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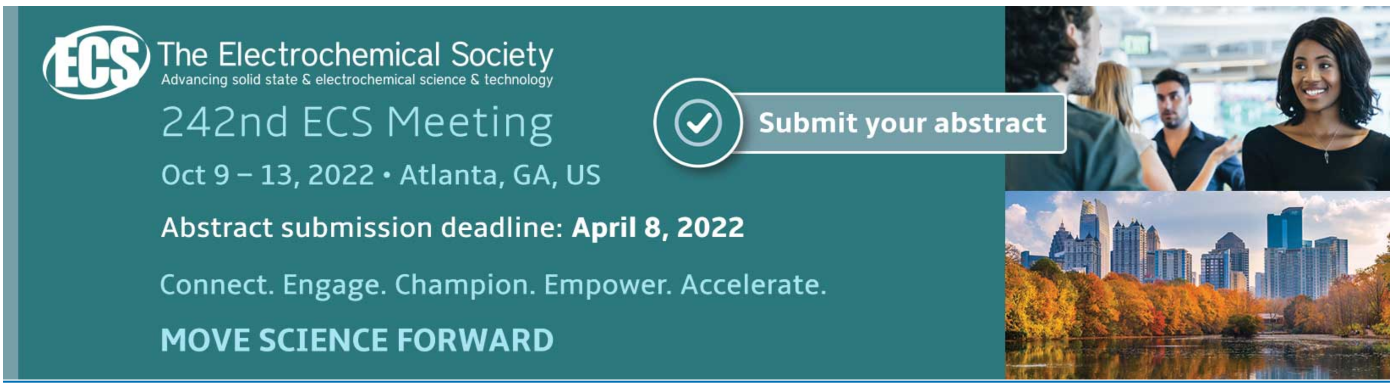

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Modal testing of the Francis-99 runner

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Abstract. The Francis-99 low specific speed Francis runner has undergone much study in the years since it was first made available to the public. The High Head Francis(HiFrancis) project, hosted by the Waterpower Laboratory at NTNU, have conducted multiple experimental campaigns to supply validation data for numerical simulations of the RSI phenomenon for the runner. Due to the amount of instrumentation on board the runner an asymmetry exists in the runner structure that naturally affects the structural response of the runner. From numerical analysis the runner has been found to exhibit multiple natural modes of vibration, within narrow frequency bands. In order to validate the identified natural frequencies, with their corresponding mode of vibration and the amplitude, an experiment has been conducted. The experiment utilises piezo electric patches mounted on the runner hub to excite the runner in a defined mode of vibration and the response at the trailing edge of all blades is measured with a 1D Laser Doppler Vibrometry scanner. Preliminary results are shown that demonstrate the possibilities with the presented experimental method.

Keywords: Francis runner, Vibration, Modal testing

1. Introduction

During operation a hydraulic turbine runner will be subjected to oscillating loads from multiple sources caused by the interaction between the water and both the rotating and stationary structure. For a turbine runner to operate safely, none of the present oscillations may fall within any of the natural modes of vibration of the runner. The confidence in the identification of these modes of vibration during the design phase of the runner must therefore be high in order to ensure safe operation and a long technical lifetime.

The Francis-99 runner is a low specific speed bolted Francis runner with 15 + 15 splitter and full-length blades that has been made available to the public The runner has undergone multiple experimental and numerical campaigns over the years, most recently the HiFrancis project[1] and Francis-99 workshops[2]. Both of these projects were hosted by the Waterpower Laboratory, and have focused on the RSI phenomena found in low specific speed Francis runners[3, 4, 5, 6]. During these experimental

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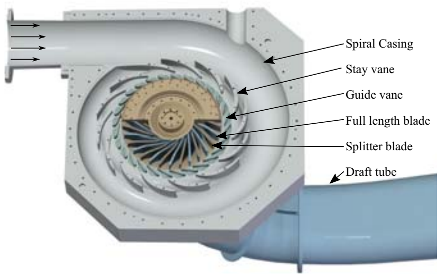
campaigns, the Francis-99 runner has been found to operate at resonance condition with the second harmonic of the guide vane passing frequency[3].

