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Fluid-Structure Interactions Analysis of a Drag-Type Horizontal Axis Hydraulic Turbine

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Fluid-Structure Interactions Analysis of a Drag-Type Horizontal Axis Hydraulic Turbine

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Abstract. The Fluid-structure interaction characteristics on the two drag-type horizontal axis hydraulic turbinesare investigated. The results show that the two drag-type horizontal axis hydraulic turbines are suitable for operation under low flow rate and low *TSR* conditions. The Tuebine 2 has a higher C_P value from *TSR*=0.5 to *TSR*=2.0, and has a lower C_T value in the whole *TSR* rangethan the Turbine 1. The maximum stresses are at the blade root area, and the maximum deformations are at the blade tip for both turbines. The Turbine 1 has a higher stress level and total deformation than the Turbine 2. The frequency on 1st, 2nd, 3rd, 4th and 5th order vibration modes of the Turbine 1 is higher than the Turbine 2, and the 6th one is not.The results provide a reference for the drag-type horizontal-axis hydraulic turbines.

1. Introduction

The use of fossil fuels has brought a lot of problems such as environmental pollution, climate changeand global warming. As an excellent alternative to traditional fossil fuels, hydropower is a reliable and clean energy resource [1]. Nowadays, the hydraulic turbine is considered to be the most promising hydropower technology.According to the operation mode, the hydraulic turbine can generally be divided into the horizontal axis type and vertical axis type [2-3], and the horizontal axis typehas higher efficiency and stability. Most horizontal axis type mainly relies on the lift force acting on the blades to produce torque, which is also known as the lift-type horizontal axis turbine.However, traditional lift-type horizontal axis turbines need a certain current speed to obtain the established efficiency [4]. Thus, this typeof turbine is not suitable for areas with low flow rates.To expand the application scope of horizontal-axis hydraulic turbines, two drag-type horizontal-axis hydraulic turbines with different blade inclination angles are designedbased on Archimedes' spiral principle [5-6]. The advantages of the drag-type horizontal axis hydraulic turbineare more obvious under many circumstances, such as the operating rotation speedof this turbine is lower, thus, the noise is smaller. Besides, due to its unique spiral structure, it can be automatically directed in the current directionwithout the help of any yawing equipment, which has saved manufacturing costs. In this paper, the characteristics of the Fluid-structure interaction on the two drag-type hydraulic turbines are investigated by the CFD and FSI methods. The research results provide a certain references for the drag-type horizontal axis hydraulic turbines.

2. Numerical Model

2.1. Hydrodynamic Coefficients

The hydraulic turbine's coefficients, including tip speed ratio (*TSR*), power coefficient (C_P) and thrust coefficient (C_T) are as follows:

$$TSR = \frac{\omega R}{V} \tag{1}$$

$$C_P = \frac{P}{0.5\rho AV^3} \tag{2}$$

$$C_T = \frac{T}{0.5\rho AV^2} \tag{3}$$

Where P is output power, T is thrust, V is current velocity, ω is angular velocity, R is ratio of the turbine, A is reference surface (πR^2).

2.2. Turbine Model

The two drag-type horizontal axis hydraulic turbines have three spiral blades, the blade diameter is 300 mm. The section thickness of each blade is equal to 3.6 mm and the hub diameter ratio is 0.1. For the Turbine 1, the 1st, 2nd and 3rd rotating blades of the three rotating blades are 60° distributed with the hub, while the 1st, 2nd and 3rd rotating blades of the three rotating blades of the Turbine 2 are 30°, 45° and 60° distributed with the hub as shown in Figure 1, the main parameters are shown in Table1.

