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Determination of the natural frequencies of a prototype Kaplan turbine

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Determination of the natural frequencies of a prototype Kaplan turbine

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Abstract. The natural frequencies of a turbine can be calculated from numerical methods. By comparing these natural frequencies with excitation sources, one can know the danger of a resonance and a possible failure in a component of the turbine. Therefore, it is often very important to have an accurate numerical model of the turbine to determine these natural frequencies. There are not many publications on the determination of the natural frequencies of reduced-scale models of Kaplan turbines. More papers exist for pump turbines or Francis turbines. For real Kaplan turbines, very few experiments can be found to determine mode shapes and natural frequencies. In this paper a Kaplan turbine of 37MW (maximum power), 12.5m (maximum head) and 50 m^3/s (maximum flowrate) was tested. The turbine was equipped to determine the natural frequencies of the runner in air. For this purpose, one accelerometer in each blade of the runner was installed and a total of 16 impacts were done in each blade. Frequencies and mode shapes were obtained. In parallel, a numerical model was obtained. Numerical and experimental results were compared and an accurate numerical model is presented. With this numerical model the natural frequencies of the runner in water were calculated.

1. Introduction

Variable New Renewable Energies (VNRE) are constantly growing, generating more and more energy. By 2030 the share of VNRE in the energy mix is forecast to be 35%. The most important (wind and solar) are intermittent and non-dispatchable.

Under present and future conditions, new challenges arise for hydroelectric technology. Hydropower is a relevant energy source that can be dispatched on demand by power grid operators, according to the needs of the electricity grid. Therefore, in order to integrate the variable renewable energies, its main role nowadays (and even more in the future) is to provide flexibility in the electricity market (increase the capacity to respond to changes that may affect generation and consumption of electricity). This increase in the flexibility services of hydropower provokes an increasing trend to experience a higher degree of wear and fatigue (tear). A better understanding of the modal behavior of the runners can help to increase the lifetime of the machines.

Looking at the literature, a lot of authors have paid attention to the modal behavior of Francis and Pump turbines[1]-[11], but very few publications are devoted to Kaplan turbines. Some numerical studies for real prototype in [12] and experimental studies for a single blade in laboratory tests are presented in [13] for a real prototype.

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In this paper, a complete modal analysis of the runner of a real Kaplan turbine in air was done. Frequencies and mode shapes of the runner were obtained for this turbine. Also, a numerical simulation of this machine was done to obtain frequencies and mode shape theoretically. With the experimental results the model in air was validated. Then, the runner of the model was surrounded by water and the modal analysis in water was carried out.

2. Description of the machine

A Kaplan turbine located at Volgergrün Power Plant (France) was instrumented to determine the natural frequencies of the runner in air.

The turbine has a runner with four blades, twenty-four guide vanes and it rotates at 1.39Hz. The generator has seventy-two poles. The machine is supported by one thrust bearing with eight tilting pads and two radial bearings located on the upper part of the generator and near the runner (turbine bearing). The nominal power of the machine is 35MW with a minimum power of 12MW and a maximum power of 37MW. The nominal head is 12 m with a minimum head of 10.2m and a maximum head of 12.5m.

The CAD model used for the study of the machine is shown in Figure **1**. All the dimensions are the same as the prototype. The runner CAD was provided by ANDRITZ.