The runner features a bolted design, where the runner vanes are placed in slots in the hub/shroud and fastened with bolts at specific position with a limited contact surface. The degree of contact between the runner vanes and the hub/shroud on these surfaces, and along the non bolted parts of the slot are a source of uncertainty. The numerical work conducted on the structural behaviour of the Francis-99 runner have thus met challenges when defining the model in these regions[6].

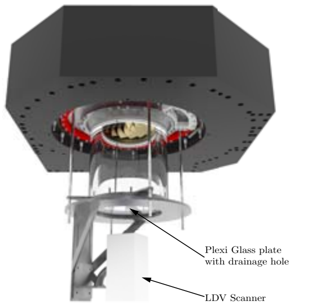
Due to the above mentioned uncertainty in the modelling of the runner, an experiment has been designed to identify the modes of vibration of the Francis-99 runner while at standstill in the test rig when filled with both water and air. By utilises piezoelectric patches(MFCs) mounted on the hub, the experiment enable excitation of the runner at any frequencies and modal shape, defined by nodal diameter (ND). This again enables the identification of both frequency and modal shape for each mode of vibration.

2. Experimental setup

The experiments were conducted with the runner installed in the Francis test rig at the Waterpower Laboratory. Experiments were done with the runner standing still in the rig filled with air and water. During the water filled experiments the draft tube cone was capped with a plexi glass plate which included a valve used for filling and emptying the rig. The structural response of the runner was measured with a 1 dimensional Laser Doppler Vibrometer (LDV) scanner from PolyTec (model PSV-500-NH). Figure 1 (b) shows a render of the LDV scanner and plexi glass cap mounted on the Francis rig.



(a) Model Francis turbine installed in test rig with draft tube installed.



(b) Francis rig with PSV-500-NH LDV scanner mounted without draft tube.

Figure 1: Full test rig illustration(a) and test rig with LDV system installed(b)

The amount of contact/bonding between the blade and ring close to the trailing edge in the Francis-99 runner has previously been a point of uncertainty[6]. To remove this uncertainty, the ring has been machined in order to ensure that no contact between the ring and blade is present, after which the blade and ring was bonded together with SikaFlex. SikaFlex is a flexible rubber base adhesive that was chosen to ensure no pressure leakage between the pressure and suction side of the blade in the area without a significant effect on the natural frequency, while still allowing disassembly. This alteration is believed to mimic the setup presented by Østby et al[6].

The LDV scanner performs vibrational measurements using laser doppler vibrometry at distinct positions, denoted scan points, on the geometry of interest. Measurements conducted in the experiments presented here were conducted by the instrument in the frequency domain, and the time needed for each scan point was thereby dependant on the frequency range and resolution required. The LDV includes an analogue output of the raw vibrational amplitude of the point where the laser is currently situated. This output was utilised in the initial evaluation of the frequency response of the runner to the different modal shapes in order to select relevant resonance peaks.

For all measurements the sampling rate for the LDV scanner was 10 kHz, the range 5 Hz to 2000 Hz and the bin size, i.e. resolution, of 0.2 Hz, which lead to a measurement time for each scan point of 200 ms. The above measurement time is needed to obtain an individual measurement of a single scan point, during the measurements at least 3 measurements were required and the average of these were used as the output for a given scan point. Hence, a single scan of the trailing edge of all the 15 full blades is strongly dependant on the number of scan points defined.

The software driving the LDV scanner enables the importing of 3D points which where mapped on the image obtained by the system to relate the scan points position to a 3D model of the runner. A 3D model of the runner geometry was used to define a set of equally spaced scan points along lines co-linear with the trailing edge. Each blade was given the same number of points placed at each 10% of the trailing edge length visible from the location of the LDV scanner. The initial point was placed at 5% and 9 points were added with the above distance resulting in the last point being placed at 95% of the width. Initially 6 lines upstream the trailing edge with increasing distance were defined, but due to limitations in the maximum possible excitation time only the 3 lines closest to the trailing edge were used. Figure 2 shows the runner outlet and trailing edge of one individual blade, with the measured points indicated in green and ignored points shown in purple.

(a) (b)

Figure 2: Scan points seen by the LDV Scanner(a) and shown on a single runner blade in 3D(b). Green points on both figures indicate the points measured during the experiments.