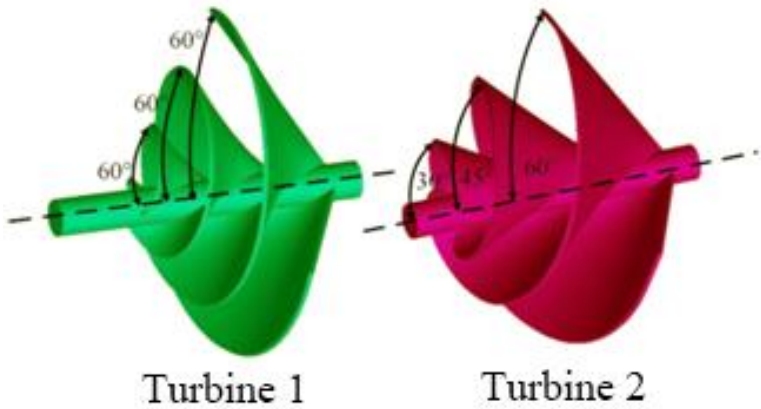


Figure 1. Three-dimensional modelof thetwo turbines.

Table 1. Main parametersof turbines.

Parameters	Values
Number of blades	3
Rotor radius	0.125 m
Rated current speed	0.5 m/s

2.3. CFD Model and Boundary Conditions

The domain has two parts, which is the stationary domain and the rotatory domain, as shown in Figure 2. The turbine is located in the rotatory domain the stationary domain is under the action of the incoming flow. The inlet and outlet of the stationary domain were set as velocity inlet and outflow, respectively. Additionally, the surface of the turbine was set as non-slip walls, and the surrounding boundary of the stationary domain was set as free-slip walls. The turbine is located 5*D* from the inlet and 10*D* from the outflow with a blockage ratio of <1%.

The mesh is generated with an unstructured mesh. The Reynolds number is about 1.5×10^5 based on the turbine diameter. The turbine surface has prism layers which the first layer height satisfies $y^+=1$ condition and meets the requirements of the SST *k-ω* turbulence model. A four sets of meshes independence assessment of the Turbine 1 at *V*=0.5 m/s and *TSR*=1.5 is shown in Table 2, and the mesh detail is shown in Figure 3. The set of 5.0 million is selected for the subsequent calculations.

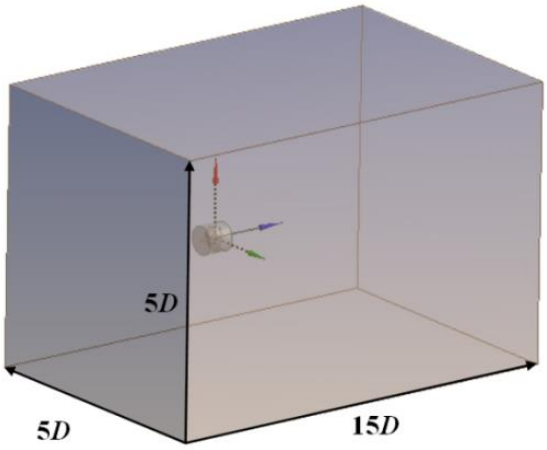


Figure 2. CFD computational domain.

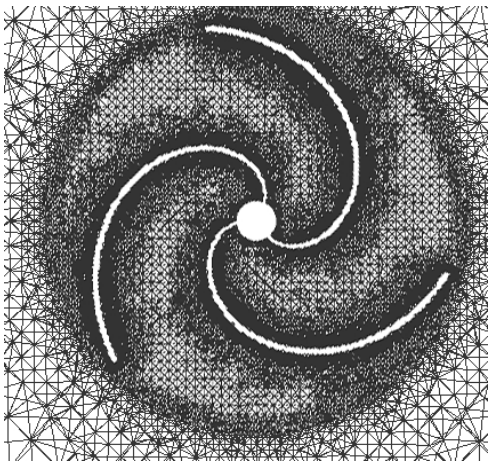


Figure 3. CFD mesh detail.

Table 2. Assessment of mesh size independence.

Number of grids (million)	C_P
3.0	0.178
4.0	0.183
5.0	0.189
6.0	0.186

2.4. Fluid-Structure Interaction Model and Boundary Conditions

The structure model of the two turbines developed with shell elements, including about 35500 nodes and 18000 elements, as shown in Figure 4. Further refinements are made at the turbine surface as it is the coupling boundary to exchange hydrodynamic forces and structural displacement. The FSI modeling used the one-way coupling method. The hydrodynamic pressure on the turbine surface obtained from the CFD is mapped to the structure. A large deflection assumption is used. In addition to hydrodynamic loads, the gravity loads and the centrifugal loads are also acting on the blades of the turbine. Besides, a fixed support is applied to the blade hub.

