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# Decomposition of the structural response of the Francis-99 runner during resonance.

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**Abstract.** In this work, the complex structural response of the Francis-99 turbine runner is further investigated by decomposition of the output signal from previous Laser Doppler Vibrometry (LDV) measurements into the motion of each nodal diameter. During the structural measurements, the non-rotating runner was installed in the turbine pit, submerged in a non-flowing water, and excited with piezoelectric patches mounted on the hub. The patches were excited with phase shifted sinusoidal voltage to create overall excitation of the runner with a desired number of nodal diameters. The deflection of selected locations on the trailing edges were scanned with LDV, one point at a time, and the global movement was reconstructed by combining the data for all points.

The Francis-99 runner has its blades bolted to an over-dimensioned hub and shroud, where the hub is not fully axi-symmetrical and has several hollows in it. This, together with the fact that one patch was found to be non-functional, is believed to have excited other ND patterns in addition to the one that was intentionally excited, therefore contaminating the movement of the trailing edges with movements that does not belongs to the excited ND. To mitigate this and create a better representation of the movement of the trailing edge, which is not affected by the bleed from other ND, the LDV signal for each excited frequency of a particular ND is post-processed using discreet Fourier transformation to decompose the motion of each nodal diameter in the range ND0 to ND7. This unveils the contribution of each nodal diameter within the output signal where a spike is seen for the excited ND in all measurements. Influence from other nodal diameters were found, where the failed patched is believed to cause a ND1 like movement. In addition the clustering of multiple eigenmodes with differing nodal diameters previously found in narrow frequency bands were also found as interfering contribution when exciting at the relevant frequencies.

*Keywords*: Resonance, Experimental Study, Modal Testing

## 1. Introduction

The ability to correctly predict the eigenfrequencies and mode shapes of High Head Francis runners is paramount to ensure reliable operation for such runners. A decade ago, several

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runners failed due to resonance in the runner due to pressure pulsations from Rotor-Stator Interaction(RSI)[1]. Today, the methods used to numerically calculate the eigenfrequency of the submerged-in-water runners are considered mature and are well established in the field[2]. The methods have often been validated with a runner submerged in a container of water without regards to the nearby walls and sealing surfaces[3].

In this article we present an improved post processing method for quantifying the motion of eigenmodes measured on the open low specific speed Francis-99 runner while installed in the turbine with actual sealing clearances, submerged in water without rotation.

## 2. Previous Work

The Francis-99 runner has undergone multiple experimental campaigns in the recent years, including hydraulic and structural measurements. For this paper the work conducted by Agnalt et al.[4] and Solemslie et al.[5] are used as a basis for the presented study. The basis is a submerged, non-rotating, modal test, artificially excited at specific ND-patterns, and the results show multiple eigen modes for all ND-patterns within the frequency range 200 Hz to 600 Hz [5]. On the contrary, Agnalt et al.[4] used the convective rotor/stator interaction between the guide vanes and rotating runner blades to enable the natural excitation of the turbine. For the optimal guide vane opening $\alpha_{GV}$, a discreet "BEP-sweep" was performed by increasing the head and the rotational speed accordingly to retain the optimal value of the speed factor $n_{ED}$. Assuming linear combination of a convective and an acoustic pressure field, the measured pressure signal was accordingly decomposed and resonance was found at 272.49 Hz and 325.53 Hz. Both eigenmodes were excited by the second harmonic of the RSI with four nodal diameters.

During the test performed on the non-rotating runner, the eigen modes found were believed to include influence from eigen modes with different nodal diameters. As seen in Figure 1 multiple eigen modes were found across multiple nodal diameters in a narrow frequency band.