Figure 3 show the placement of the patches on the runner seen from the top and bottom view. Each MFC was driven by signals from a HVA 1500/50 high voltage amplifier supplied by Smart Materials. The amplifier was controlled by an in-house developed LabView program also responsible for logging data from both the monitoring channel on the amplifiers and other sensors utilised.

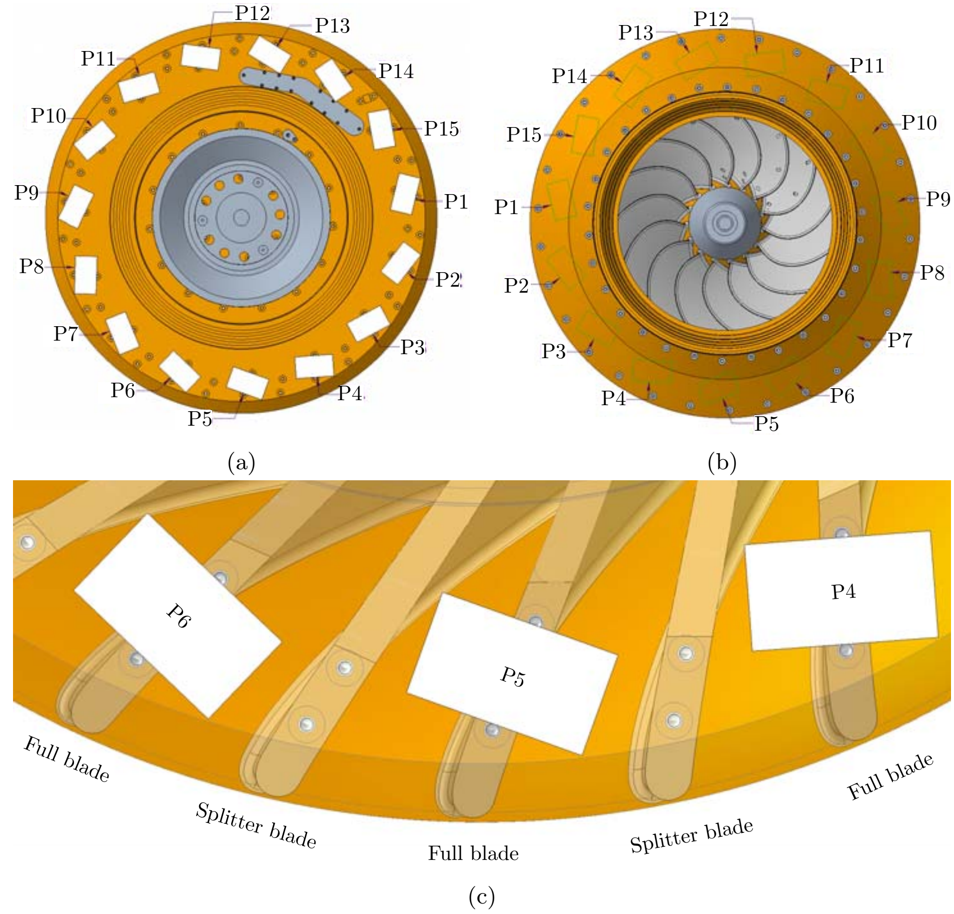


Figure 3: Patch placement on runner viewed from the top (a), the bottom (b) and shown relative to the blade mounting surfaces (c)

The excitation of the structure was conducted by the travelling wave method[7], where the excitation of each patch was phase shifted in order to induce the correct modal shape on the structure. The spacing between each MFC was equal to the spacing of full blades around the runner ($^{360°}/_{15} = 24°$), so that the phase shift (ϕ_{P_i}) for patch P_i during excitation of the modal shape corresponding to number of nodal diameters (ND) can be found by Equation 1.

$$\phi_{P_i} = 24° \cdot \mathrm{ND} \cdot i \tag{1}$$

This type of excitation on a circular structure produces a wave with the the same number of periods as the prescribed nodal diameter, which travels in the counter-clockwise direction in the top view as seen in Figure 3 (a).

By utilising the travelling wave excitation method the testing can be seen as independent of any asymmetry present in the runner structure .

Table 1 and Table 2 shows the relevant information regarding the input and output channels used during the measurements.