In this present study, it is considered that the material of the turbine is aluminum alloy and the material parametersare summarised in Table 3.

Table 3. Main parametersof turbines.

Parameters	Values
Density	2770 kg/m^3
Poissions ratio	0.33
Young's modulus elasticity	71 GPa
Bulk modules	69.6 GPa
Shear modulus	26.7 GPa
Tensile yield strength	310 MPa

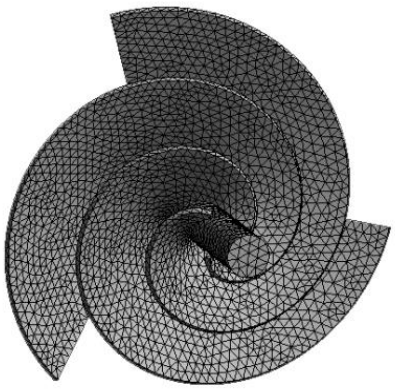


Figure 4. Structuremesh detail.

3. Results and Discussion

3.1. Power and Thrust

Figures 5 and 6 show the C_p and C_T variation *TSR* curves of the two turbines at *V*=0.5m/s. It can be seen that the two turbines are suitable for operation under low flow rate and low *TSR* conditions. The maximum value of C_P reaches 0.237 for the Turbine 2 at *TSR*=1.5, and the maximum value of C_P reaches 0.205 for the Turbine 1 at *TSR*=2.0. Hence, the Turbine 2's performance increased by 16% than the Turbine 1. Besides, it is noted that the C_T of both turbines showed a monotonic downward trend with the increase of *TSR*. The Turbine 2 has a lower C_T value in the whole *TSR* range, and the C_T difference between the two turbines increases with the increase of *TSR*.

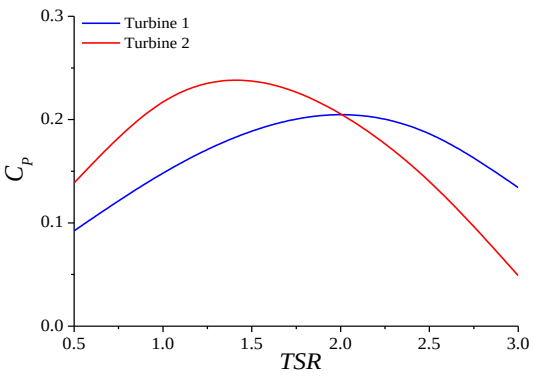


Figure 5. C_P versus *TSR* curves.

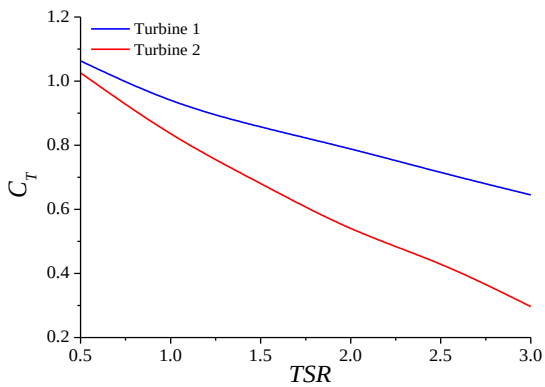


Figure 6. C_T versus *TSR* curves.

3.2. Stress and Deformation

Figures 7 and 8 show the stress levels and total deformations for the two turbines at *V*=0.5 m/s and *TSR*=1.5. It can be observed that the maximum stresses are at the blade root region for both turbines. The Turbine 1 and the Turbine 2 are found to be 2.13 MPa and 1.78 MPa, respectively, which are well below the tensile yield strengthof the aluminum alloy. In this case, the turbine is unlikely to experience fatigue failure. Besides, the maximum deformations are at the blade tip for both turbines. The Turbine 1 and the Turbine 2 are found to be 0.045 mm and 0.028 mm, respectively. Such small deformations are not likely to affect hydrodynamic performance or strike on the nearby components under operational conditions. Moreover, it can be observed that the Turbine 1 has a higher stress level and total deformation than the Turbine 2.

a) Turbine 1 b) Turbine 2

Figure 7. Normal stress distributions.

a) Turbine 1 b) Turbine 2

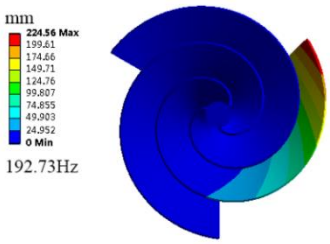
Figure 8. Total deformations.