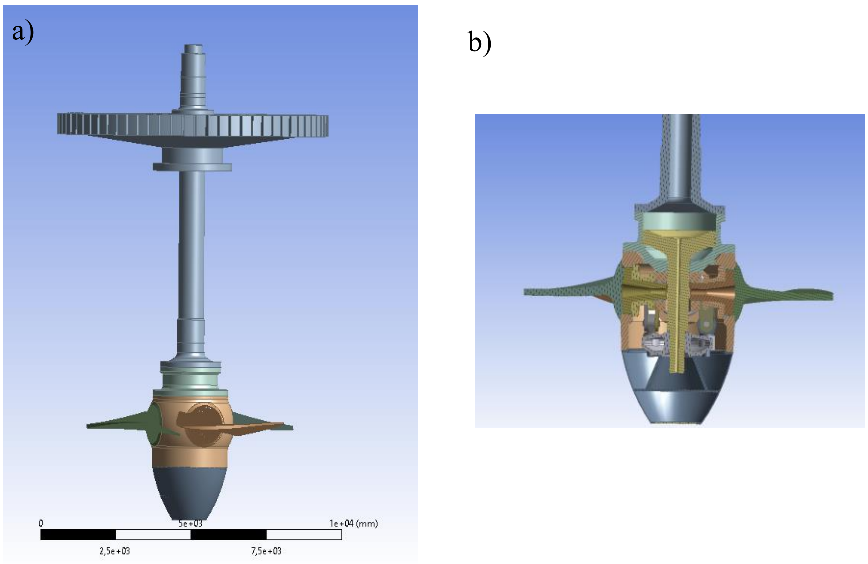

Figure 1 Geometrical model used for the numerical analysis of the Kaplan turbine a) the whole machine b) detail the runner.

3. Modal analysis in air

3.1. Numerical simulation in air

A FEM (finite element model) of the Kaplan turbine was done. After a sensitivity analysis, the final mesh had 1,487,332 nodes and 931,562 elements (Figure 2). The whole machine was taken into account (FEM model includes the blades, hub, control system, shaft and generator). Boundary conditions were imposed on the bearings (axial and radial bearings) (see Figure **1**).

Using Ansys Workbench 16 software for FEM, the natural frequencies of the Kaplan turbine and the mode shapes were found.

For the whole machine, three main types of mode shapes can be distinguished (Figure 3):
-Shaft modes: the alternator and the runner moves almost as a rigid body.

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-Runner + alternator modes: runner and alternator have deformation. The shaft, as the case before, has almost no displacement.
-Runner modes: only the parts of the runner have deformation. The shaft has almost no displacement.

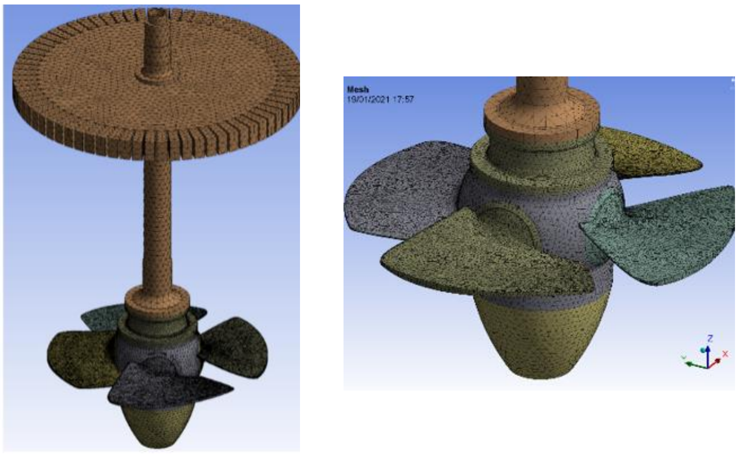


Figure 2 Detail of the mesh

a) b) c)

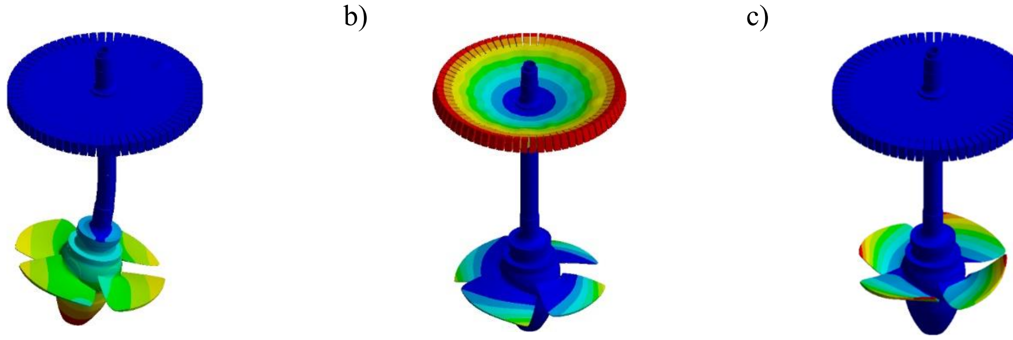


Figure 3 a)Shaft modes with the runner moving as a rigid solid, b)runner+alternator modes c) runner modes

In this paper only runner mode shapes without shaft displacement were studied.

