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Modal Analysis on Fluid-Structure Interaction of MW-Level Vertical Axis Wind Turbine Tower

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Abstract: In order to avoid resonance problem of MW-level vertical axis wind turbine induced by wind, a flow field model of the MW-level vertical axis wind turbine is established by using the fluid flow control equations, calculate flow's velocity and pressure of the MW-level vertical axis wind turbine and load onto tower's before and after surface, study the Modal analysis of fluid-structure interaction of MW-level vertical axis wind turbine tower. The results show that fluid-structure interaction field of MW-level vertical axis wind turbine tower has little effect on the modal vibration mode, but has a great effect on its natural frequency and the maximum deformation, and the influence will decrease with increasing of modal order; MW-level vertical axis wind turbine tower needs to be raised the stiffness and strength, its structure also needs to be optimized; In the case of satisfy the intensity, the larger the ratio of the tower height and wind turbines diameter, the more soft the MW-level vertical axis wind turbine tower, the lower its frequency. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Tower, Fluid-structure interaction, Modal analysis, MW-level wind turbine.

1. Introduction

With the increasingly serious energy crisis, most of countries in the world want to alleviate the influence of energy crisis by using a variety of technical means [1, 2]. With the continued growth of energy demand around the world [3] and the more and more stringent environmental laws and regulations. The MW-level wind turbine has become the mainstream of wind power equipment [4, 5]. The tower of the MW-level wind turbine not only loads the weight of the MW-level wind turbine, but also bear the wind pressure on the MW-level wind turbine and its dynamic load in running [6, 7]. Thus, the tower is one of the important parts of MW-level wind turbine which influence the normal operation. It is the premise of the MW-level wind turbine normal operation that tower is safe and reliable under different conditions, so the design and manufacturing of the tower is particularly critical.

So far, the research of wind turbine vibration mainly concentrated in the yaw system and blade [6-10], and there are not any researches adopt fluid-structure interaction method. Such as the literature [11] has used the multidimensional modal analysis theory and the method of time space iteration method for mathematical modeling and simulation of the vibration modes of horizontal axis wind turbine tower. Literature [12] has used the finite element method for the construction of the finite element model of wind turbine tower for dynamic performance analysis, and some ideal results were obtained. Literature [13] has done some checking calculation of the static deflection, bending moment, bending stress and the tensile stress of connecting bolt of the tower bottom in wind speed changing process, which can provide a good basis of improving wind machine design for the resistance the typhoon. Literature [14] has putted the hypo load calculation method into the ocean wind turbine tower load calculation, it consider the design should pay attention to the mutual coupling effect of wind and wave load. Literature [15] has analyzed the stress distribution of large horizontal axis wind turbine tower under the action of wind on the ground, for the problem of air flow around the cylinder has given a calculation method of tower's vibration response induced by constant wind and unsteady wind.

When the vertical axis of MW-level wind turbine is running, flow of gas has great impact on MW-level vertical axis wind turbine tower's job performance and vibration characteristics. At the same time, MW-level vertical axis wind turbine tower's disturbance will affect the wind field in turn, which is a typical fluid-structure interaction model [16]. Therefore, this paper calculate the velocity distribution and pressure distribution of the internal flow field which near MW-level vertical axis wind turbine tower based on the simplified physical model and high precision numerical algorithm, then load onto tower's before and after surface, calculate the fluid-structure interaction of the MW-level vertical axis wind turbine tower and determine MW-level vertical axis wind turbine tower modal parameters, which can be used for improving MW-level vertical axis wind turbine tower structure so as to avoid being destroyed by the resonance that is induced by wind and provide the theory basis of the tower failure analysis at the engineering practice.

2. Modal Simulation Model of the MW-level Vertical Axis Wind Turbine Tower

2.1. Conservation Equation

Because the load of wind acting on the MW-level vertical axis wind turbine tower is instantaneous and unstable, the inertia of the structure can't be ignored in the analysis. Convenient to analysis problems, let the subscript f shows the fluid, s shows the solid.

1) Fluid control equation.

Fluid flow conform to the law of conservation of physical, such as the law of conservation of mass, the law of conservation of momentum, the law of conservation of energy. And if the fluid contains other ingredients, the mixtures follow the law of conservation of components. As general compressible Newton flow, conservation law can be described by the following equation.

