Analysis of the dynamic response of pump-turbine runners-Part I: Experiment

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Abstract. When in operation, pump-turbine runners have to withstand large pressure pulsations generated by the rotor-stator interaction. The analysis of the dynamic behavior of these structures is necessary to avoid damage. For this analysis a realistic model of the runner is necessary. When the runner is submerged in water and inside the casing, its dynamic response is greatly affected. The added mass effects of the surrounding fluid and the proximity of the head-cover and bottom-cover may reduce the natural frequencies. The frequency reduction produced by the added mass effects and the influence of the boundary conditions has to be known for a safe design of the runner. In this paper an experimental investigation on the dynamic response of a model runner is presented. A reduced scale model of a pump-turbine was tested outside and inside the casing with different boundary conditions. For the excitation of the runner at different frequencies piezoelectric patches were used. The response was measured with miniature accelerometers located in several positions inside the runner. From the measurements the natural frequencies and mode-shapes of the runner were calculated using EMA. The influence of the added mass and of the boundary conditions is presented and discussed.

1. Introduction

Rotor-stator interaction generates pulsations that can reduce the life of the runner, due to fatigue. Fatigue problems are caused by dynamical excitation and therefore the dynamical response of the runner has to be analyzed in detail. Up to now the analysis of the dynamical response of the runner has been carried out for prototype and model runners hanged in air and hanged in water but without taking in account the effects of the shaft and of the casing.

In [1] Lais et.al carried out an experimental investigation with a Francis turbine Runner hanged in air and hanged in water. Results were contrasted with numerical simulation, but no effect of the attached shaft and of the casing was considered. In [2] Escaler et.al studied the dynamical response of the same pump-turbine runner used in this paper, making an extensive study of the mode shapes and added mass effect, but only for the runner hanged in air and water. Some tests in a real pump-turbine prototype have been carried out by E Egusquiza et al. in [3]. Nevertheless, the influence of the shaft and of the boundary conditions when the runner is inside the spiral casing, haven't been calculated yet. In all these experimentations the response is obtained with classical excitation methods, such as a hammer. Nevertheless when the runner is inside the casing and not accessible it is necessary to use

exciters attached to the runner, such as piezoelectric patches. There are many studies, using piezoelectric patches as exciters [4] but most of them are only used to excite frequencies of small structures with simple geometry (such as beams or plates) and in air.

In this paper, the feasibility to use piezoelectric patches to excite a pump-turbine runner, which is a complex and rigid structure, has been explored. Past results [2] have been verified and contrasted in this paper and the influence of the shaft and the casing is presented.

2. Experimental test rig

The reduced scale model consists in a reduced scale pump-turbine runner inside a spiral casing. The runner has 9 blades and it is attached to the casing shown in figure 1. The casing has a spiral form and it has 20 guide vanes. The response in the runner is measured with submergible accelerometers (Dytran 3006A) and excited with piezoelectric patches P-876A12 (figure 1).
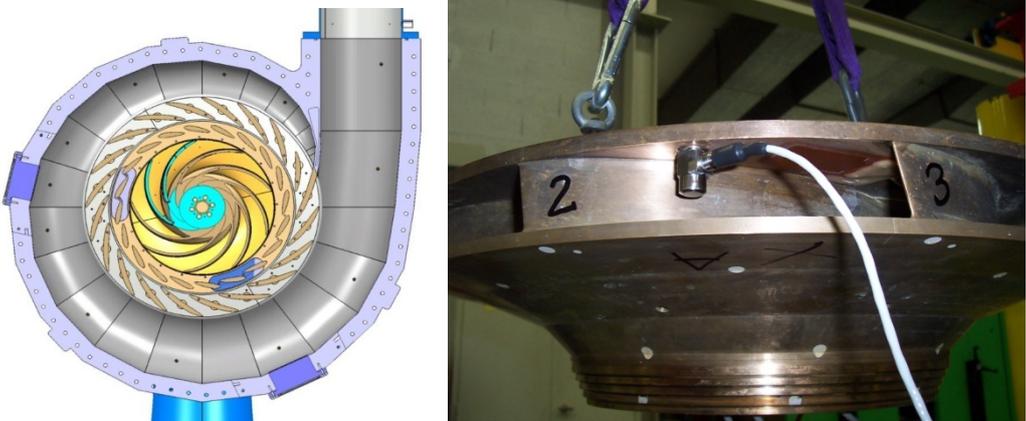

