between the axial and tangential velocity components in the draft tube at off design condition [1], the axial velocity profile will change according to Dahlhaug [7] and the static pressure in the radial direction will change. For swirl numbers higher than one, vortex breakdown occurs and the axial flow in the central region of the draft tube will reach zero and reverse flow may occur. The vortex rope is located in the shear layer between the central stalled region and the swirling main-flow with a low pressure zone in the center of the vortex rope [10]. Particle Image Velocimetry (PIV) measurements performed by Ciocan and Iliescu [12] demonstrated the movement of the rotating vortex rope. The movement of the vortex rope was also documented with Laser Doppler Vibrometer (LDV) by Vekve [2]. Reducing the maximum tangential velocity seems to be one of the keys to mitigate pressure pulsations in the draft tube, as this approach reduces the swirl number.

Different methods have been investigated to mitigate pressure pulsations, such as air injection, water injection and other passive installations in the turbine. Different methods of air injection have been investigated by different authors [3][13][14][15][16]. Results are case dependent, meaning a decrease in pressure pulsation amplitudes at one turbine, does not mean the same result in another. Both an increase and a decrease in pressure pulsation amplitudes were observed by Muntean et.al. [16], depending on operational point. Further, March [14] pointed out there may be significant efficiency losses, up to 4% related to air injection. The efficiency loss is dependent on method of air injection and amount of air. Increased air volume flow lead to increased losses as shown by March [14].

Passive installation such as fins and runner cone extension has been tested by different authors [2][17][18][19]. A runner cone extension tested at NTNU by Vekve [2] showed promising results in reduction of pressure pulsation amplitudes. Vekve tested two different lengths with three different diameters of $0.1D_2$, $0.21D_2$ and $0.41D_2$. The longest runner cone extension with largest diameter showed the best dampening of pressure pulsastion amplitudes. This resulted in a full scale test at Litjfossen Hydro Power Plant in Norway. The test showed minor reduction in efficiency ($\tilde{0}.5\%$), but 30-40% reduction in pressure pulsation amplitudes at part load. Vekve concluded that the shaft extension moves the initiation point of the vortex rope further downstream and can reduce the strength of the vortex rope (i.e., the amplitude of the RVR). The further downstream the vortex breakdown occurs, the shorter the distance the RVR has available for longitudinal development. Eventually, the bolt keeping the runner cone extension in place suffered mechanical failure, and the runner cone extension was found further downstream. This indicates high amplitude pressure pulsations in the draft tube centre.

A numerical investigation of a counter rotating cone in a Kaplan elbow was performed by Cervantes [20]. Though he did not extend the runner cone, he found that a slower rotation than the runner increased pressure recovery and reduced the losses. The results also found a stationary runner cone to be beneficial for the draft tube performance. This paper will further investigate a freely rotating runner cone extension at a model turbine. The focus of the paper will be possible improvements with a freely rotating runner cone extension (FRUCE).

3. Experimental setup

The experiment was carried out at the Waterpower Laboratory at NTNU in Trondheim. The Tokke model runner, which is a high head Francis runner, was used for the experiments. This turbine is also the model runner used as a reference in Francis-99 workshops [21]. In order to investigate the pressure fluctuations in the draft tube cone, four Kulite 701A dynamic pressure

Table 1. Operational points

Operational points	Guide vane opening [degrees]	Volume flow $[m^3/s]$	Relative Volume flow Q/Qbep [-]
1	3,999	0,086	0,43
2	5,009	0,106	0,53
3	6,020	0,127	0,63
4	7,031	0,147	0,73
5	8,129	0,169	0,84
6 (BEP)	9,887	0,202	1,00
7	11,030	0,223	1,11
8	11,997	0,241	1,20
9	13,051	0,256	1,29

sensors were flush mounted as shown in Figure 2. Two sensors in the upper cone labeled P1 and P2, and two in the lower cone labeled P3 and P4. Two and two sensors were mounted directly opposite to each other. Additional pressure sensors were mounted at inlet and downstream the runner cone, but the analysis from these will not be included in this paper. The rotation of the runner cone extension was measured optically.