Furthermore, for the runner mode shapes, two more types of mode shapes were obtained numerically:
-Local mode shapes: these modes affect only the blades. Basically two types of local modes exist: bending (B) and torsional (T). Bending and torsional modes can have different sub-modes depending on the number of the nodal lines (NL: lines without displacement). To name these modes, a nomenclature can be adopted: B or T as we refer to bending or torsion modes and, to distinguish the sub-mode, the number of nodal lines can be used. For bending modes for example B 0NL as seen in Figure 4a; for torsional modes T 0NL as shown in Figure 4b and T 1NL as seen in Figure 4c.

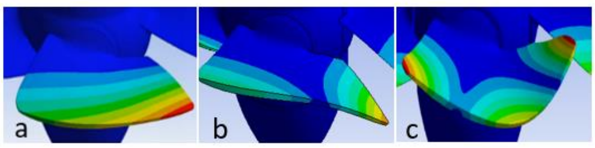
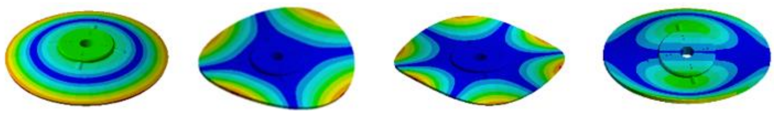


Figure 4 Mode shapes for a blade of the Kaplan runner

-Global mode shapes: The behavior of this runner with four blades can be compared to the behavior of a disk, looking at global deformation for some mode shapes. For a disk, it is well known [14] that the shape modes can be characterized according to the number of its nodal diameters (ND) and nodal circles

(NC). A nodal diameter is a line that bisects the circle across the diameter without deformation, and a nodal circle is a circumferential line without deformation. The mode with d ND and c NC can be denoted as mode (d, c) as seen in Figure 5.



(0,1) (2,0) (3,0) (1,1)

Figure 5 Mode shapes for a disk

For the runner of the Kaplan turbine, the deformation of the 4 blades can produce the appearance of points with maximum and minimum deformation. Because the runner is bladed, sometimes the nodal diameters are not a real line, but can be defined as an imaginary line. If all the blades are in phase, a 0ND is obtained (Figure 6a), if the two alternate blades are in phase, a 2ND is obtained (see Figure 6b) and a 1ND (see Figure 6c) can be obtained if two alternate blades are in counter phase and the other ones are without deformation.

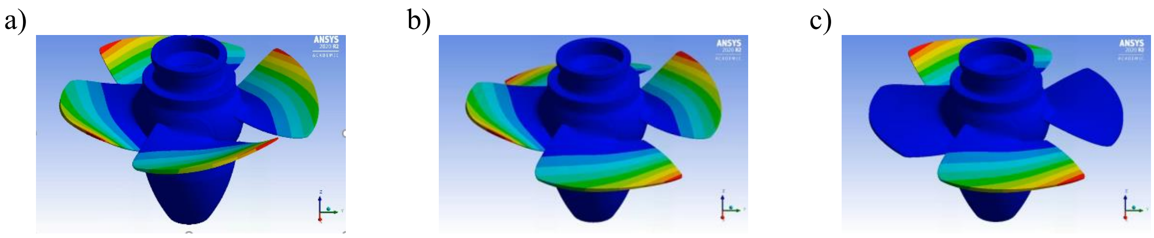


Figure 6 Global mode shapes for a Kaplan turbine runner with 4 blades

For the first runner mode shapes, the main results obtained from numerical simulation, are shown in Table 1.

3.2. Experimental modal analysis in air

The runner was instrumented with one accelerometer in every blade (see Figure *7*a). 16 impacts in the periphery of all blades were carried out at equidistant points (see Figure *7*b).

The roving hammer method was used to determine the natural frequencies and mode shapes of the runner. Runner natural frequencies and mode-shapes were identified for the case of air.