Figure 1. Casing and detail of the runner (accelerometer 3006A and the patch P-876A12 mounted on the crown)

Four patches are located on the runner; three on the crown and one on the band (patch D). The accelerometers and patches are placed according to figure 2.
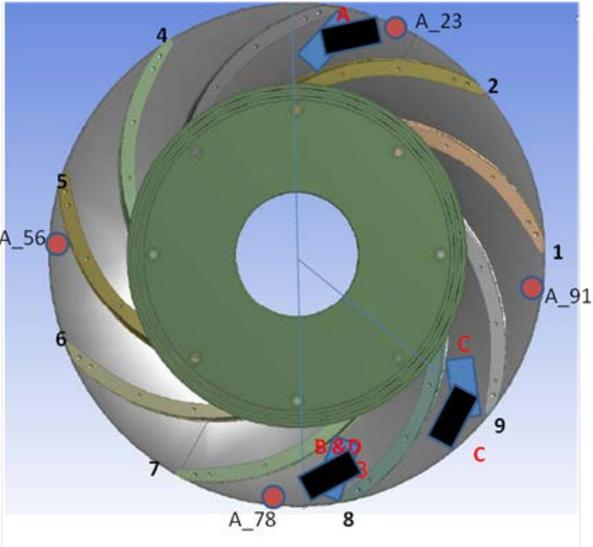

Figure 2. Position of the accelerometers and position of the patches

In the first part of the tests the runner is hanged in air, the natural frequencies are obtained and the patches are calibrated. In a second part, to see the effects of the casing, the runner is attached to it. The whole assembly is shown in figure 1.

The patches are excited with a signal generator and amplified with the amplifiers PI E-835 OEM. These patches work between -100V and 400V. Since the gain of the amplifiers is 25, the excitation signal is always between -4V and 16V. To validate the excitation method with the patches and to check reciprocity of the structure, the hammer Kistler type 9722A2000 has been used.

A Brüel & Kjær PULSE platform has been used to acquire and record the signals. The Frequency Response Functions (FRF) are obtained with the relation between the response and the excitation in (ms^{-2}/V). The FRF's obtained with the patches excitation are compared and validated with the FRF's obtained with the hammer excitation. Then, the set of FRF's has been exported to ME'scopeVES software which has been used to animate the mode shapes.

3. Experimental tests

The experimental procedure is divided in the following parts: calibration of the patches, dynamical response of the runner hanged in air, inside the casing in air and inside the casing with water. Once the signals of the different experiments are registered, these will be analyzed with different treatments depending if the excitation is carried out with the hammer or with piezoelectric patches.

3.1. Calibration of the patches

In the first part of the tests the runner is hanged in air. The runner is excited with the impulse hammer and with the piezoelectric patches in the same points. Both FRF's are compared to see if the peak values are the same.

3.2. Runner hanged in air

The runner is hanged in air. The runner is excited with the patches and with the hammer. The used patch to excite the runner is A (figure 2). The signal is a sweep sine signal from 100Hz to 3200Hz in 300s. After perform the excitation with patches the rowing hammer method is used to determine the mode shapes. The crown of the runner is impacted on each blade axially.

3.3. Runner inside the casing in air

In this part the runner is attached to the shaft as figure 3 shows. The runner is excited with the patches and with the hammer. For the excitation with the patches the same signal as described in *section 3.2* is used. The rowing hammer method is applied impacting on the band to obtain the mode shapes. This part shows the effect of the shaft in the natural frequencies

3.4. Runner inside the casing with water

Finally the casing is filled with water. Since the runner is not more accessible, the excitation is carried out with the piezoelectric patches. All the patches are used separately and with combinations of two at the same time, to excite the runner. The used signal is the same as in *section 3. 2*. This part shows the effect of the proximity of the walls in the natural frequencies, when the surrounding fluid is water.