The measurements was carried out with a constant head of 12 m and constant rotational speed at 333 rpm. NI Labview was used to acquired the data. The pressure data was amplified and acquired with a logging frequency of 2777.8 Hz with NI 9239 logging card. The different operating points are shown in Table 1.

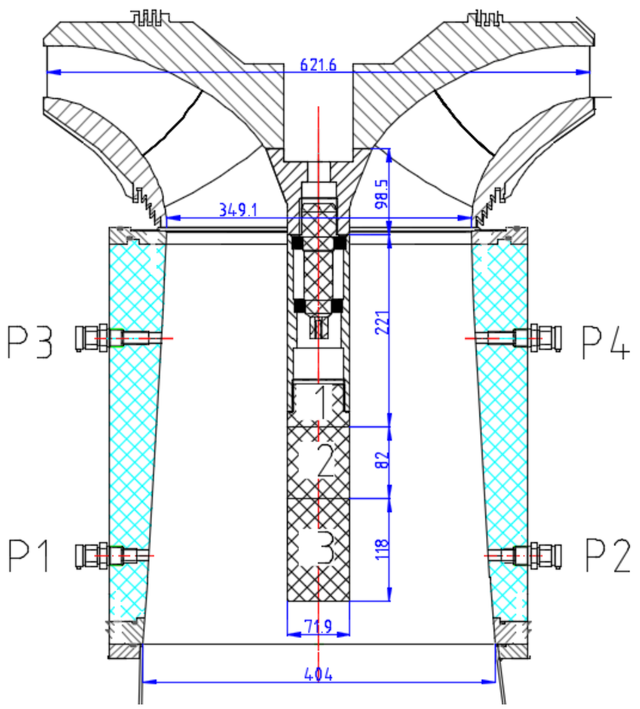


Figure 2. Freely rotating runner cone extension with the different lengths; FRUCE 1 = $0.62D_2$, FRUCE 2 = $0.86D_2$ and FRUCE 3 = $1.20D_2$. The location of pressure sensors can be seen on the draft tube wall. The dimension in the drawing is given in millimeters

IOP Conf. Series: Earth and Environmental Science **49** (2016) 082019 doi:10.1088/1755-1315/49/8/082019

4. Freely rotating runner cone extension

The runner cone extension was designed as a cylinder. The runner cone was modified to fit the extension. Figure 2 shows the drawing of the modified runner cone and with the extension. A transition part with bearings was fitted between the runner cone and the extension to allow the extension to rotate freely. The runner cone extension was tested with three different lengths; $0.62D_2$, $0.86D_2$ and $1,20D_2$, where is D_2 the outlet diameter. The diameter of the runner cone extension, D_s, was $0.21D_2$ for all lengths.

5. Data processing

The pressure data was processed to investigate the frequency spectra, peak-to-peak values. For this paper the data was resampled to a frequency of 500 Hz. An antialiasing Finite Impulse Response (FIR) lowpass filter was applied and the time delay introduced by the filter was compensated for. Further, a lowpass Butterworth filter was applied with a cut-off frequency of $2.2f_n$, where f_n is the runner frequency equals to 5.55 Hz. The cut-off frequency was chosen to filter out rig specific frequencies at 15 Hz and 40 Hz. Peak-to-peak values was found by using a 99% confidence interval. The effective confidence interval is lower than 99% since a filter has been applied to the data. Fast Fourier Transform (FFT) was applied to achieved the frequency spectra.

6. Results and discussion

6.1. Measurements of rotation

The rotation of the runner cone extension was measured optically and shown in Fig. 2. The largest rotational speed is reached at full load, where the FRUCE is rotating the opposite direction of the turbine. The rotational speed reached -1.08 relative speed for the longest FRUCE. The velocity of FRUCE seems to have linear relationship from $0.84Q/Q_{BEP}$ to full load at $1.29Q/Q_{BEP}$. At full load there is not much separating the different FRUCEs.