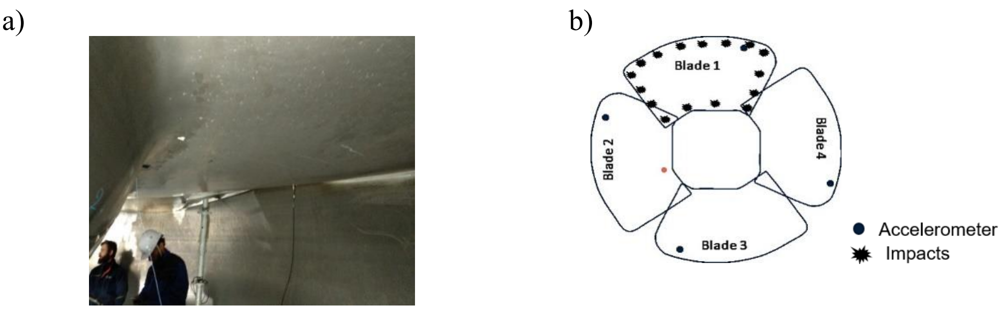
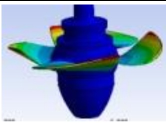
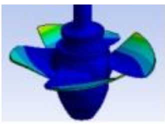
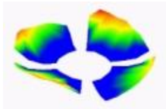
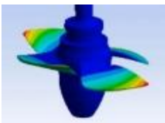
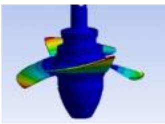
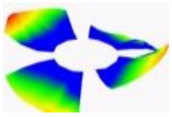
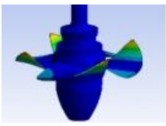
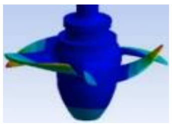
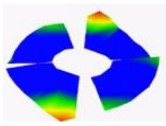
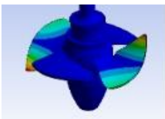
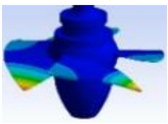
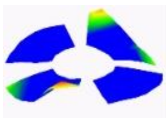


Figure 7 (a) Picture of the runner of the prototype during tests with the accelerometer (red line); (b) a drawing of the runner with the impacts made and the position of the sensors for all the blades

Experimental results for the runner in air compared with the simulated ones are shown in the follow table. The maximum error obtained is about a 5%.

Comparing numerical and experimental results, two families of local modes were found: a family of blade bending mode shapes and a family of blade torsional mode shapes.

Table 1. . First runner mode shapes for Kaplan turbine with four blades

GLOBAL MODE					
FAMILY	**Numerical (Hz)**		**Experimental (Hz)**		**Error(%)**
Bending 0NL	(0,0) 35		-	´-	-
	(0,0)/alternator 42		(0,0) 40		4,8
	(-,-) 39		-	-	-
	(2,0) 38.4		(2,0) 36,8		3,8
Torsional 1NL	(-,-) 50		-	-	-
	(1,0) 44,3		(1,0) 46		-4,0
	(1,0) 51		-	-	-
	(2,0) 50,2		(2,0) 49,8		1,0

For the bending mode shapes (always with 0NL), different sub-modes can be observed depending on the nodal diameters: two 0ND (one 0ND only with the runner participation, and another 0ND with the participation of the generator), and a 2ND can be distinguished; also one more mode with the participation of all the blades, but unrelated to the modes of a disk. The 0ND with the participation of the generator and the 2ND were also detected in the experimental tests.

For the torsional mode shapes with 1NL, two 1ND and one 2ND were found from numerical simulation; also a torsional 1NL was obtained, but unrelated with the modes of a disk. From experimental results, only one 2ND and one 1ND were detected.

4. Modal analysis in water

4.1. Numerical simulation in water

The runner was surrounded by water to check the natural frequencies and mode shapes using Ansys Workbench 16. After a sensitivity analysis, the final mesh had 1,866,955 nodes and 1,269,632 elements (see Figure 8).