Measurand	Channel names	Logging rate
Patch Monitoring	Vmon1...Vmon15	10.24 kHz
LDV Response	LDV	10.24 kHz
LDV Scanner	-	10 kHz

Table 1: Input channels information

Output	Channel names	Logging rate
Patch Excitation	P1....P15	25 kHz

Table 2: Output channels information

3. Experimental Procedure

After the runner was installed in the test rig and all sensors were set up for acquisition, each patch was tested at 600 Hz with the rig filled with air, in order to evaluate if they functioned as planned. The patch test showed a significant non uniformity in the response to excitation on the different patches as seen in Figure 4. This non uniform behaviour may in the future be used to scale the results when viewing the modal movement. During these tests, patch number 10 was found to be non functional, the cause of the fault was found to be a malfunction in the amplifier. Due to the a very limited available time for the LDV scanner, patch 10 was disabled in all measurements.

The experiment followed the below steps for each modal shape ($ND = 1, 2, 3, 4$) with the runner installed in the test rig filled with both water and air.

(i) An initial frequency sweep was conducted with the single point response measured by the LDV at 35% of the trailing edge on one of the blades

(ii) The Frequency Response Function (FRF) for the sweep was calculated and the resonance peaks of the FRF were selected for further study. An example of an FRF can be seen in Figure 5 (a) where the two sweeps for ND1 with the rig filled with water is shown.

(iii) The runner was subsequently excited at each of the selected resonance frequencies with the relevant modal shape for approximately 600 s.

(iv) During the excitation all scan points on the runner outlet were measured by the LDV and the resulting FFT was stored.

After all resonance frequencies were measured, the above procedure was repeated with the single point response measures at 55% of the trailing edge. This was done in order to ensure that the response was not measured in a node of the vibrational shape of the trailing edge.

4. Post Processing

The data acquired with the LDV scanner was stored in the proprietary *SVD* format, which Polytec provide importing functions for MATLAB which were used to synchronise the measurands.

Measurements from the LDV Scanner were stored as complex numbers and frequencies, and the complex number was split into magnitude and phase for each