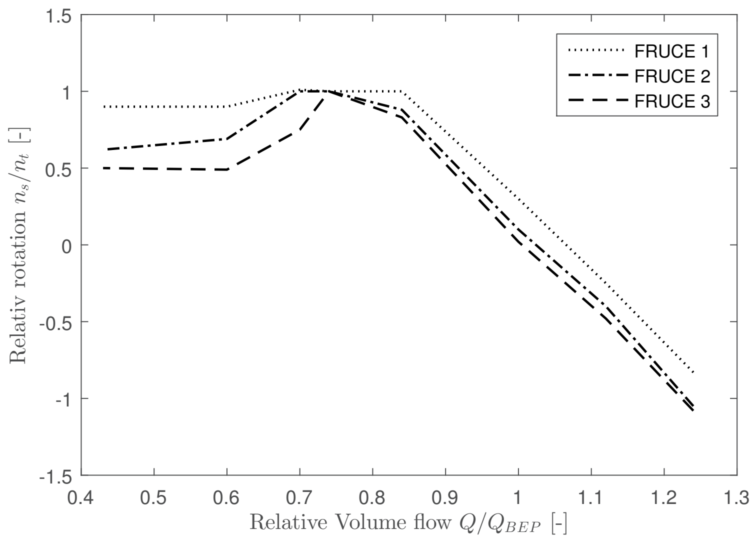


Figure 3. FRUCE rotation as a function of flow rate. The relative speed is given by the FRUCE rotational speed, n_s, and the runner speed, n_t.

Compared to a locked runner cone extension, the velocity of the FRUCE is reduced at low load. The lowest rotational speed is found for the longest FRUCE. This is due to the tangential velocity in the lower part of the draft tube is reduced. The lower tangential velocity is helping to reduce the speed of the runner cone. This is also the area where the largest amplitudes related to the Rheingans frequency is found.

At part load the length clearly has influence on the rotational speed of the FRUCE. All the three FRUCEs reached runner speed at $0.73Q/Q_{BEP}$, but they never increase above rotational speed of the runner. The longest FRUCE reduces the speed first and reached the lowest speed when moving toward lower flow rate.

6.2. Pressure analysis

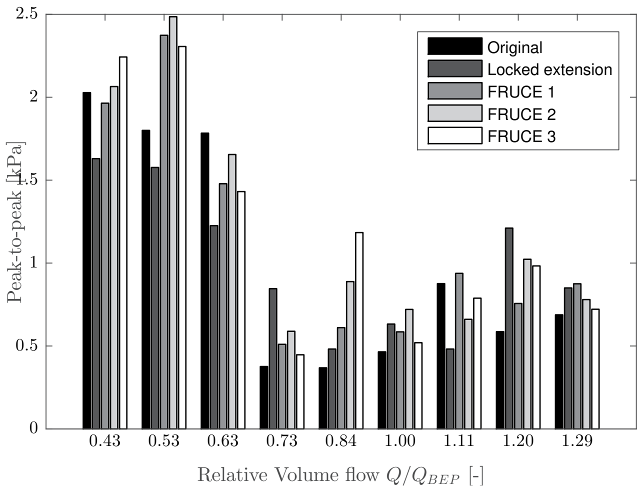


Figure 4. Peak-to-peak values for a 99% confidence interval for the upper measuring plane of the Francis model draft tube

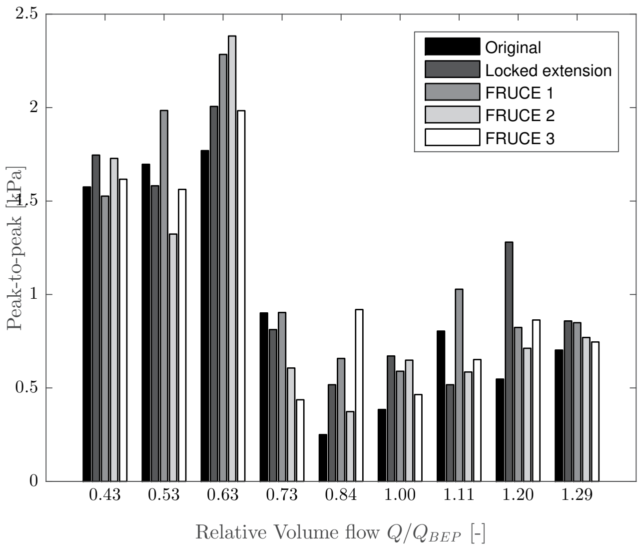


Figure 5. Peak-to-peak values for a 99% confidence interval for the lower measuring plane of the Francis model draft tube