Conservation equation of mass:

$$\frac{\partial \rho_{\mathrm{f}}}{\partial \tau}+\nabla \cdot\left(\rho_{\mathrm{f}} \boldsymbol{v}\right)=0, \tag{1}$$

where τ is the time, s; ∇ is the Hamiltonian operator, $\nabla=(\partial/\partial x)i+(\partial/\partial y)j+(\partial/\partial z)k$; ρ_f is the fluid density, $\mathrm{kg \cdot m^{-3}}$; v is the fluid velocity, $\mathrm{m \cdot s^{-1}}$.

Conservation equation of momentum:

$$\frac{\partial \rho_{\mathrm{f}} \boldsymbol{v}}{\partial \tau}+\nabla \cdot\left(\rho_{\mathrm{f}} \boldsymbol{v} \boldsymbol{v}-\tau_{\mathrm{f}}\right)=\boldsymbol{f}_{\mathrm{f}}, \tag{2}$$

where f_f is the volume force, $\mathrm{kg \cdot m^{-2} \cdot s^{-2}}$; τ_f is the shear stress, Pa, can be written as:

$$\tau_{\mathrm{f}}=-(p+\frac{2}{3} \mu \nabla \cdot \boldsymbol{v}) \boldsymbol{I}+2 \mu \boldsymbol{e}, \tag{3}$$

where p is the fluid pressure, Pa; μ is the dynamic viscosity, Pa·s; I is the unit tensor; e is the speed of stress tensor, $e=(\nabla v+\nabla v^T)/2$.

2) Solid control equation.

Solid mass conservation equation:

$$\rho_{\mathrm{s}} \frac{\mathrm{d}^2 \boldsymbol{d}_{\mathrm{s}}}{\mathrm{d} \tau^2}=\nabla \cdot \boldsymbol{\sigma}_{\mathrm{s}}+\boldsymbol{f}_{\mathrm{s}} \tag{4}$$

where ρ_s is the solid density, σ_s is the cauchy stress tensor, Pa; f_s is the volume, $\mathrm{kg \cdot m^{-2} \cdot s^{-2}}$; d_s is the Solid domain local displacement, m.

3) Fluid-structure interaction equation.

In the region of the fluid-structure interaction, the pressure of wind load on the MW-level vertical axis wind turbine tower can change vibration modal of the tower, while the vibration modal will impact the airflow velocity and the distribution of the pressure in the upper stream and down stream of the MW-level vertical axis wind turbine tower. Therefore, load the calculated velocity and pressure of the flow field of the MW-level vertical axis wind turbine tower onto tower's before and after surface, and coupling solve for the fluid control equation and the solid control equation.

Fluid-structure interaction of MW-level vertical axis wind turbine tower follow the basic principles of conservation, so on the fluid-structure interaction interface, the fluid stress τ_f, the solid stress τ_s, the fluid displacement d_f and the displacement of solid d_s and so on should equal, and is

$$\begin{cases}\boldsymbol{\tau}_{\mathrm{f}} \cdot \boldsymbol{n}_{\mathrm{f}}=\boldsymbol{\tau}_{\mathrm{s}} \cdot \boldsymbol{n}_{\mathrm{s}} \\ \boldsymbol{d}_{\mathrm{f}}=\boldsymbol{d}_{\mathrm{s}}\end{cases}, \tag{5}$$

where n_f is the fluid-structure interaction interface fluid normal unit vector, n_s is the fluid-structure interaction interface in solid method to the unit vector.

4) Modal analysis equation.

Natural frequency and vibration mode is the intrinsic attribute of system, which has nothing with the load. The undamped free vibration equation of the structure can be written as:

$$\boldsymbol{M} \frac{\mathrm{d}^2 \boldsymbol{S}}{\mathrm{d} \tau^2}+\boldsymbol{K} \boldsymbol{S}=0, \tag{6}$$

where, M is the structural mass matrix; K is the structural stiffness matrix; S is the node displacement vector.

For a linear system, free vibration can be described by simple harmonic form:

$$\boldsymbol{S} = \boldsymbol{\Phi}_i \cos \omega_i t \,, \tag{7}$$

where Φ_i is the $i(i=1,\ 2,\ \dots,\ n)$ order's natural frequency corresponding eigenvectors, the modal vector; ω_i is the i order's natural frequency, rad/s.