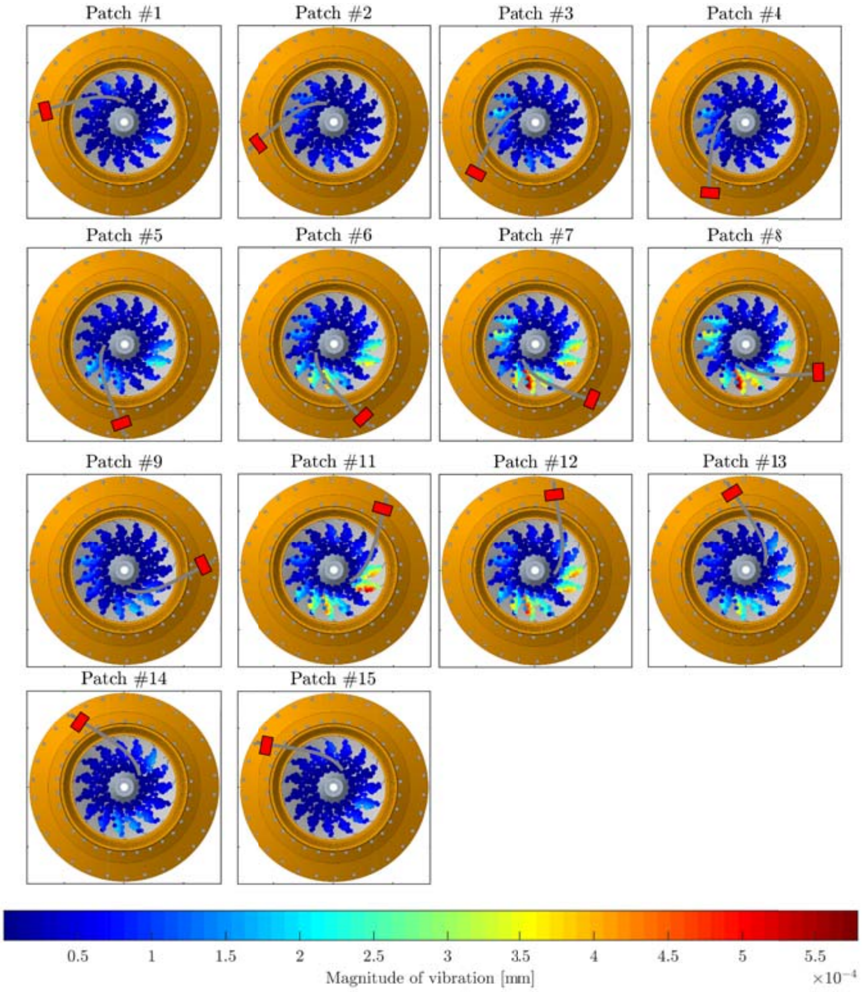


Figure 4: Magnitude plot from patch test conducted in air at 600 Hz

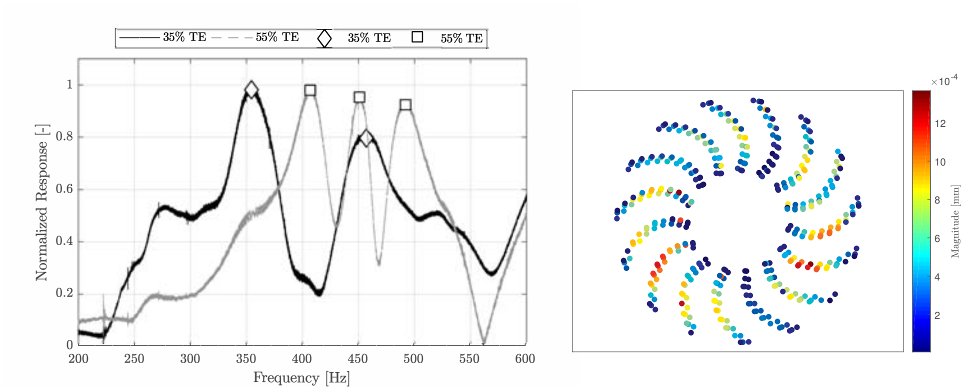
frequency. Figure 5 (b) shows an example of the output from the LDV scan, where the magnitude for each of the measurement points are shown by colour.

Locations on the outlet of the runner are defined by the position in the radial(spanwise) and angular(ϕ) direction.

As seen in Figure 5 (b) the LDV scanner produced results with a high degree of resolution in both the magnitudal and spacial dimension. Hence, the local response of the trailing edge caused by the excitation was possible to evaluate both in magnitude and actual deflection. For a scan point of the LDV (j) the actual deflection (x_j) at the frequency (f_j) with the magnitude ($\mathbf{Mag}_j$) and phase ϕ_j relative to the excitation at any point in time may be calculated from Equation 2.

$$x_j(t) = \mathbf{Mag}_j \sin(2\pi f_j t + \phi_j) \tag{2}$$

Magnitude was evaluated by isolating the scan points on each of the three lines located on the 15 individual trailing edges and processing them together. Actual deflection



(a) FRF Output for ND1 in a water filled rig

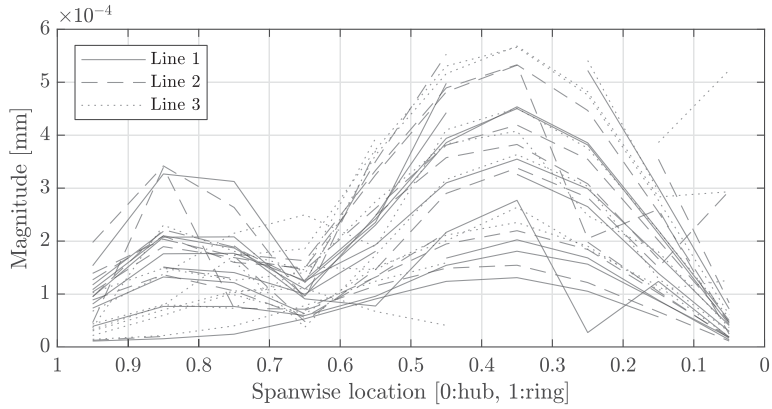
(b) Example of magnitude measured by the LDV Scanner from ND1 in a water filled rig.