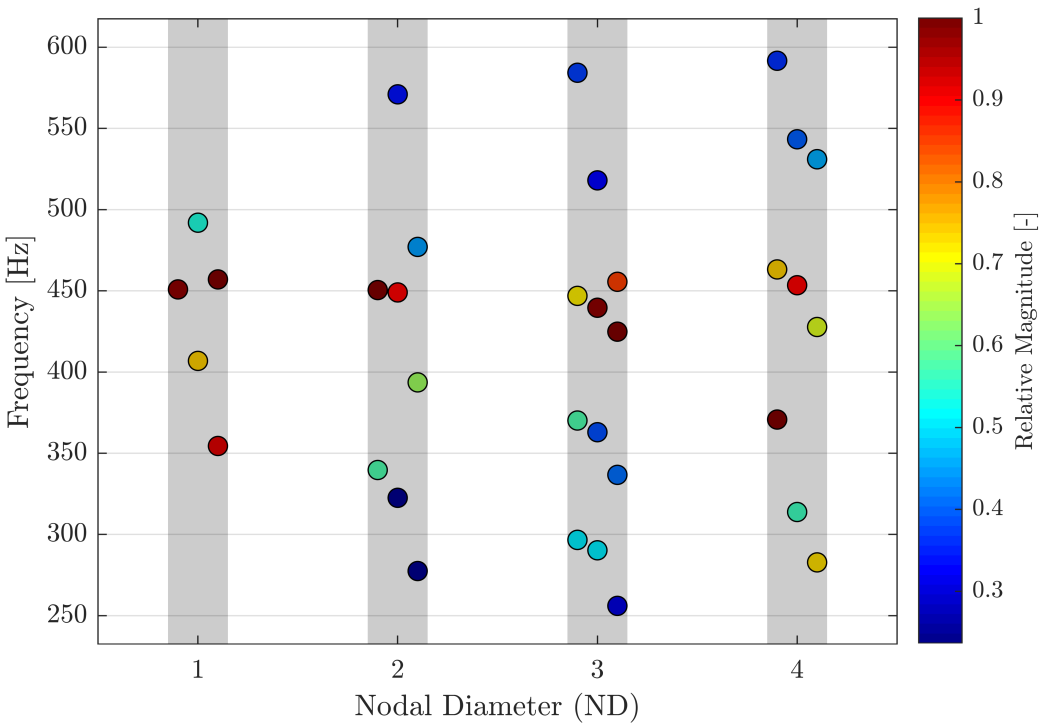


Figure 1: Eigen modes found during non-rotating tests

The excitation for the non-rotating tests were conducted with Piezo-electric patches, model P-876.A15 from PI Ceramic, mounted on the runner hub as seen in Figure 2. The runner has 15 full-length blades and 15 splitter blades, and the patches were mounted on top of each full-length blade. The results from the tests included measurements of the deflection magnitude of the trailing edge of the runner blades as seen in Figure 3, which were measured with a Laser Doppler Vibrometry(LDV) scanner from Polytec (model PSV-500-NH).