Add the formula (7) to formula (6), then the results can be expressed as:

$$(\boldsymbol{K} - \omega_i^2 \boldsymbol{M})\boldsymbol{\Phi}_i = 0 \,, \tag{8}$$

The condition of the formula (8) has a zero solution ($\boldsymbol{\Phi}_i$ could't be all zero) is that the determinant in the parentheses must be zero, the characteristic equation shows:

$$\boldsymbol{K} - \omega_i^2 \boldsymbol{M} = 0 \,, \tag{9}$$

Eigen value ω_i^2 can be solved through formula (10), put ω_i^2 into formula (3), the corresponding eigenvectors ($\boldsymbol{\Phi}_i$) can be obtained.

2.2. Finite Element Mesh of the MW-level Vertical Axis Wind Turbine Tower

At present, some common towers such as drum, braced, concrete type, etc. The object of this study is the 1.5 MW vertical axis wind turbine tower, which structure is taper cylinder. The geometrical and physical parameters of the tower as shown below: tower height H=78 m, the outer diameter of the bottom Ddown=4.2 m, the outer diameter of the top Dup=2.3 m, wall thickness B=24 mm, materials is Q345, $E=2.06\times10^{11}$, $\mu=0.3$, $\rho=7.850\times10^3$ kg/m^3, allowable stress $\sigma=237$ MPa, allowable tensile strength $\sigma=425$ MPa.

As the Fig. 1, MW-level vertical axis wind turbine tower's main load is horizontal thrust *F,* the gravity of cabin, blade and wheel hub is G_1, self-respect of tower is G_2, wheel torque *M.* Because the wind pressure effect on the tower is small compared with the rotor thrust of the wind wheel, it can be ignored.

Therefore, a three-dimensional entity model of MW-level vertical axis wind turbine tower is established as Fig. 2, 8 node SOLID185 three-dimensional hexahedron entity unit is chose as unit type, hexahedral SWEEP partition method is adopted to mesh.

Because the size of tower is very lager, consider the numerical precision and computing speed, unit size is selected 0.1 m. The finite element model of the tower has 151708 nodes, 76538 units, 151709 nodes are generated after creating contact of the top line of tower model, tower model's force and moment are applied at these nodes, and underside's DOF of the tower model is restrained.

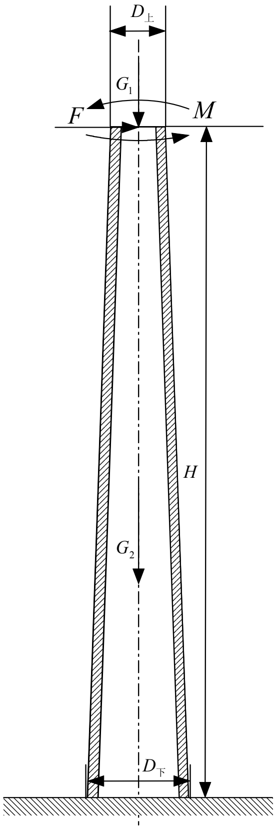

Fig. 1. Stress diagram of MW-level vertical axis wind turbine tower.

Fig. 2. Finite element model of MW-level vertical axis wind turbine tower.

2.3. Conditions of the Fluid-structure Interaction Field Simulation

Fluid domain of computational model should be set before the fluid-structure coupling field boundary conditions being set, the physical model is chosen the static analysis of steady state, air is selected as fluid of the fluid domain, ρ=1.18415 kg/m^3, turbulence model is a standard K-Epsilon model, temperature is normal temperature and heat insulation, reference a standard atmosphere pressure, because fluid flow in the fluid domain is low, so use separate solver, and set the initial conditions and boundary conditions in the fluid domain.

1) Initial conditions and boundary conditions of the entrance: The fluid is incompressible fluid flow in the region, the initial wind speed is constant wind speed, V=25 m/s.

2) Boundary conditions of the export: its boundary conditions are export pressure, the size of the pressure set as a standard atmospheric pressure.