3.5. Signal analysis

When the excitation is an impulse (hammer), the FRF is the linear average of 5 impacts and with a resolution of 0,5Hz. All these signals are analyzed to 3,2Khz. A transient window is applied on the response and on the excitation. When the excitation is a sweep sine (piezoelectric patches) a Hanning window is applied on the response and on the excitation, since both signals are harmonic signals. To detect the frequency content of a signal which is changing continuously it's frequency content, a resolution of 2Hz is selected (therefore time signals of 0,5s) and in each average the window is displaced 25ms. Each average gives a spectrum, which has the energy concentrated in a small frequency band. Superposing all these spectras with the peak method, the averaged spectrum is obtained (figure 3).
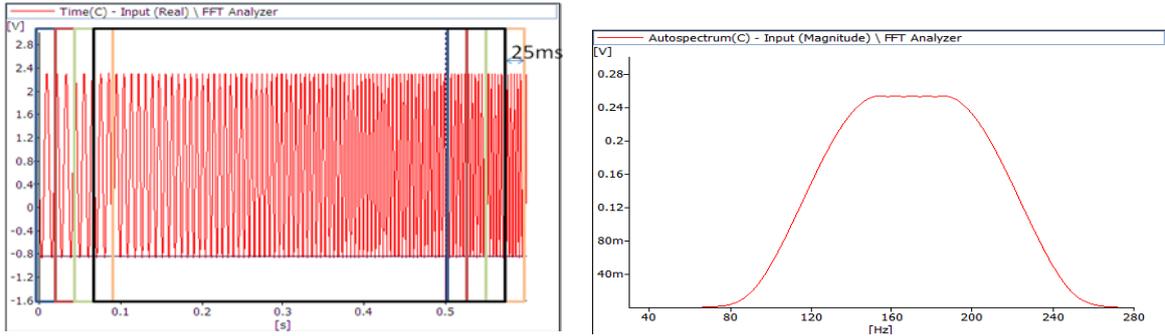
Figure 3. Time signal with 5 windows (5 averages) and Δt=25ms. Averaged spectrum with 5 averages (Peak method)

4. Results and discussion

Once the data is acquired, the signals are treated with the procedure described in *section 3.5*. The following results are obtained.

Calibration of the patches

Comparing the response analyzed when the runner is excited with a sweep sine force (patches) and when the force is an impulse (hammer), it is clear that the both methods give the same values for the natural frequencies (figure 4).
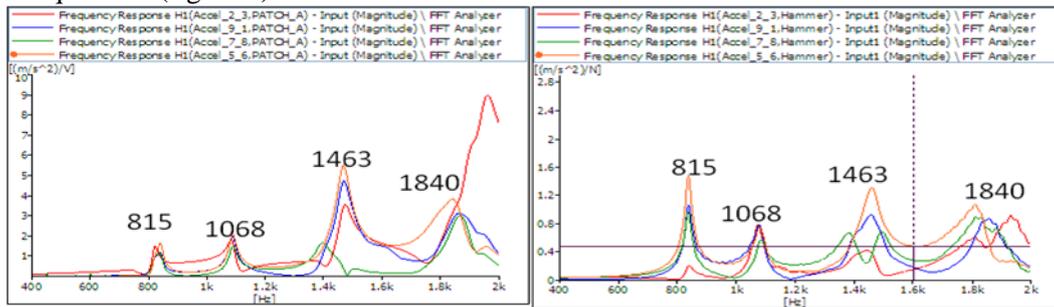

Figure 4. Excitation with patches and with impulse hammer

Nevertheless, the damping calculated with the half-power bandwidth method is not suitable for the FRF(ms-2/V) obtained with the patches, since the patches have a non linear behavior voltage-frequency. Also for the magnitudes there is not a direct relationship between the two methods of excitation.