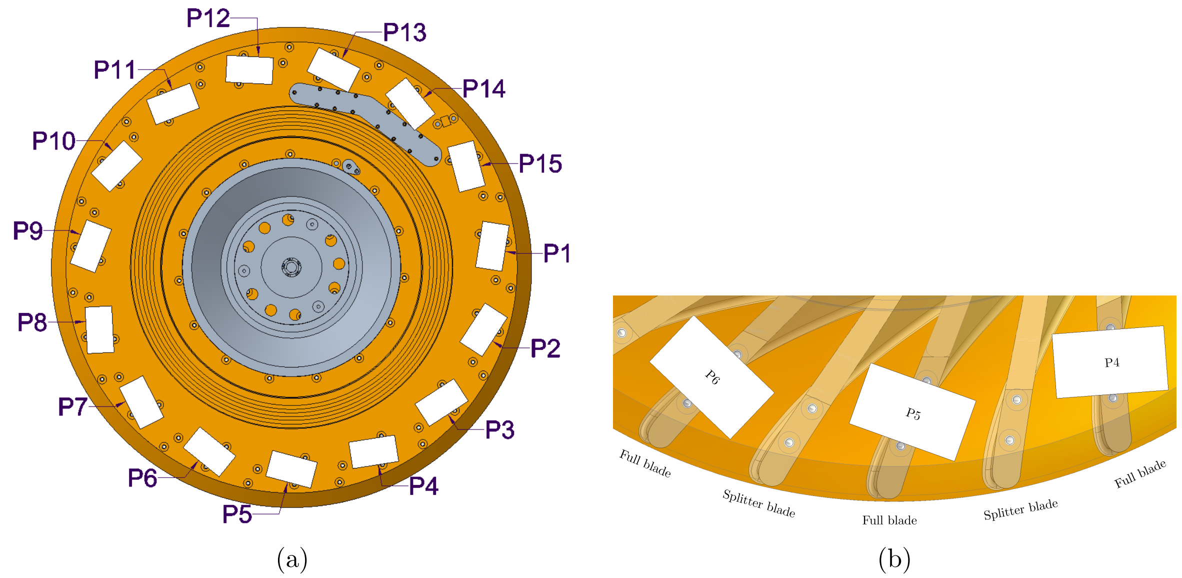


Figure 2: Position of the patches used by Solemslie et al. (a) and the location relative to runner blades (b)

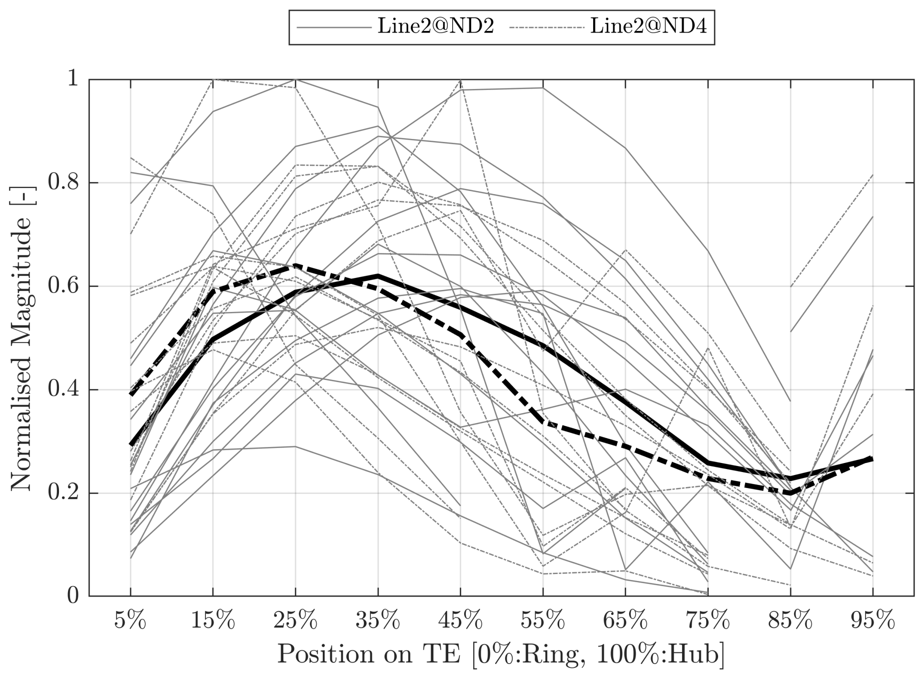


Figure 3: Normalised magnitude of deflection of a spanwise line on all blades at ND2@340 Hz and ND4@283 Hz with their average plotted as dashed and solid bold lines

## 3. Post-processing

The modeshape, $\Phi$, of a rotational symmetric structure is identical on each symmetrical part, only phase shifted by $(2\pi ND)/15$. By utilising a Discrete Fourier Transform (DFT), Equation 1, the measured signal $A$ from each blade $k$, can be combined and decomposed to the motion of each Nodal Diameter. If the excitation was perfectly symmetrical this transformation would be unnecessary, as it would only excite one ND. But since one patch failed during the experiment, i.e. patch 10, some energy from the excitation mode is leaked into the other modes as well. The DFT decomposes the result so that each ND can be isolated and examined separately.