3) Surface condition: the boundary conditions of fluid domain bottom and tower surface are set as wall, the roughness of the wall is set as smooth. For viscous fluid, using adhesion conditions, which means the fluid velocity on the wall is same as the wall velocity, velocity of no slip wall is zero, the wall's fluid velocity is zero. The ground and the surface of MW-level vertical axis wind turbine tower is stationary, so select no slip wall's condition; the top, former and behind surface of the fluid domain is slip boundary conditions.

3. The Implementation of the Fluid-structure Interaction Field Modal Simulation

3.1. The Result and Analysis of Fluid-structure Interaction Field Modal Simulation

MW-level vertical axis wind turbine tower's first 10 modal shape is basically consistent no matter weather considering the influence of the fluid-structure interaction, but its natural frequency and the maximum deformation of first 10 modal are obvious different. In addition, constant wind speed has little effect on MW-level vertical axis wind turbine tower's vibration mode.

The natural frequency and the maximum deformation of first 10 modal of MW-level vertical axis wind turbine tower are f_s, δ_s when the fluid-structure interaction has been considered, are f_c, δ_c when the fluid-structure interaction has not been considered. The relative error of tower's natural frequency and the maximum deformation are $\eta_f=(f_c-f_s)\times100\%/f_s$, $\eta_\delta=(\delta_c-\delta_s)\times100\%/\delta_s$, respectively.

Vibration mode of the MW-level vertical axis wind turbine tower is present in Fig. 3. According to Fig. 3, the deformation of the tower in the first order vibration mode is very large, especially the top edge's deformation of the tower is reach 2.135 mm; in the third modal shape, the deformation are relatively large at tower's top and waist, 2.542 mm and 3.134 mm respectively, where are easy to be damaged and their stiffness need to be increased; As is shown in Fig. 3(e), Fig. 3(f), Fig. 3(g), Fig. 3(i), Fig. 3(j), in the 5th, 6th, 7th, 9th and 10th modal shape, the tower's bottom and waist have expansion deformation, where are easy to be damaged, the MW-level vertical axis wind turbine tower's stiffness needs to be increased, and its structure also needs to be optimized.

The comparison results MW-level vertical axis wind turbine tower's natural frequency and the maximum deformation whether fluid-structure interaction effect is considered as shown in Table 1. As is shown in Table 1, the effect of whether fluid-structure interaction effect is considered on natural frequency of the MW-level vertical axis wind turbine tower's first 10 modal is inconsistent. Comparing with when fluid-structure interaction effect is considered, when fluid-structure interaction effect is not considered the tower's 2th, 3th, 5th, 7th, 8th and 10th natural frequency are enlargement, increasing rate are 8.9 %, 3.62 %, 0.71 %, 0.47 %, 0.90 % and 0.33 %, respectively, but the 1th, 4th, 6th, 9th natural frequency is decrease, reduce rate are 6.25 %, 2.18 %, 0.87 % and 0.60 %, respectively, but the absolute value of relative errors of natural frequency of tower decrease with the increase of the order. It is mainly because the fluid-structure coupling field has inhibition effect on the vibration mode of the MW-level vertical axis wind turbine tower, thus the fluid impact has a great influence on the natural frequency of lower order modal of the MW-level vertical axis wind turbine tower, and has little influence on the higher order modal of the MW-level vertical axis wind turbine tower.

Comparing with when fluid-structure interaction effect is considered, when fluid-structure interaction effect is not considered the relative error of the maximum deformation of tower's first 10 modal are -9.79 %, -9.44 %, -9.48 %, -9.89 %, -6.52 %, -6.07 %, -4.00 %, -4.07 %, -4.68 % and -3.95 %. Obviously, the relative error change trend is decline when the order is increased, but the maximum deformation is decrease. It is mainly because the fluid impact has an influence on restraining the deformation of higher order modal shape of the MW-level vertical axis wind turbine tower. And fluid has a more great effect on the maximum deformation of tower's lower order than higher order.

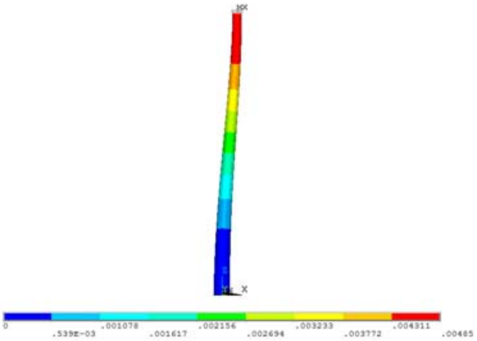

Fig. 3 (a). Vibration mode of MW-level vertical axis wind turbine tower: the first modal shape.