To compare the mode shapes of hammer excitation and patch excitation the COMAC is used [5]. The COMAC between two mode shapes (vector of complex numbers) is defined as:

$$COMAC = \left(\{X\},\{Y\}\right) = \frac{\left\|\{X\}\cdot\{Y\}\right\|^2}{\left\|\{X\}\right\|\left\|\{Y\}\right\|} \qquad (1)$$

When this value is higher than 0.9 [5], then both mode shapes are equal. Using Eq. 1 with the used accelerometers for the natural frequencies below 2 kHz:

Table 1**.** COMAC for the frequencies below 2kHz.Comparison patches and hammer excitation

Frequency	COMAC
815	1
1068	1
1463	0,89
1840	0,95

These results show a very good agreement between both methods, therefore piezoelectric patches are suitable to excite the right shape of each natural frequency (mode shape).

Runner hanged in air

The mode shapes of the natural frequencies obtained with the procedure explained in *section 3.2* are now presented. The results of the rowing hammer method give the following mode shapes in the periphery of the runner (displacement in the axial direction).
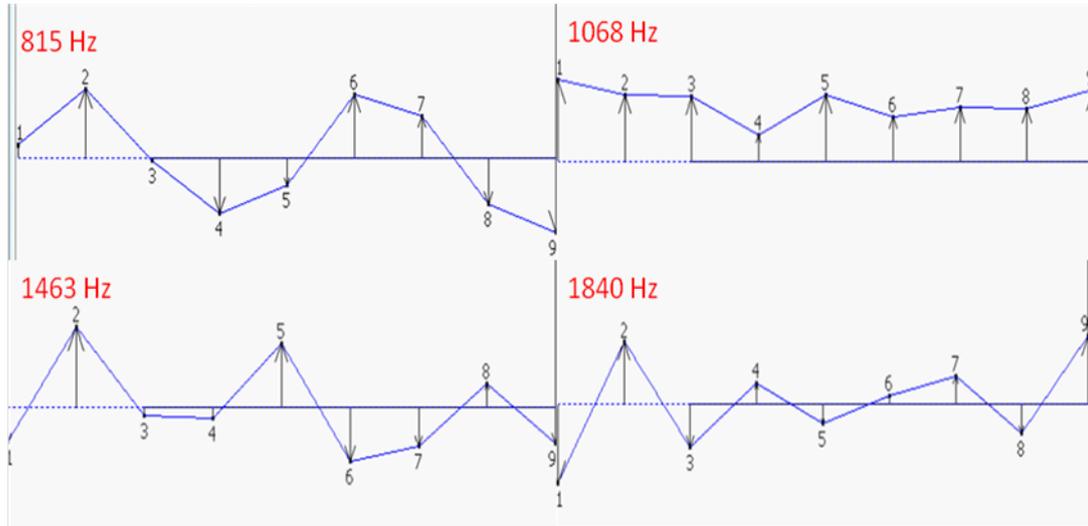

Figure 5. Mode shapes for the first modes of the runner in air

Comparing the results in the periphery (figure 5) with results of the numerical simulation for the same runner [6] (figure 6), these are coincident. The mode shapes for this kind of runners are defined by the number of nodal diameters (diameters with no displacement) on the crown. *XND* for instance means that X nodal diameters are found in the current mode shape. For this runner the first modes are 2ND, 0ND, 3 ND and 4ND as experimental and numerical results show.
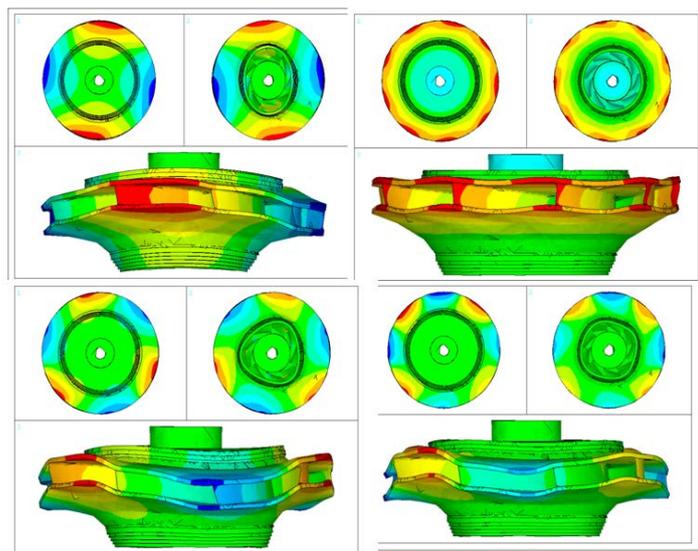

Figure 6. 2ND, 0ND, 3 ND and 4ND obtained by numerical simulation [6]

When the runner is inside the casing in air, only the attachment to the shaft has an influence, since the runner becomes more stiffness in the points where it is attached (central part of the runner). The following table summarizes the frequencies and modes of the runner attached to the shaft.