The results from the LDV measurements previously conducted are utilised as an input to the DFT for nodal diameter 0 to 7. The input is extracted from the individual points on the trailing edge seen in Figure 4 (a) and organized so that the results are located at a constant radius around the runner centre as seen in Figure 4 (b).

$$\Phi_{ND} = \frac{1}{15} \sum_{k=0}^{15-1} A_k e^{-j2\pi ND/15} \quad (1)$$

By plotting $\Phi_{ND}$ for all points measured at the outlet of the blade, the complex modeshape of the runner is found.

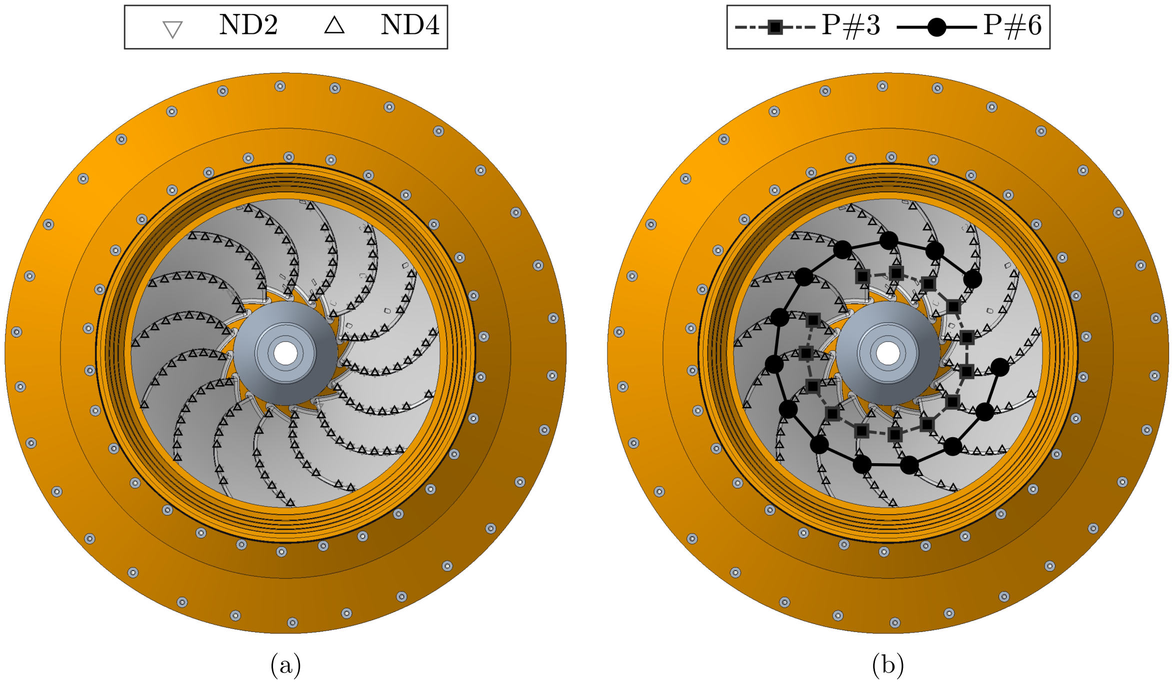


Figure 4: Position of measured points for ND2 and ND4 (a) and examples of the lines used as input in the DFT processing of point#3 and 6(b)

An example of the real component of the complex FFT output from the LDV measurements can seen in Figure 5 and the DFT result of the seen lines are shown in Figure 6.