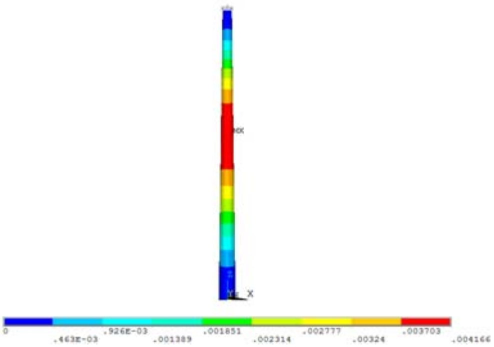

Fig. 3 (b). Vibration mode of MW-level vertical axis wind turbine tower: the second modal shape.

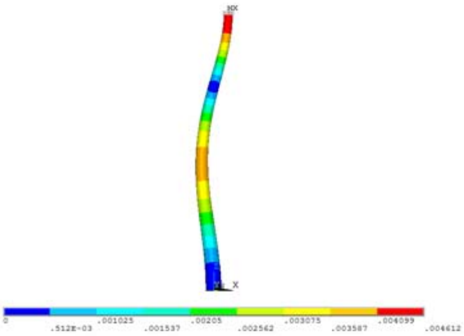

Fig. 3 (c). Vibration mode of MW-level vertical axis wind turbine tower: the third modal shape.

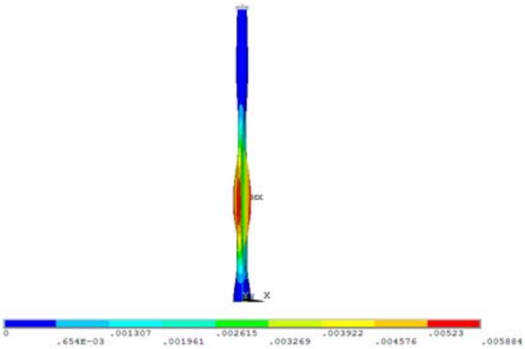

Fig. 3 (d). Vibration mode of MW-level vertical axis wind turbine tower: the fourth modal shape.

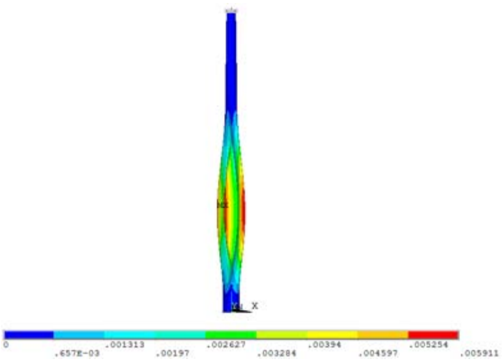

Fig. 3 (e). Vibration mode of MW-level vertical axis wind turbine tower: the fifth modal shape.

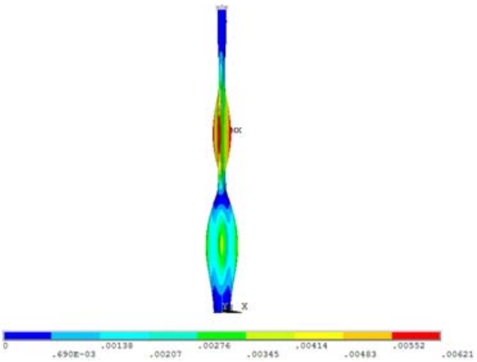

Fig. 3 (f). Vibration mode of MW-level vertical axis wind turbine tower: the sixth modal shape.

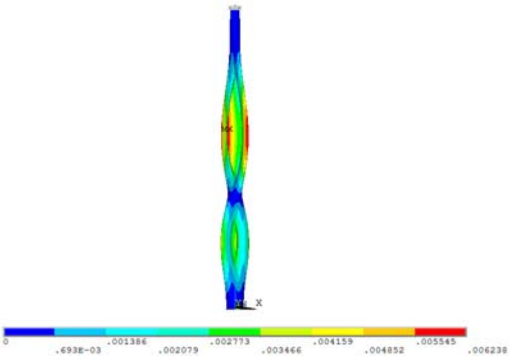

Fig. 3 (g). Vibration mode of MW-level vertical axis wind turbine tower: the seventh modal shape.

