Research on hydrodynamic performance of a tubular turbine under tidal wave condition

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Abstract. Tubular turbine running environment will be affected by ocean tidal wave, under the influence of the tidal wave, the hydrodynamic performance of the tubular turbine and its water-energy conversion efficiency have become the focus of our research and discussion. This paper explores the mechanism of wave-current coupling under surface fluctuations, considering the influence of tidal wave flow and gravity influence in flow field and flow characteristics of tubular turbine. The study on the performance of the influence of hydraulic characteristics of tubular turbine under the condition of wave flow has been carried out. Results show that the wave flow conditions with considering gravity leads to mechanical runner blade be damaged by tidal wave of pressure fluctuation and cyclic extrusion, causing more serious than fatigue stress damage than no wave flow condition does which make this kind of fluid machinery practical fatigue life is reduced greatly. The condition of the wave flow condition is universal, which is one of the reasons that the actual service life is always smaller than the theoretical calculation life. Considering the case of wave flow, the calculated efficiency is larger than that without considering this condition, and the difference between the two is the maximum at the optimal operating point. In the hydraulic turbine flow passage, significant pressure and velocity gradient are generated in the vertical direction due to wave action, resulting in no longer symmetrical distribution of its position. The hydraulic characteristics in the runner are obviously different from those without flow.

1. Introduction
Waves are caused by tides, and it is a vertical wave phenomenon occurring on the surface of the ocean in the form of sine wave or cosinewith long wavelength and energy transfer [1]. The tidal current is the horizontal flow form of seawater, the movement of water that rises and falls, called the wave movement [2]. Due to the complex geographical factors such as the differences in the thermal properties of the sea and the environment, the circulation of the atmosphere and the water, the tidal waves are always present themselves at the direction of increasing water in the flowing water bodies [3-5]. Tidal power station usually adopts the tubular turbine; previous studies have been done a lot on this type of unit. For example, Qian et. al [6] for the bulb tubular turbine full port pressure pulsation numerical simulation, obtained the condition of steady flow tubular turbine vibration characteristics under static water. Liu et. al [7] made the correlation of bulb tubular turbine flow field analysis of gravitational field and the influence of the hydraulic performance evaluation, considering the gravitational field and given out change of the internal flow characteristics of tubular machine [8]. But these studies are based on the precondition of static flow conditions, and tubular turbines always work in the natural ocean waves, under the influence of the tidal waves. After considering the gravity
of vertical force, the flow will be uneven, and the power of the machine installed in the fixed tube becomes unstable, thus it will inevitably affect the hydraulic characteristics of low head hydraulic units [9-12]. Therefore, it is necessary to carry out the analysis of the internal flow characteristics of the tubular units under the influence of tidal wave. In addition, it will provide guidance for the design and operation of tubular turbine [13].

In this paper, the study on the performance of the influence of hydraulic characteristics of tubular turbine under the condition of wave flow has been carried out by using numerical simulations.

2. Geometric model and computational domain grid division
In this paper, ICEM CFD software is used to divide the turbine model into high quality structure grids. When generating the grids, the whole calculation domain is divided into several components: the guide blade segment, the rotor segment, the tail water pipe section and the ocean, as shown in figure 1.

![Image of grid distribution of flow components](image1)

**Figure 1.** Grid distribution of flow components

![Graph of grid independent verification](image2)

**Figure 2.** Grid independent verification

Computing grid is of great importance to the results of numerical simulation, the grid quality directly determines the precision of the results of numerical simulation. Figure 2 displays the number of grid and directly affects the precision of numerical calculation and the calculation of the occupied resources. In order to utilize the computing resources reasonably, the computation time is saved and the grid number has to be verified independently. The total number of grids selected is 6.52 million

In this paper, the diameter of the prototype machine is \(D_p=2.5m\), having 4 S-typed blades. The number of guide vanes is 16. In addition to the calculation of the flow unit, a 25m×7.5m×18m size of ocean domain is attached.
As shown in figure 3, the boundary conditions are arranged as follows:

2.1. **Inlet boundary condition**

The ocean domain is the part which water flow into, to simulate current into the flow field, stokes wave flow equations are adopted to simulate the waves surging at the surface of the inlet edge, the ocean waters and tidal wave velocity were given on the inlet boundary. At the same time, the interface of the top was set to opening atmospheric.