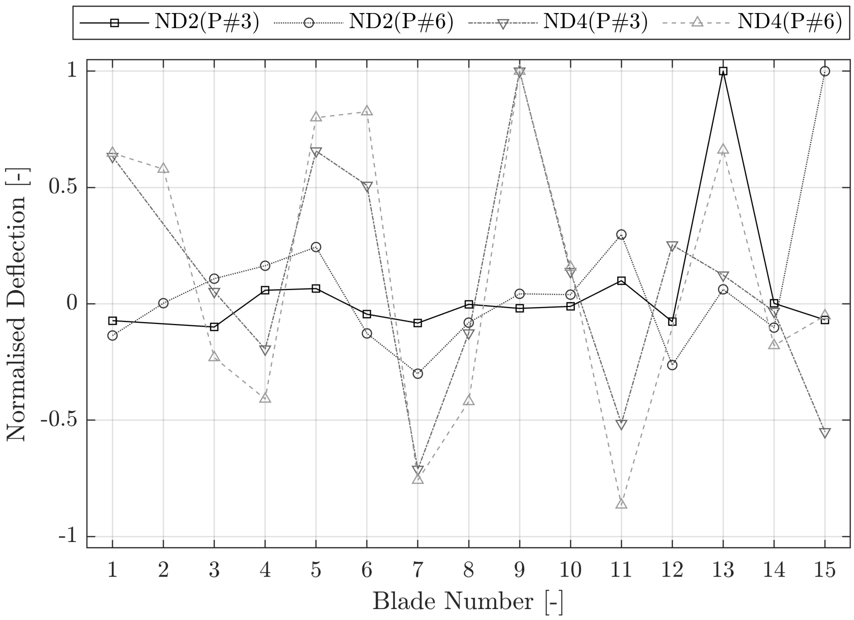


Figure 5: Magnitude along line used as DFT input for point 3 and 6 at ND2@340 Hz and ND4@283 Hz

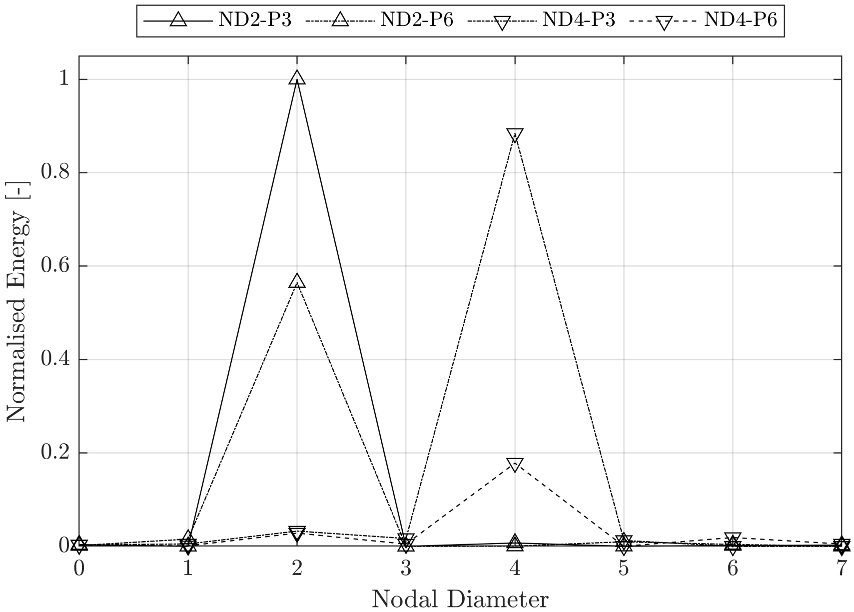


Figure 6: Normalised energy of the motion of different nodal diameters during excitation of ND2@340 Hz and ND4@283 Hz

From the results of the above DFT processing the component of the motion of ND0 to ND7 can be found for the measurements with excitation at a constant frequency and nodal diameter seen in Figure 7.