Table 2**.** Natural frequencies and mode shapes of the runner attached to the shaft

Frequency	Mode shape (number of nodal diameters)
882	2
1075	0
1497	3
1899	4

The effect of the shaft is to increase lightly the natural frequencies of the runner especially in the natural mode shapes with more deformation in the centre, like the 2ND mode[6].

Because the shaft is not a model of a real one, the results cannot be extrapolated.

Runner inside the casing in water

When the runner is inside the casing and filled with water, the hammer cannot be used in the model and the excitation is carried out by piezoelectric patches. This is the main advantage respect classical excitation methods. First of all, the runner is excited with one patch separately. Figure 7 shows the response of the accelerometer A_91 due to an excitation with patch A, with patch B and with patch D.
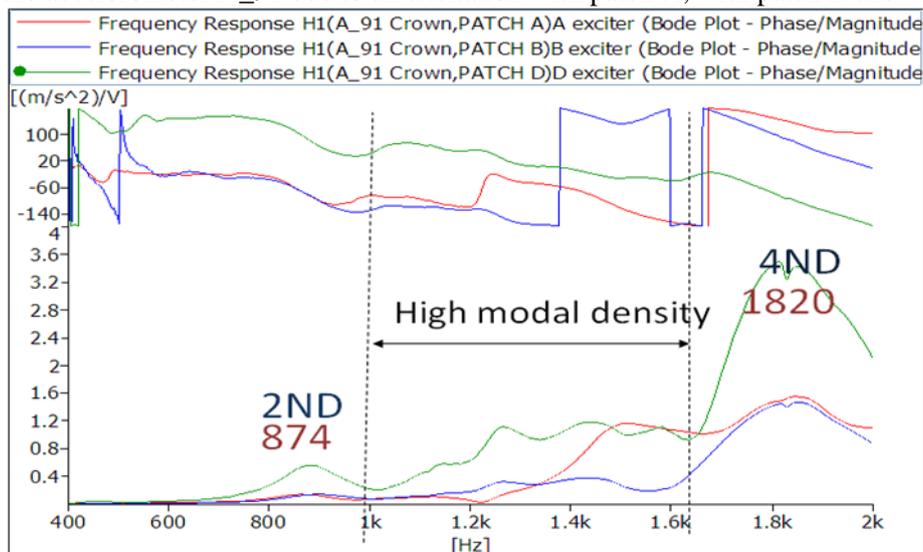

Figure 7. Response of the runner due to single patch excitation

The response shows a very complex behavior of the structure. When the gap runner-casing is small and between them the surrounding fluid is water, both structures are connected, causing this complexity. The peaks are extremely width (the dynamical behavior of this structure is quite damped) and the amplitudes are very small (about 30% of the amplitudes in air for the same excitation).With these results (low amplitudes and complex response) is difficult to identify all the modes. It can be seen, that the excitation on the band (patch D) for this model gives more response than the excitation on the crown (patch A and patch B).