2.2. **Outlet boundary condition**

For reservoir is located behind the dam with no direct connection to ocean, so the surface of the reservoir is almost free of fluctuation, and the outlet surface is set to the end of the tubular unit. The pressure on the face is given by the hydraulic pressure of the head of the flow turbine and the outlet is calibrated by its mass flow at the face.

In the traditional water flow calculation, generally do not consider the real flow of water, and simple as hydrostatic treatment, but in the actual condition of power generation, usually closely related with marine tidal wave phenomenon from the distal effect caused by the atmospheric flow[14]. In order to better simulate the marine tidal wave and tidal current to flow direction, we selected the second order stokes wave to describe remote atmospheric wave disturbance, waves and tidal currents in the direction of incoming ocean surgeswater phenomenon [15-16].

The potential function of the second order wave equation of stokes:

\[
\phi = \frac{\pi H \cosh[k(z + h)]}{kT\sinh(kh)} \sin(kx - \sigma t) + \frac{3\pi^2H}{8kT} \cosh[k(z + h)] \sinh^2(kh) \sin 2(kx - \sigma t) \quad (1)
\]

In this plane, current tidal wave transmission speed of the horizontal and vertical component of u, w can respectively by \( \frac{\partial \phi}{\partial x} \) and \( \frac{\partial \phi}{\partial z} \) is obtained:

\[
u = \frac{\pi H}{T} \cosh[k(z + h)] \sin[kx - \sigma t] + \frac{3\pi^2H}{8kT} \cosh[k(z + h)] \sinh^2(kh) \cos 2(kx - \sigma t) \quad (2)
\]

\[
w = \frac{\pi H}{T} \sinh[k(z + h)] \sin[kx - \sigma t] + \frac{3\pi^2H}{8kT} \cosh[k(z + h)] \sinh^2(kh) \sin 2(kx - \sigma t) \quad (3)
\]
The model of the turbine is simulated by using the commercial software ANSYS CFX. The velocity boundary condition at the inlet of the ocean is set as the U and W of the second order Stokes wave. A rotating interface is arranged in the runner domain to ensure relative motion between the fluid and the rotating impeller. The static and dynamic joints between runner and draft tube and guide blade are all connected by this kind of interface, and turbulence model is selected SST model. In the calculation, the solver uses the second order Euler difference scheme, and the convergence residual is set to $10^{-4}$.

### 3. Analysis of pressure and velocity in wave current condition

It is very important to study the velocity and pressure distribution in the bulb tubular turbine after adding the wave current condition, especially the inlet of the internal flow field, the front of the runner and the inlet section of the guide vane and the tail water. As shown in figure 4, the distribution of velocity and pressure on these cross flow sections is of great significance to the analysis of the pressure and velocity variations of the flow passage and the strength calculation results.

![Figure 4. Distribution of monitoring points and flow cross sections](image_url)

(a) Pressure distribution with gravity and wave current condition

(b) Pressure distribution without gravity or wave current condition
Section 1 2 3 4
(c) Velocity distribution with gravity and wave current condition

(d) Velocity distribution without gravity or wave current condition

Figure 5. Pressure and velocity distribution of important truncation surfaces

Compared with figure 5, in the case of without considering the wave flow, velocity and pressure distribution is uniform and symmetrical on the flow cross sections, and no obvious gradient change, the characteristics of the corresponding pressure distribution shows central symmetry. After considering the wave flow, each section of the pressure from top to bottom increases has obvious gradient change, the vertical direction showed no obvious changes in the distribution level. Symmetry, in the corresponding flow on the surface of the speed also showed the same distribution tendency. Compared with the flow rate of all 1st section, wave flow has direct impact on the incoming flow mode, average flow velocity of cross section is 3.75m/s, compared with 4.51m/s without gravity condition reduces the velocity of 0.76m/s fell nearly 17%. Similarly, this phenomenon also occurs on the 2nd and 3rd sections. The larger the unit size, the greater the pressure difference.