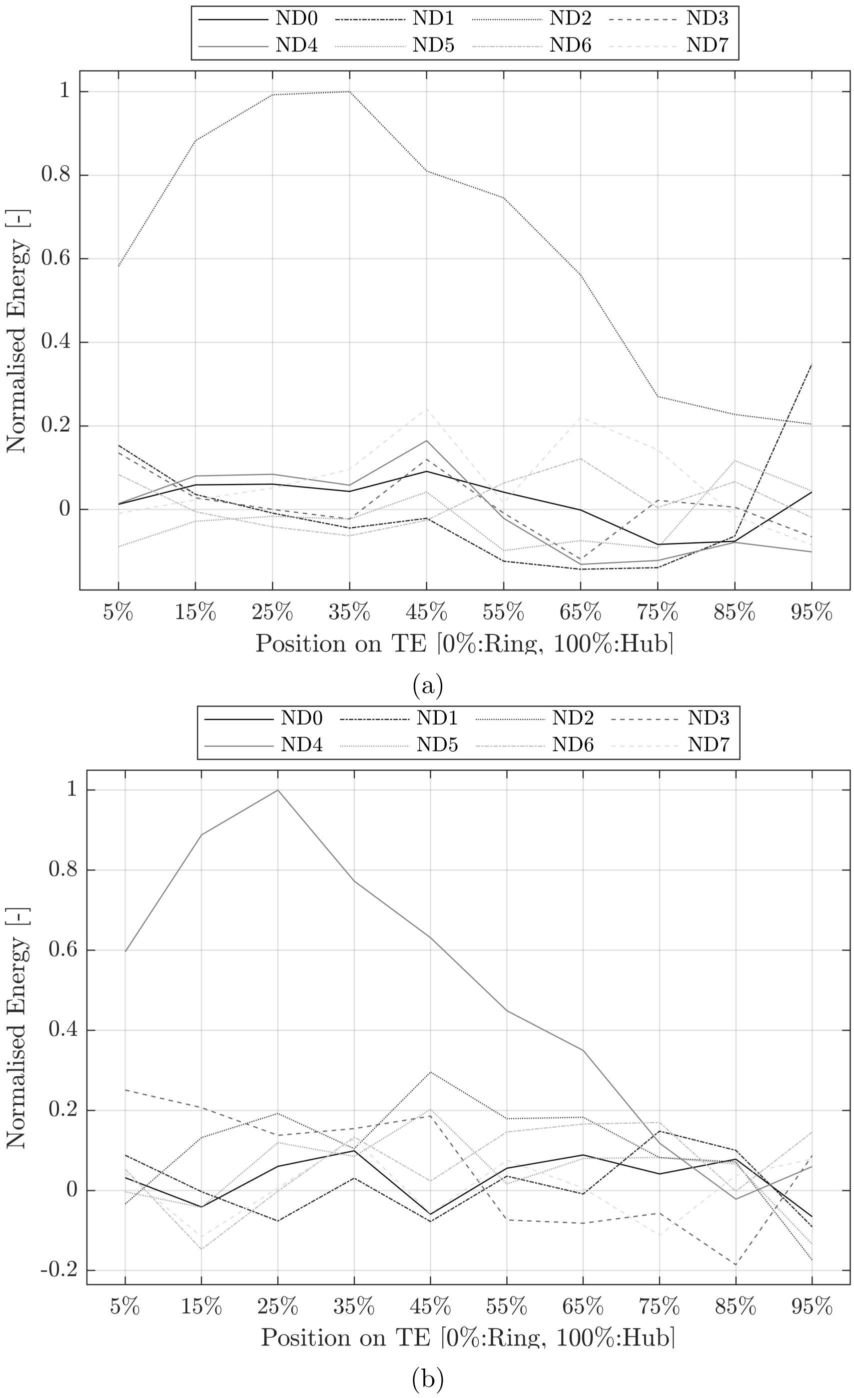


Figure 7: Deflection Contribution from ND0 to ND7 during excitation of ND2@340 Hz(a) and ND4@283 Hz(b)

## 4. Results

In Figure 8 the normalised mean of the motion of the individual nodal diameters of all the points and all frequencies at ND2 and ND4 can be seen, where the normalised standard deviation of the averaged DFT results is indicated. The standard deviation for the nodal shapes with a high contribution is naturally high due to the variation of magnitude along the blade in the spanwise direction. This variation can be seen in Figure 6 where point 3 is close to the ring, while point 6 is near the middle of the trailing edge.