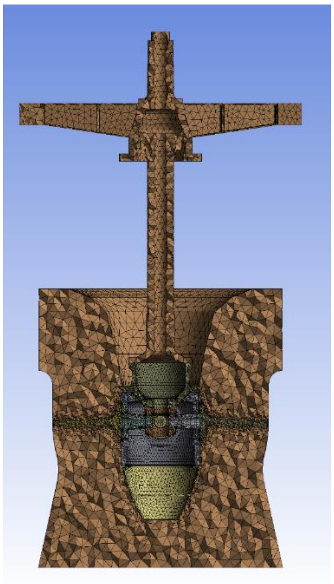


Figure 8 Detail of the mesh for the model in water

In this case, the first mode shapes and natural frequencies for runner modes obtained in water are compared with the modes obtained in air

Table 2 Natural frequencies and mode shapes in air and in water and influence of the added mass

Family	Numerical air (Hz)	Numerical water (Hz)	Difference (%)
Blade bending modes	(0,0) 34.9	(0,0) 17.2	50.8
	(2,0) 38.4	(2,0) 22.9	40.5
	(-,-) 38.8	(-,-) 23.3	39.9
	(0,0) 42	-	-
Blade torsional modes 1NL	(1,0) 44.3	(1,0) 28,3	36.1
	(-,-) 50	(-,-) 34,4	31.2
	(2,0) 50.2	(2,0) 33.7	32.8
	(1,0) 51,1	(1,0) 34.3	32.8

As can be seen in Table 2, the Blade bending modes family is more affected by the influence of the water (added mass) than the Blade torsional ones. On the other hand, for bending modes, the greatest influence of the added mass is for 0ND modes, (about a 50%). For Blade torsional modes (no 0ND found), the more influenced by the added mass is the global mode 2ND.

From the experimental tests done in the power plant during the coast down of the machine, these two families of the mode shapes can be detected with accelerometers located on thrust bearing and on turbine bearing: one family between 15-20Hz, and another one between 25-36Hz (grey circumference in Figure 9).

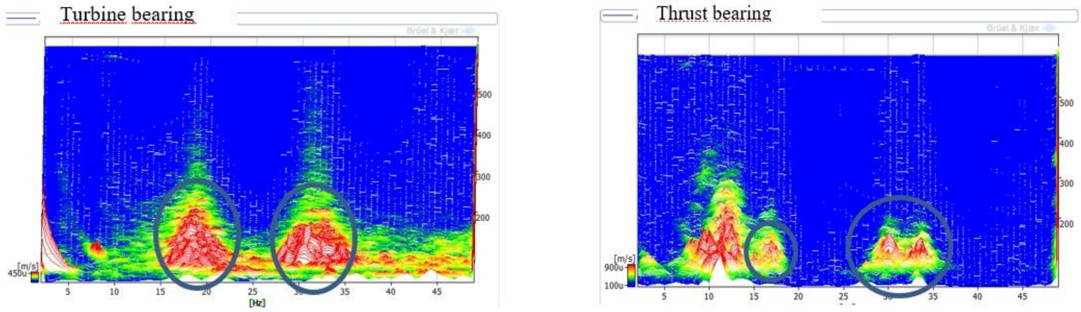


Figure 9 Waterfall of the power spectrum of the vibrations (mm/s) measured at the turbine and at thrust bearing during coast down.

More research is needed to determine with more accuracy the natural frequencies of the runner in water experimentally.

5. Conclusions

A numerical model in air and in water has obtained to determine the modal characteristics of a Kaplan turbine.

The numerical model in air and in water has shown that for this type of Kaplan turbine (four blades), there are local and global modes. Local modes affect the blades and two types of mode shapes have been studied in this case: bending and torsional; the torsional mode shapes can have one or two nodal lines. The global modes can be classified in a similar way to the mode shapes of a disk. This means, it depends on the number of nodal diameters. So, different families of the mode shapes can be found.

The numerical model in air has been validated with the experimental tests in the prototype. Families of the modes have been found experimentally as the numerical simulation has shown.

From numerical results, the influence of the added mass effect on the natural frequencies in this Kaplan turbine has been determined. The bending modes family is more affected by the influence of the water than the torsional modes family, and for each family (bending and torsional) the more affected global mode is 0ND (0,0) for bending and 1ND (1,0) for torsional.

The range of the natural frequencies of the runner surrounded by water calculated from numerical simulation is the same as the natural frequencies excited during the coast down of the machine. This is a first validation for the model in water. More research is needed to more accurately find the natural frequencies of the runner in the water experimentally.

Acknowledgment

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