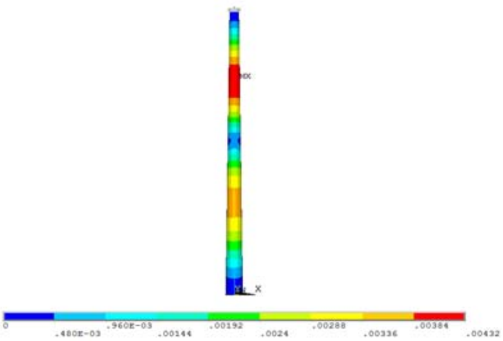

Fig. 3 (h). Vibration mode of MW-level vertical axis wind turbine tower: the eight modal shapes.

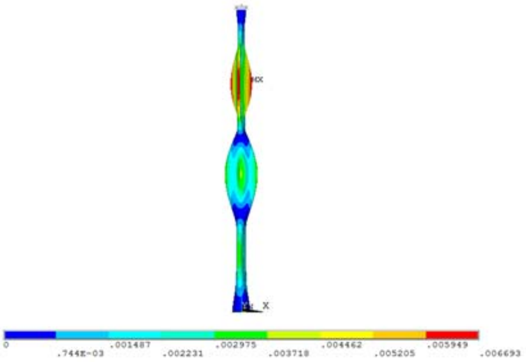

Fig. 3 (i). Vibration mode of MW-level vertical axis wind turbine tower: the ninth modal shape.

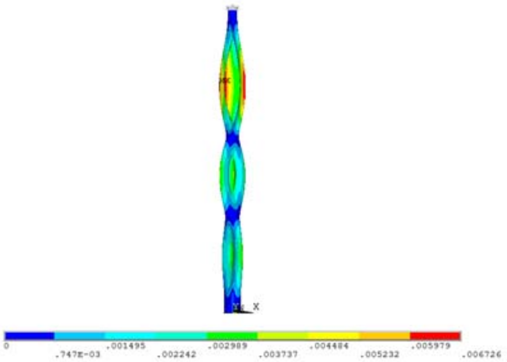

Fig. 3 (j). Vibration mode of MW-level vertical axis wind turbine tower: the tenth modal shape.

Table 1. The comparison result of the first 10 order natural frequency and the maximum deformation.

Order	Frequency			Deformation		
	f_s/Hz	f_c/Hz	η_f/%	δ_s/mm	δ_c/mm	η_δ/%
1	0.98492	0.92334	-6.25	2.135	1.926	-9.79
2	3.2658	3.5564	8.90	1.034	0.9364	-9.44
3	4.5632	4.7284	3.62	3.134	2.837	-9.48
4	5.7201	5.5952	-2.18	1.224	1.103	-9.89
5	5.7567	5.7976	0.71	1.258	1.176	-6.52
6	7.4539	7.3894	-0.87	1.269	1.192	-6.07
7	7.4979	7.5332	0.47	1.450	1.392	-4.00
8	8.7233	8.8015	0.90	1.327	1.273	-4.07
9	9.3451	9.2888	-0.60	1.368	1.304	-4.68
10	9.3928	9.4239	0.33	1.393	1.338	-3.95

3.2. Analysis on Influence Factor to the Tower's Inherent

The relationship of natural frequency with effect factor of MW-level vertical axis wind turbine tower is shown in Fig. 4, such as the section moment of inertia, tower wall thickness and ratio of height with diameter.

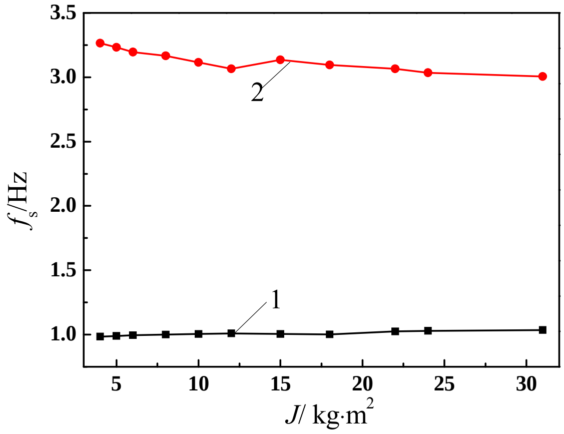

Fig. 4 (a). Relationship of the tower's natural frequency with influence factors: Tower's cross section moment of inertia.