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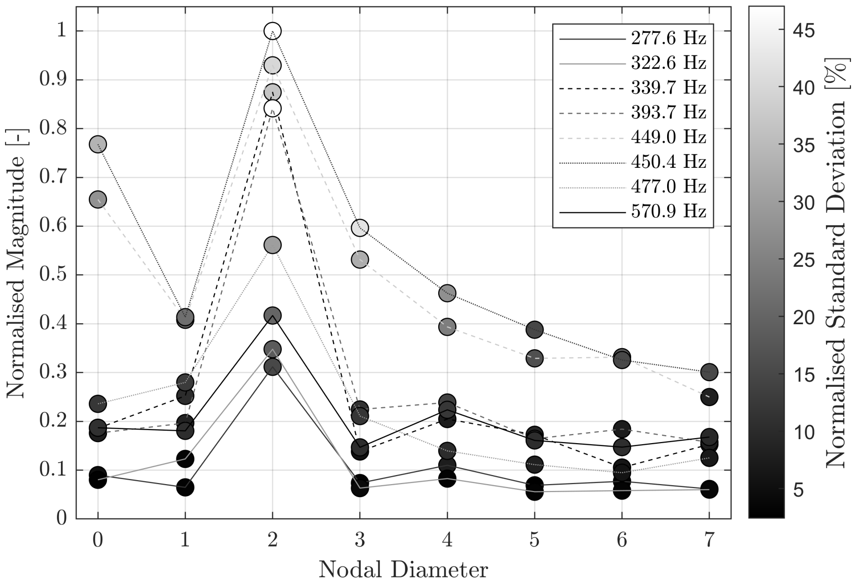
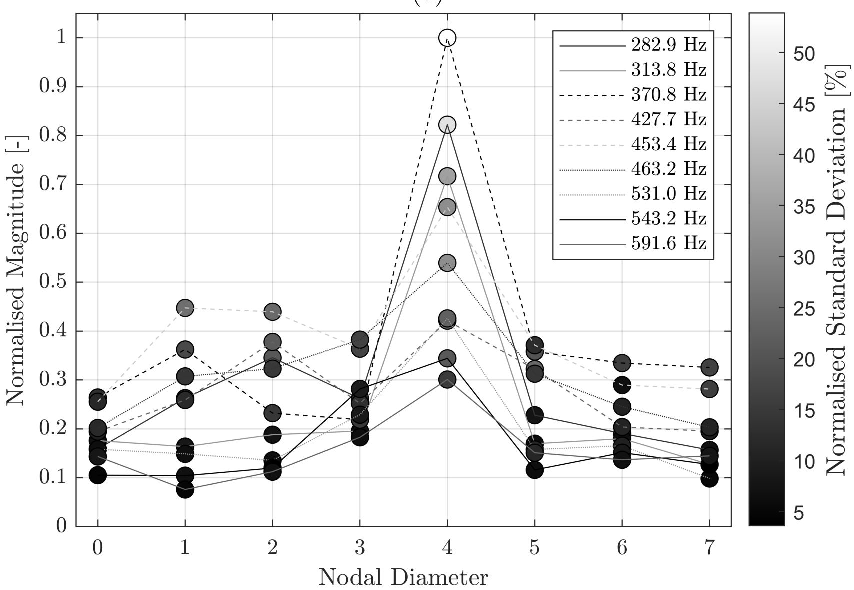