Comparing the mode shapes in air and in water with the COMAC, the modes 2ND and 4ND were identified at 874Hz and 1820Hz. To identify the modes in the frequency band with high modal density (Figure 7), combination of two patches are used to excite the runner. These are presented in figure 8.
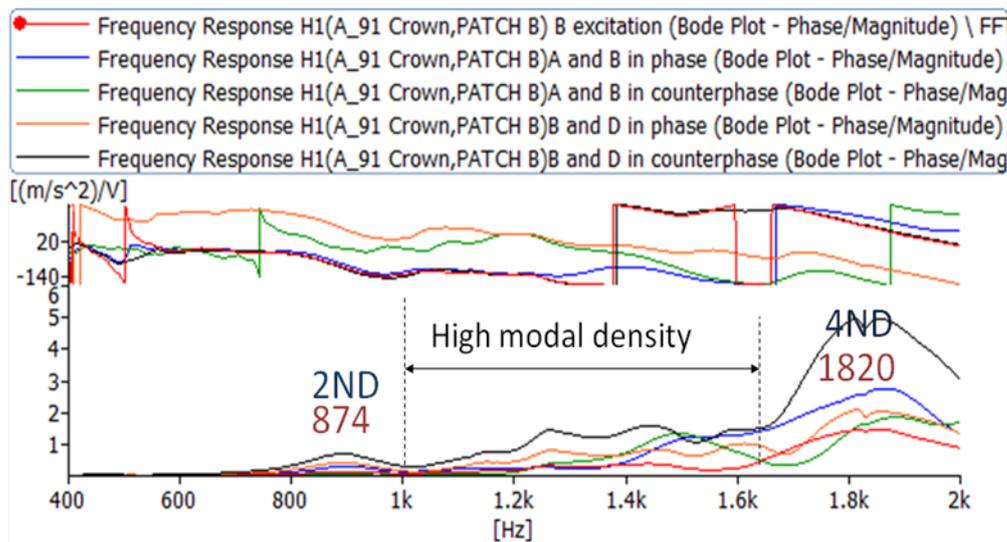
Figure 8. Excitation of the runner with combination of two patches

Taking a look in the mode shapes of figure 6, results presented in figure 8, show the expected behavior of the structure due to different excitation shapes. It can be seen that 2ND and 4ND are amplified with the shapes A&B in phase (blue line) and B&D in counterphase (black line), when comparing the response with those one with one patch excitation. Since the patches B and D are located face to face, counterphase of both produces that the force acting on the band and on the crown is in phase. Other combinations (A&B in counterphase or B&D in phase) don't amplify the response.

Nevertheless, in the frequency band between these two modes, the dynamic response is more complicated and no clear results can be extracted (no clear peaks and no clear change of phase) with any kind of excitation, when using 2 patches.

To improve the tests (improve the excitation& detection), in the future, the runner will be excited with more patches with different excitation forms. In each test the excitation will be similar to one mode shape (modal excitation) and this augment the response greatly only for the frequencies with the mode shape similar to the excitation shape [7]. In this way the peak identification will be much easier.

5. Conclusions

In this paper has been proved that a complex rigid structure, such as a pump-turbine runner can be excited with small piezoelectric patches, that are non intrusive, and the added mass of these actuators is negligible. Piezoelectric patches were used with different boundary conditions: runner hanged in air, runner inside the casing in air and runner inside the casing in water.

Patches have been calibrated first. The peak values are the same when using piezoelectric patches or hammer and the corresponding mode shapes are equal for both cases, as COMAC values show.

For the runner hanged in air the results in [2] have been confirmed using piezoelectric patches. The mode shapes have been obtained using patches and hammer excitation

As new results, the effects of the shaft for this model runner have been calculated. The shaft is not realistic but the behaviour of the assembly shaft and runner is similar to the real machines [6]. In this case the increase in frequency is much higher for the 2ND as for the higher modes (3ND and 4ND), since the deformation of the 2ND mode is more located in the central part of the runner (figure 6).

For the runner in the casing with water the dynamical response has been measured. This response is much more complicated than the response for the other boundary conditions. Results show, that the amplitude of the peaks is extremely reduced (more than 70% when comparing with the amplitudes in air) and the width of the peaks (measure of damping) is extremely increased. 2ND and 4ND were identified using only one or two patches at the same time. Results have been contrasted with the

COMAC [5]. It has been also proved experimentally, that when using two patches, the modes with a shape similar to the excitation shape are increased. Nevertheless, for the frequency band between these two modes (2ND and 4ND), an excitation with two patches is not enough to excite and detect all the modes separately.

Therefore, as future test, it is proposed to excite the runner with a modal excitation. This means, using more patches at the same time with an excitation form similar to the mode shapes of the runner. This will make possible, the identification of the modes in the band with high modal density (between 2ND mode and 4ND)

References
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