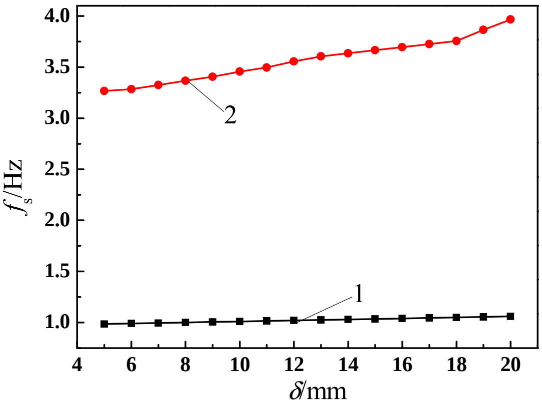

Fig. 4 (b). Relationship of the tower's natural frequency with influence factors: Tower's wall thickness.

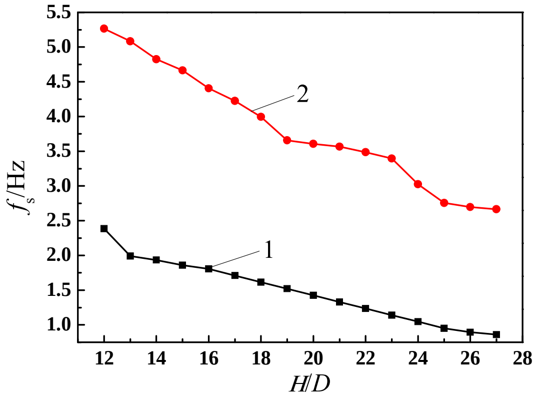

Fig. 4 (c). Relationship of the tower's natural frequency with influence factors: H/D.

In Fig. 4: 1 – the frequency-mode 1; 2 – the frequency-mode 2.

Fig. 4(a) shows that the frequency-mode 1 increase with the cross section moment of inertia J increase, the increasing rate is small; but the frequency-mode 2 is decrease with J increase, and decline fast, the reason is when tower's cross section moment of inertia is increasing, its quality also change. The change trend of frequency-mode 2 as is shown in Fig. 4(a) is influenced by tower's quality and cross section moment of inertia combined action. If the first modal shape's frequency is changed by changing tower's cross section moment of inertia, it need to consider the size of the diameter of MW-level wind turbine tower in practical application, because its size of the diameter is generally controlled within 5 m due to some reasons such as the strength, buckling design, transportation and so on.

Fig. 4(b) shows that if the wall thickness (δ) increase, the MW-level vertical axis wind turbine tower's strength and buckling resistance will be improved, the tower's bending frequency and buckling frequency will increase, and the tower's second modal frequency increase fast, but the first modal, which has mainly effect on the dynamic performance of the MW-level vertical axis wind turbine tower, its frequency increase less. So, it is not suitable to increase MW-level vertical axis wind turbine tower's natural frequency by increasing the wall thickness in the case of the strength is enough. Because if the wall thickness increases, the tower's quality will increase, the cost of manufacturing and material will multiply.

As is shown in the Fig. 4(c), when the ratio H/D of height H with tower diameter D increase, the tower's natural frequency decrease fast, its rigid drop and flexible reinforced. Therefore, when the actual strength have been satisfied, the MW-level vertical axis wind turbine tower's classification of the frequency is depend on H/D, the higher the ratio, the more soft the MW-level vertical axis wind turbine tower, the lower the frequency.

4. Conclusion

1) The MW-level vertical axis wind turbine tower's natural frequency and relative error of the maximum deformation are decreasing with the order increase when fluid-structure interaction effect is considered. It is mainly because the fluid-structure coupling field has an influence on restraining the deformation of higher order modal shape of the MW-level vertical axis wind turbine tower. And fluid has a more great effect on the maximum deformation of tower's lower order than higher order.