The peak-to-peak values with a 99% confidence interval for the upper plane is shown in Figure 4 and in Figure 5 for the lower plane. The locked runner cone extension clearly has an dampening effect on the amplitudes in the upper plane at part load. However, the difference in the lower plane is minor. In both cases the locked runner cone extension has a negative effect at $1.2Q/Q_{BEP}$. The FRUCEs have increased peak-to-peak values in the upper plane at $0.53Q/Q_{BEP}$, while a small dampening can be seen for the two longest FRUCEs in the lower plane. The opposite effect can be observed when the flow is increased to $0.63Q/Q_{BEP}$. Higher amplitudes for the FRUCEs in the lower plane, but dampened in the upper plane.

The high peak-to-peak values at the upper plane is probably a consequence of the FRUCE diameter. It removes the forced votex in the draft tube center and allow the free vortex to develop towards the FRUCE diameter. The free vortex will therefore reach a higher velocity at the surface of the FRUCE than it would without. The authors assume this is the reason for the increasing pressure amplitude. Considering conservation of angular momentum, the tangential velocity profile will change due to the expansion of the draft tube cone. The tangential velocity profile will therefore reach a lower velocity at the FRUCE as shown with the modified velocity profile in Figure 6. The speed of the FRUCE will be influenced by the sum of the viscous forces working in tangential direction.

At $0.63Q/Q_{BEP}$ the peak-to-peak values are lower in the upper plane, than in the lower. A small dampening can be found in comparison to the original design in the upper plane. The authors have no explanation for this phenomenon. However, the FRUCE velocity is increased at this flow rate compared to lower flow rate where the FRUCE speed is fairly constant. This may cause a transmission of energy to lower measuring plane and therefore an increase in peak-to-peak values.

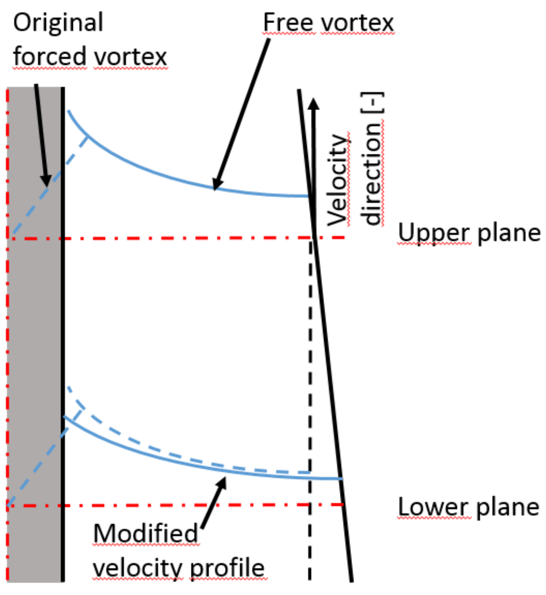


Figure 6. Ideal tangential velocity profiles at upper an lower measuring plane with FRUCE. The ideal velocity profile is shown with a dashed line in the lower plane and the modified velocity profile is shown with a solid line.

At high load the FRUCEs generally performs better than the locked runner cone extension for flows larger than $1.2Q/Q_{BEP}$. The peak-to-peak values are clearly more consistent from upper to lower plane with higher flows than $0.73Q/Q_{BEP}$. From $0.84Q/Q_{BEP}$ and higher, the original design shows the smallest peak-to-peak values except at $1.11Q/Q_{BEP}$.

The frequency spectra presented are focused on the low frequency amplitudes, especially related to the RVR. The runner frequency, f_n, is 5.5 Hz for all operational points as the runner speed was kept constant.