When the impeller works, its flow field and the load on blade will be periodic asymmetric unsteady state change under the affected by tidal waves. The flow velocity of the wave in most cases is relatively low, stress and flow distribution has a big difference in the vertical direction.

4. Fluctuation analysis of flow field in wave carrying flow
The flow turbine works in reverse condition and the water will directly rush for the blade without front guide vanes. As shown in figure 6, the blades will be subject to more loads coming from the axial flow. When the wave current and gravity are taken into consideration, the blade's front and back pressure will vary with each blade, and the blades near the bottom of the flow field will suffer more pressure. Due to the different leaf position under pressure not equal, leaf position at the bottom suffered the maximum stress, leaf position at the top suffered minimum pressure, so the blade pressure experienced a process from small to large then to small in the spinning process.

Figure 6. Analysis diagram of wheel running condition
Because the tidal wave itself is affected by gravity, it will inevitably lead to the corresponding pressure and velocity gradient along the Z axis at the same section. This is also the basic difference between the wave flow condition and the wave free flow condition. The flow characteristics will eventually lead to the stress fluctuation of blade. However, the periodicity of the wave current does not always coincide perfectly with the frequency shift of the runner, that is to say, the frequency of the runner and the frequency of the wave current are different. These two factors act on the flow field and cause two kinds of pressure pulsation respectively. These two kinds of pressure fluctuations act on the blade simultaneously, which will greatly increase the fatigue stress of the blade, which is the reason of the fluid mechanical fatigue in actual environment damage situation in calculation will be higher than the design value.

![Pressure fluctuations diagram](image)

**Figure 7.** Pressure fluctuation diagram of truncated surface
Figure 7 is the pressure pulsation in the frequency – amplitude under one working condition with a blade opening under the same wave flow of the 4 main flow cross section, runner turning frequency is 1.50Hz and wave current frequency is 3.0Hz. When the fluid machinery working in the wave current condition, two kinds of pressure fluctuation will act in the flow field at the same time, which exacerbated the instability in the flow field. Under the normal working conditions, the impeller will be affected by this wave frequency and runner frequency, which results in more fatigue stress and less fatigue life of the impeller, which will cause harm to the unit.

At the same time, two distinct pressure fluctuations are observed at the 1st and 3rd sections in the reverse working condition, and the amplitude of the point “A” is obviously higher than point “B”. The 4th section is located in the pier, due to the existence of the pier, channel is divided into two relatively independent parts, the pressure of B fluctuation amplitude flow wave is much lower than that of A, this is due to the gradient difference of the vertical direction in the field of memory, at the same time as the pier itself being blocked, monitoring little fluctuation at the same height also has the difference.

5. Efficiency fluctuation analysis

After considering the influence of gravity and tidal flow, the pressure and velocity distribution in the flow field are obviously changed, in table 1 can be seen, we would get a larger efficiency in considering the wave flow and gravity situation than that without the wave current or gravity, the difference between two maximum value will be found at the optimal point difference, which is 1.3%. The unit efficiency increases with the increase of the flow rate, and the best efficiency is at the optimal operating point. Then the efficiency decreases. Considering the fluctuation of the efficiency under different conditions, the time average efficiency value defined in Eq. (4) of the unsteady results has been compared:

\[ \eta = \frac{1}{T} \int_{t}^{t+\Delta t} \eta dT \]  

\[(4)\]

| Blade Angle | Q11 (m3/s) | n11 (r/min) | With wave? | Efficiency | Difference |
|-------------|------------|-------------|------------|------------|------------|
| 8°          | 1.34       | 170         | no         | 67.9%      | 3%         |
| 8°          | 1.4        | 180         | yes        | 70.9%      |            |
| 9°          | 1.4        | 170         | no         | 68.3%      | 1.3%       |
| 9°          | 1.5        | 180         | yes        | 69.6%      |            |
| 10°         | 1.45       | 170         | no         | 68.2%      | 1.4%       |
| 10°         | 1.45       | 180         | yes        | 69.6%      |            |
| 11°         | 1.5        | 170         | no         | 64.4%      | 4%         |
| 11°         | 1.5        | 180         | yes        | 68.4%      |            |
| 12°         | 1.5        | 170         | no         | 62.1%      | 4.1%       |
| 12°         | 1.5        | 180         | yes        | 66.2%      |            |