2) The analysis result of the first 10 mode of the MW-level vertical axis wind turbine tower shows, the deformation of the tower top in the first order vibration mode is very large, and the deformation of the tower top and waist in the third order vibration mode is large, where are easy to be damaged, so the stiffness should be improved; and in the 5th, 6th, 7th, 9th and 10th modal shape, the tower's bottom and waist have expansion deformation, where are easy to be damaged, the MW-level vertical axis wind turbine tower's stiffness needs to be increased, and its structure also needs to be optimized.

3) The frequency-mode 1 increase with the cross section moment of inertia J increase, the increasing rate is small, it is not suitable to increase MW-level vertical axis wind turbine tower's natural frequency by increasing the wall thickness in the case of the strength is enough. When the actual strength have been satisfied, the MW-level vertical axis wind turbine tower's classification of the frequency is depend on H/D, the higher the ratio, the more soft the MW-level vertical axis wind turbine tower, the lower the frequency.

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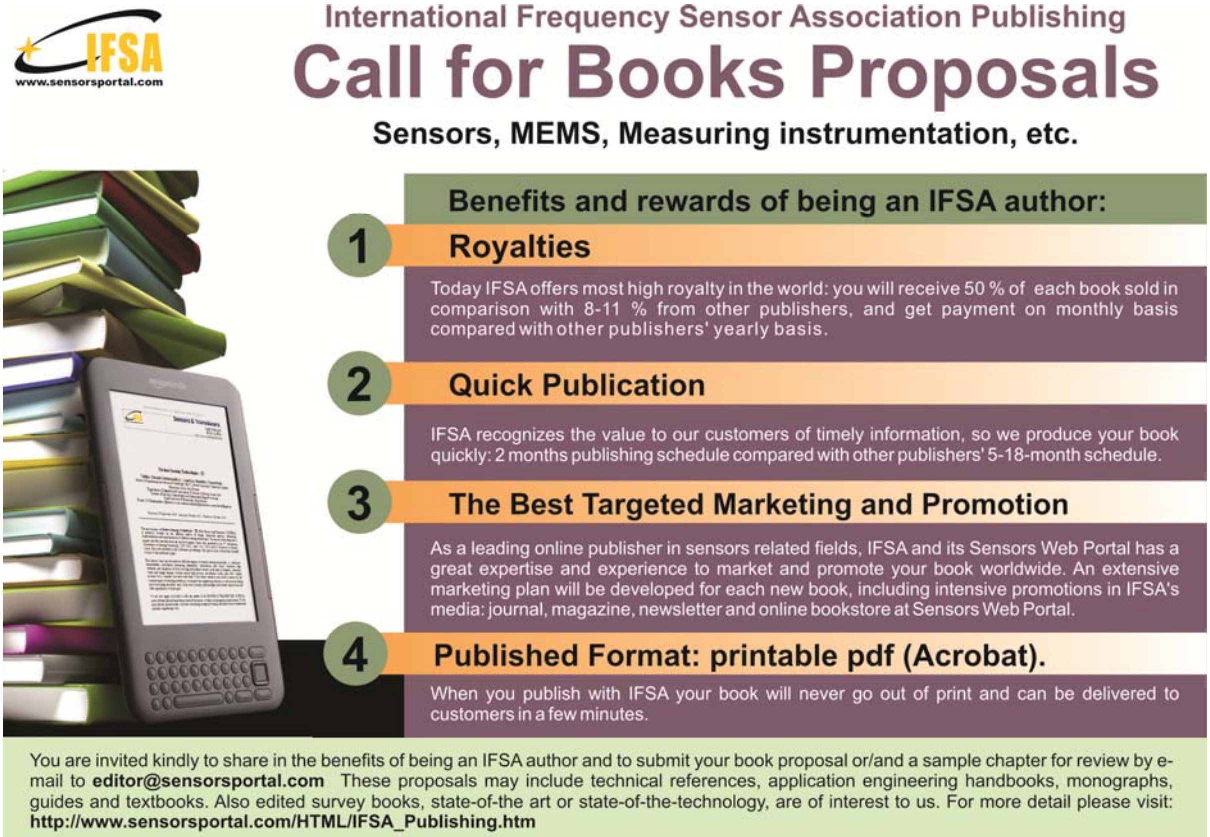
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