3.3. Modal Analysis

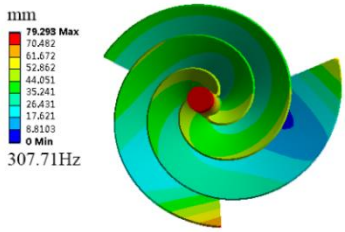
The first six orders modal were extracted, as shown in Table 4, Figures 9 and 10. The 1st, 2nd, and 3rd vibration modes are similar. The maximum deformations are at the blade tip, which is twist deformation. The 4th and 5th vibration modes are similar, which is swing deformation. The maximum deformations are at the hub. The sixth vibration mode is also twist deformation, the maximum deformations are at the blade tip. The turbine operating frequency is far less than the natural frequency, thus, it is not likely to meet sympathetic vibration. Moreover, it can be seen that the natural frequency on 1st, 2nd, 3rd, 4th, and 5th order vibration modes of Turbin 1 is higher than the Turbine 2, and the 6th one is not.

Table 4. Natural frequency of the first six orders modalon the two turbines.

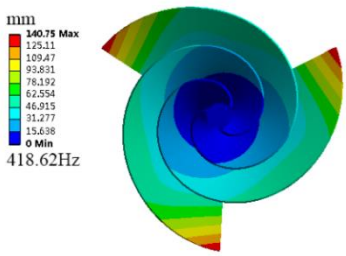
	Turbine 1	Turbine 2
1st	192.73 Hz	191.44 Hz
2nd	192.78 Hz	191.55 Hz
3rd	192.84 Hz	194.63 Hz
4th	307.71 Hz	265.22 Hz
5th	307.79 Hz	265.24 Hz
6th	418.62 Hz	432.65 Hz



a) 1st

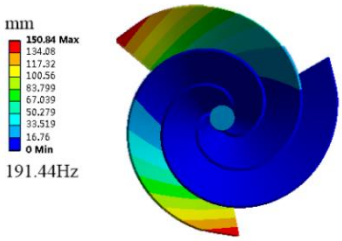


b) 4th

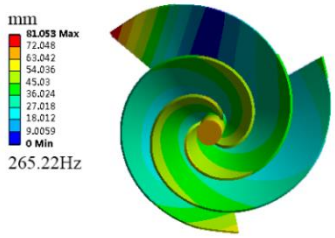


c) 6th

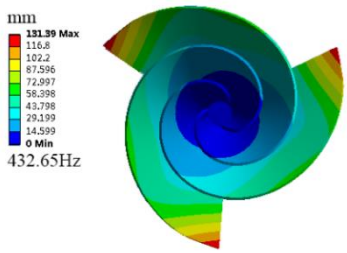
Figure 9. Modal shape of the Turbine 1.



a) 1st



b) 4th



c) 6th

Figure 10. Modal shape of the Turbine 2.

4. Conclusion

The two drag-type horizontal axis hydraulic turbines are suitable for operation under low flow rate and low *TSR* conditions. The Turbine 2 has a higher C_P value from *TSR*=0.5 to *TSR*=2.0 than the Turbine 1, and the Turbine 2 has a lower C_T value in the whole *TSR* range. The maximum stresses are at the blade root region. The maximum deformations are at the blade tip for the two turbines. The Turbine 1 has a higher stress level and total deformation than the Turbine 2. The frequency on 1st, 2nd, 3rd, 4th, and 5th order vibration modes of the Turbine 1 is higher than the Turbine 2, and 6th one is not.

Acknowledgments

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