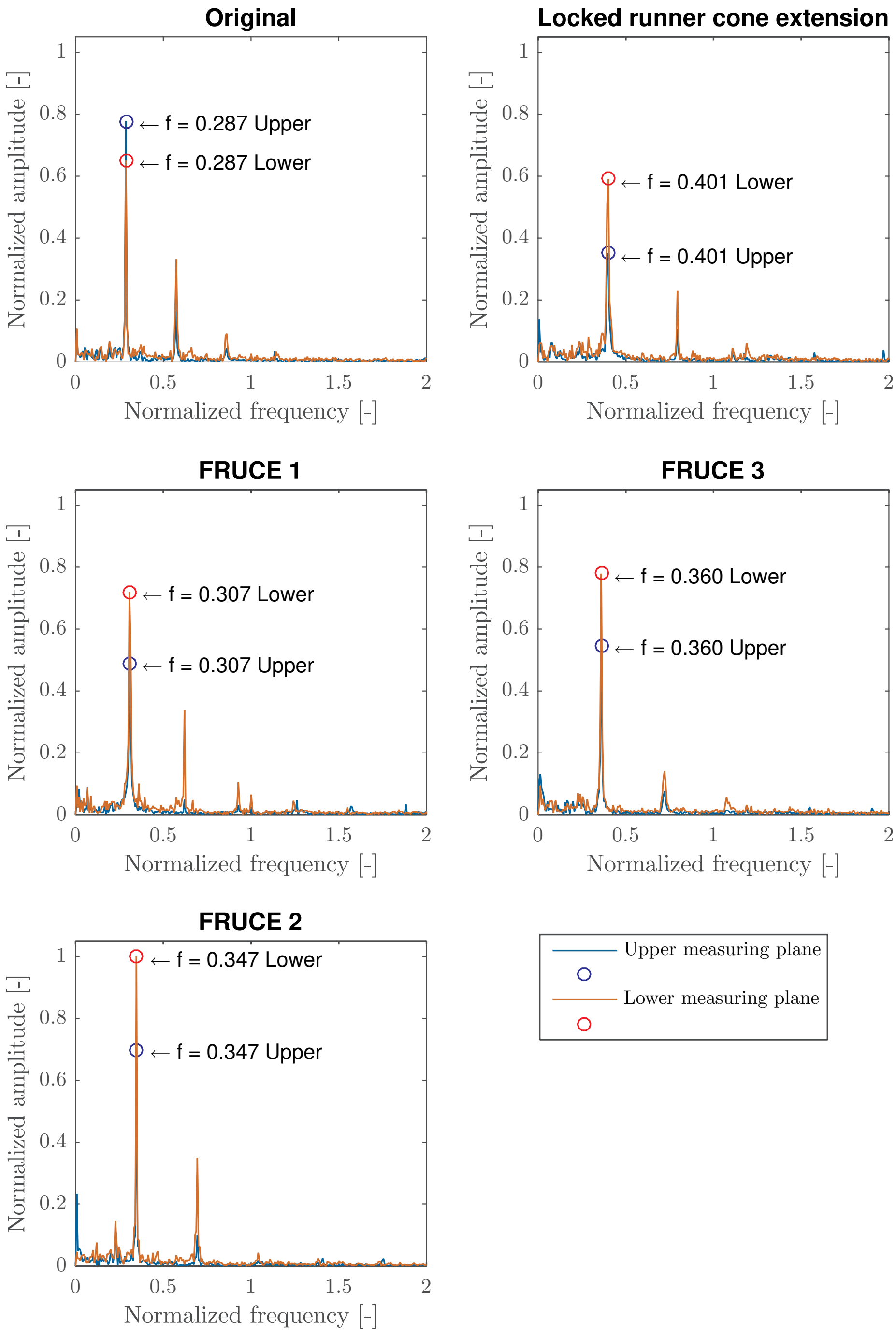


Figure 7. Frequency analysis for $0.63Q/Q_{BEP}$ with upper and lower measuring plane

The frequency spectra from upper and lower measuring plane shown in Figure 7 show two significant peaks at $0.29f_n$ and $0.57f_n$. The dominant frequency at $0.29f_n$ is the vortex rope frequency for the original design. In the lower measuring plane this frequency has an increased amplitude for FRUCEs while a small dampening can be noted for the locked runner cone extension. However, in the upper measuring plane there are a significant dampening for all runner cone extensions. The amplitude for the dominating frequency for FRUCE 3 is decreased by 30%, while for the locked runner cone extension the reduction in amplitude is 55%. The reduction in amplitudes are greater than what can be seen from the peak-to-peak analyses. The vortex rope frequency is also shifted towards a higher frequency with the installation of the FRUCEs. The trend is the longer FRUCE, the higher dominating frequency. However, the locked runner cone extension produces the highest frequency.