6. Conclusions

The following conclusions can be summarized:

Under the same conditions, the efficiency of no wave flow condition is obviously higher than that with wave current efficiency. But in actual natural conditions, the wave current effect is universal. The fluctuation of efficiency is caused by tidal wave, and the fluctuation of the optimal working condition is the smallest.
Compared with the case without consideration of the condition of wave flow, the pressure distribution in the runner chamber is no longer symmetrical due to the influence of gravity, wave thrust and water mass transport in the runner flow path with wave flow. The gradient along the Z-axis is particularly noticeable, much closer to the actual operating conditions.

The computational model of wave-containing flow conditions is taken into account when wave-current coupling is applied, the frequency of the hydro-mechanical self-tuning and the wave frequency under investigation will not be the same in most cases, and the blades of such an impeller will be affected by the pressure pulsations and periodic squeezes caused by the tidal waves, producing more severe fatigue stress destruction than the no-flow conditions, resulting in a substantial reduction in the actual fatigue life of such fluid machines.

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References
[1] GuojunZhu, PengchengGuo, Xingqi Luo, GuoqingQi 2014, Multidisciplinary optimization design of runner blades in tubular turbine. *Journal of agricultural engineering*, volume30 pp47 - 55.
[2] D. Sharpe 1990 Wind turbine aerodynamics. Freris，LL Wind Energy Conversion Systems， *Prentice Hall*, pp36-43.
[3] ZiniuWu 2001 *Basic principles of computational fluid dynamics*. First edition. *Science Press*.
[4] XingyanZhao, ChuhuaZhang, MorningSu, et al. 2000 CFD method in fluid machinery design using *fluid machinery*. volume 28 chapter3 pp 22-25
[5] YapingZhao, WeiliLiao, Zhihua Li, et al. 2013 Flow field performance of bulb turbine with C-type or S-type blades. Chinese Journal of agricultural engineering volume 29 chapter 17 pp47 - 53.
[6] ZhongdongQian, WeiWei, XiaoboFeng. 2014 Numerical simulation of pressure pulsation in the whole flow passage of bulb turbine. *Proceedings of the society of hydroelectric power*, volume33 chapter 4 pp242-249.
[7] YanzeLiu, JinshiChang. 2008 Influence of gravity on flow field analysis and hydraulic performanceevaluation of bulb turbine. *Journal of hydraulic engineering*, chapter1 pp96-102.
[8] LigongZhao, Shuxiu Liang. 2016 Wave current coupling simulation of large bulb tubular turbine. *Chinese wind down water*, volume16 pp100-103.
[9] YixiangLiu. Development and application of large scale bulb turbine unit. *Red River*, volume 2 chapter 19 pp 41-44.
[10] ZhishengGong, HaihongLi, XinchunZhang, ZhaoweiWang. 2007. Hydraulic Vibration Reason Analysis of Bulb Tubular Turbine. *Qinghai electric power*, volume 3 pp58-63.
[11] Xijin Ma, BiaoMa and ZhengguiLi. 2014 Analysis of Numerical Values of Bulb Turbine Pressure Fluctuation. *Gansu science journal*, volume 5 pp 76-80.
[12] ZhiliZou. *Coastal dynamics*, Fourth Edition, 2009, people's communications agency.
[13] SongrenWu, YixinYan *Marine dynamics* Third Edition, October24 2002 China Communications Press.
[14] Yueqing Bay Water Development Commission. JiangSha tidal test station 2008, *China Electric Power Press*.
[15] YuepingWang, *tide generator*, September 2014 edition, *China Water Power Press*.
[16] YuepingWang, ChunmingZhao, ManshuiFang, JianhuiYe. *Comparison test report of F03A and F03B Model Runner of Jiang Xia tidal power station*. March 1993 the Fu Chun Jiang hydropower equipment General Factory.