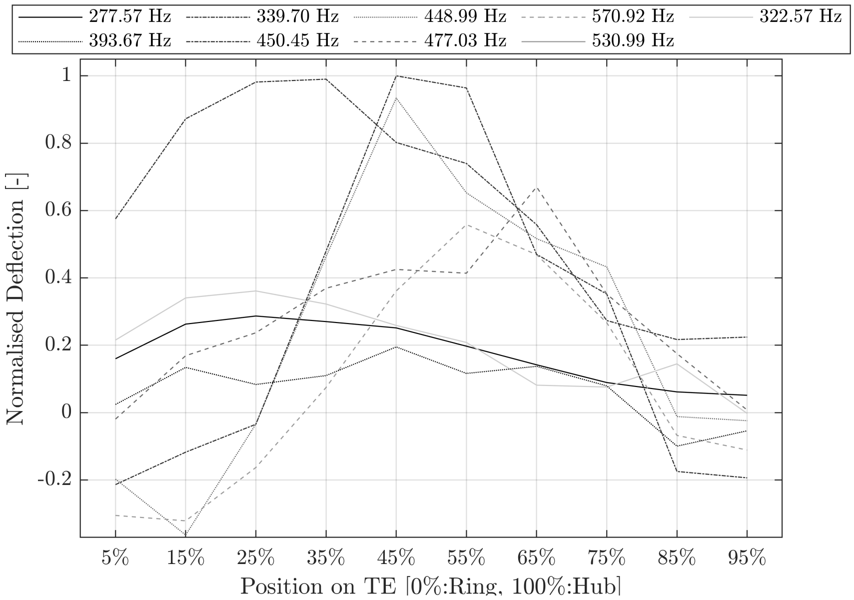

(a)



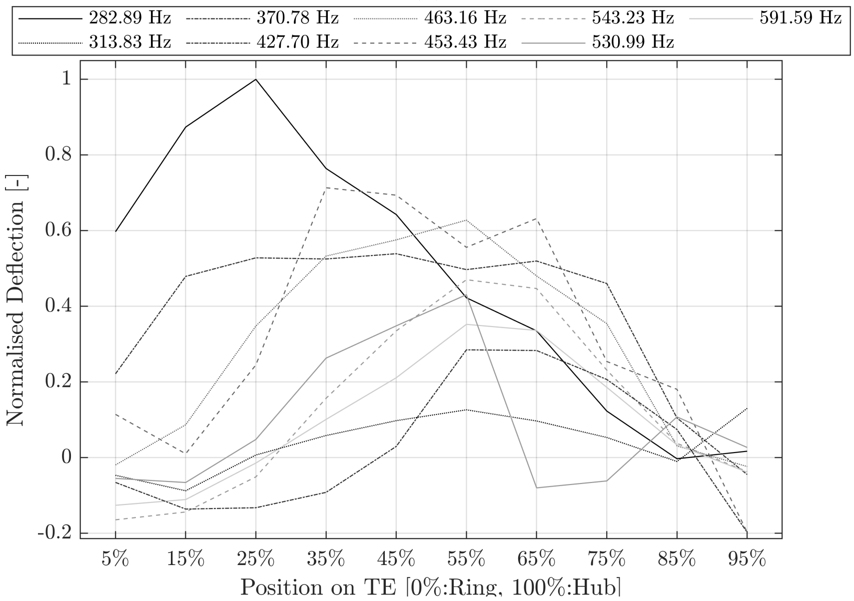

(b)

Figure 8: Normalised magnitude of motion of the different nodal diameters during excitation at ND2(a) and ND4(b)

Based on the mapped contribution from the different modal shapes during excitation it is possible to find the deflection on the blade caused by the excited nodal diameter. Figure 9 shows the deflection found to be purely a motion of the excited nodal diameter.




(a)




(b)

Figure 9: Contribution to motion caused purely by the excited nodal diameter for ND2(a) and ND4(b).

## 5. Discussion

The bolted nature of the Francis-99 runner, in addition to the many hollows within the hub structure included to mount sensors and lead cables out through the shaft, has caused some structural asymmetry. This asymmetry is believed to increase due to the failed piezo electric patch, which yields an impure excitation at the desired nodal diameter. Contribution from the failed patch is believed to be cause an excitation of all nodal diameters, as seen in Figure 8, due to the fact that it introduces a non symmetric excitation of the whole structure. The same figure also indicates a large motion of all nodal diameters for frequencies around 450 Hz for both ND2 and ND4 excitation. This corresponds well with the large amount of eigenmodes found around this frequency in Figure 1.

## 6. Conclusion

The method presented here enables a possible insight into the expected motion caused by an excitation with a pure nodal diameter and a fully symmetric runner structure. The benefits of utilising an LDV scanner for measuring the structural response of a model runner at stand still is also further shown through the increased insight into the motion of the different nodal diameters. It may be possible to utilise the method presented in the work by Solemslie et al. and the revised post processing methodology presented here to estimate the motion of the trailing edge for a solid runner construction based on measurements on a model with some non-symmetric features. This could again ease the comparison with FEA analysis conducted with a symmetric condition.

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