7. Conclusion

The results show that the freely rotating runner cone extension has an dampening effect in some cases at part load. However, only the locked runner cone extension shows better dampening effect in most cases. From $0.84Q/Q_{BEP}$ and higher, the original design shows the smallest peak-to-peak values expect at $1.11Q/Q_{BEP}$.

The tangential velocity of the water is highest at $0.73Q/Q_{BEP}$. However, the highest peak-to-peak values are found at lower flow rate than $0.73Q/Q_{BEP}$.

The FRUCE did not achieve the dampening which was hoped for. This is most likely due to a to small diameter of the FRUCE. Previous results from Vekve [2] shows improvement with increased diameter. An increased diameter will also increase the axial velocity more and thereby decrease the swirl number.

References

[1] Lucca-Negro O and O'Doherty T 2001 *Progress in Energy and Combustion Science* **27** 431–481 ISSN 0360-1285
[2] Vekve T 2004 *An experimental investigation of draft tube flow* Ph.D. thesis
[3] Baya A, Muntean S, Câmpian V C, Cuzmoş A, Diaconescu M and Bălan G 2010 *IOP Conference Series: Earth and Environmental Science* **12** 012007 ISSN 1755-1315
[4] Cassidy J J and Falvey H T 1970 *Journal of Fluid Mechanics* **41** 727–736 ISSN 1469-7645
[5] Jonsson P, Mulu B and Cervantes M 2012 *Applied Energy* **94** 71–83 ISSN 03062619
[6] Sloan D G, Smith P J and Smoot L D 1986 *Progress in Energy and Combustion Science* **12** 163–250 ISSN 0360-1285
[7] Dahlhaug O G 1997 *A study of swirl flow in draft tubes* Ph.D. thesis
[8] Hardin J C 1982 *Physics of Fluids* **25** 1949 ISSN 00319171
[9] Alekseenko S and Kuibin P 1995 *Numerical methods in laminar and turbulent flow.* **9** 382–393
[10] Nishi M and Liu S 2013 *International Journal of Fluid Machinery and Systems* **6** 33–48
[11] Dörfler P, Sick M and Coutu A 2012 *Flow-Induced Pulsation and Vibration in Hydroelectric Machinery: Engineers Guidebook for Planning, Design and Troubleshooting* (Springer Science & Business Media)
[12] Ciocan G D and Iliescu M S 2007 Vortex rope investigation by 3D-PIV method *Proceedings of the 2nd IAHR International Meeting of the Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems, Timisoara, Romania* pp 159–172
[13] Papillon B, Sabourin M, Couston M and Deschenes C 2002 Methods for Air Admission in Hydro Turbines *21st IAHR Symposium on Hydraulic Machinery and Systems, Lausanne, Switzerland, September* pp 9–12
[14] March P 2011 Hydraulic and Environmental Performance of Aerating Turbine Technologies *EPRI, Palo Alto, California, Proceedings of EPRI/DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers Report*
[15] Casanova Garcia F and Mantilla Viveros C A 2010 *Revista Facultad de Ingeniera Universidad de Antioquia* 90–98
[16] Muntean S, Susan-Resiga R, Campian V C, Dumbra C and Cuzmos A 2013 *Proc. of the 6th Int. Conference on Energy and Environment (CIEM)*
[17] Qian Z D, Li W, Huai W X and Wu Y L 2012 *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* **226** 137–150 ISSN 0957-6509, 2041-2967

[18] Thicke R 1981 *Water Power & Dam Construction* **Februray 1981** 31–37
[19] Nishi M, Wang X, Yoshida K, Takahashi T and Tsukamoto T 1996 An experimental study on fins, their role in control of the draft tube surging *Hydraulic Machinery and Cavitation* (Springer) pp 905–914
[20] Cervantes M J 2009 Counter rotating runner cone in a Kaplan elbow draft tube for increased efficiency *3rd IAHR International Meeting of the Worksgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems*
[21] Fossen C Francis-99 URL `http://www.ntnu.edu/nvks/francis-99`