Figure 5: Examples of output from the LDV scanner, FRF plot (a) and vibrational magnitude (b)

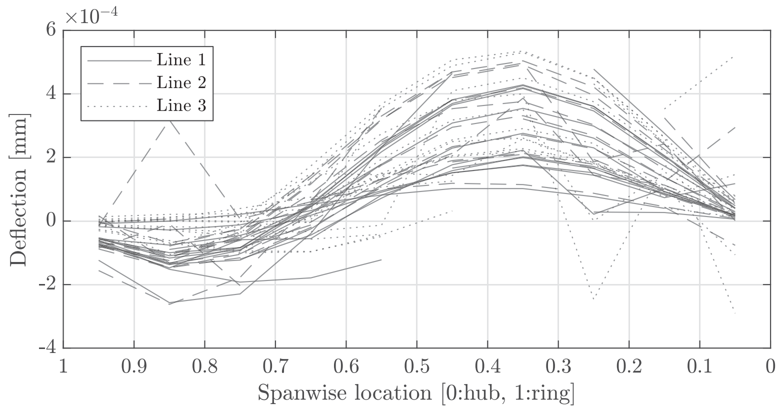
on trailing edges of all the blades were evaluated together by synchronising the phase of each blade according to the nodal diameter of the excitation, i.e. the reverse of the phase shifting applied to the excitation signal for the MFCs seen in Equation 1. Equation 3 shows the equation used to calculate the phase shift with a blade #1 (b_1) used as reference with a given number of nodal diameters.

$$\phi_{b_i} = (i-1) \cdot 24^\circ \cdot \mathrm{ND} \tag{3}$$

In Figure 6 examples of evaluation of the magnitude and actual deflection to excitation on the trailing edge of all the blades can be seen.



(a)



(b)

Figure 6: Example of trailing edge response evaluation of both magnitude(a) and actual deflection(b)

The results have also been evaluated in the angular direction to show the change in actual deflection when moving in the angular direction, as seen in Figure 7.

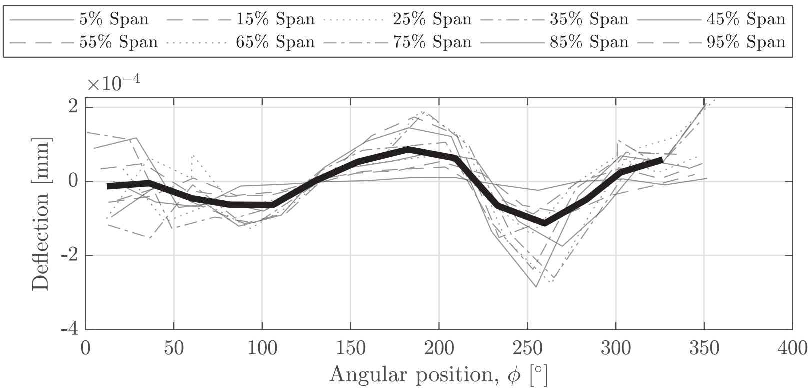


Figure 7: Example of actual deflection in the angular direction along each span wise position of the trailing edge for an ND2 in a water filled rig, average of each blade plotted as solid black line

5. Results

From the experiments a number of frequencies were studied and Figure 9 shows them for the runner in the rig when filled with water and air. For each frequency the magnitude and deflection shape of the trailing edge and the deflection shape evaluated in the angular direction was found, as the examples seen in Figure 6 (a), 6 (b) and 7 respectively. The study found that the vibrational shape of the trailing edge followed a similar pattern for increasing frequencies for all nodal diameter excitation. Figure 8 shows examples of the 3 mode classifications found on the trailing edge of the runner blades.

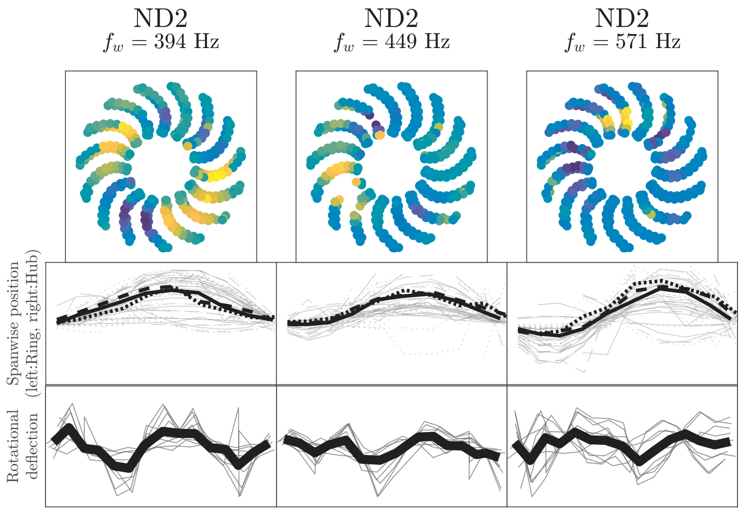
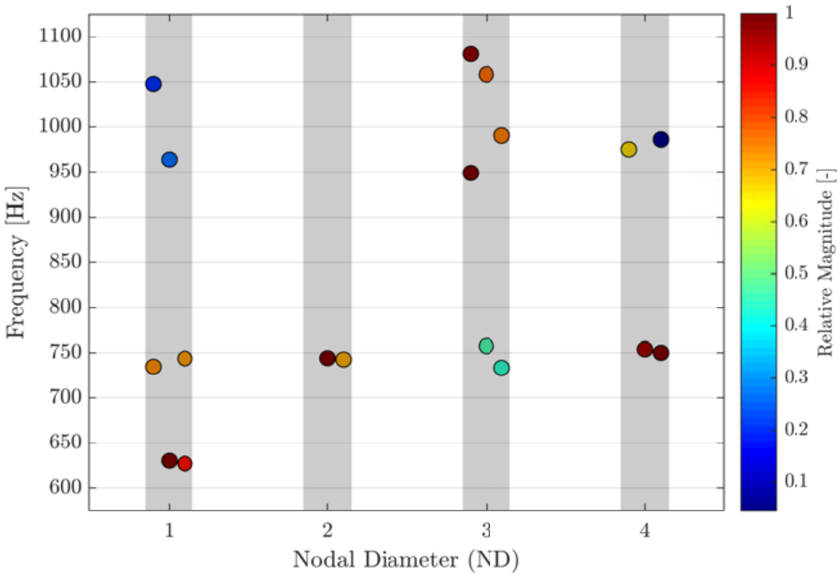
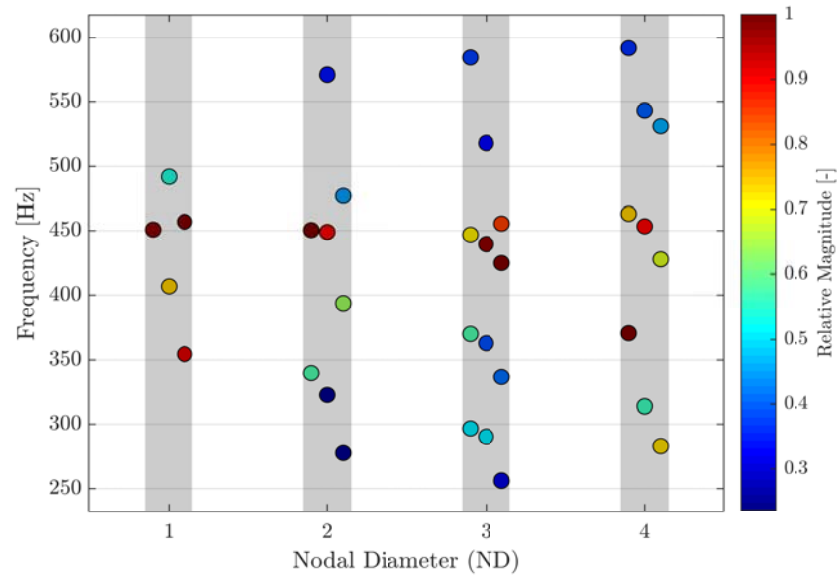


Figure 8: Normalised examples of deflection shape, where solid lines indicate the mean.



(a)



(b)

Figure 9: All frequencies investigated during the experimental campaign with the runner in air(a) and in water(b). Colour denotes the relative magnitude of the vibration compared to the maximum found for the specific ND excitation

6. Conclusion

The presented experimental setup produced results that give a high resolution insight into the structural properties of turbines runners installed in the operational environment. Measurements of the deflection shape of the trailing edge may be utilised to further understand which areas of the runner vane trailing edge are exposed to the largest strain.

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