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Composite propeller's strain modal and structural vibration performance

HUANG Zheng, XIONG Ying, YANG Guang

Department of Naval Architecture Engineering, Naval University of Engineering, Wuhan 430033, China

Abstract: The natural frequency and displacement strain modal vibration mode is comparative studied using validated finite modal algorithm and strain modal experiment, the result showed that the deviation of tested and calculated first three natural frequency of copper and carbon fiber propeller is within 3% and 12%, respectively. The carbon fiber propeller has smaller natural frequency, similar strain modal and four times structure damping compared with copper propeller. Further calculation of the wet modal of two propellers, the first four wet modal natural frequency of copper propeller reduced 18%-33% compared with the corresponding dry modal, while the carbon fiber propeller's reduction is 54%-64%. More research on vibration performance of propeller is carried out. The fiber orientation beneficial for vibration attenuation is obtained, and the total acceleration level of optimized carbon fiber propeller is 2 dB less than the tested carbon fiber propeller.

Key words: composite propeller; strain modal; natural frequency; vibration response; vibration acceleration level

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0 Introduction

Composite propeller has the advantages of high elasticity, light weight, low magnetism, high designability, strong impact resistance and corrosion resistance, damping vibration attenuation, etc. The structural vibration performance must be considered when the composite materials are used instead of routine nickel-aluminum bronze materials. In terms of the structure, it is necessary to measure the modal and natural frequency of propeller, and because of its complex geometry, the natural frequency is measured by means of attaching electrical resistance strain gauges. Besides, the vibration performance of composite propeller are studied together with copper propeller to explore the difference of vibration frequency response between the carbon fiber propeller and the copper propeller and put forward the improvement method.

In the calculation of propeller modal and natural frequency, Young et al.[1-7] verified the modal and natural frequencies of different propeller models by theoretical calculation and test respectively, and obtained the change law of modal vibration mode and natural frequency with the change of propeller parameters. The percussion method by means of the acceleration sensor measurement is adopted in all experiments, and the calculation method adopts the finite element software. However, the influence of the additional mass of the acceleration sensor is not explored.

In the studies of propeller strain modal, Suneetha et al.[8] used ABAQUS to calculate the deformation and stress of the propeller. Herath et al.[9] studied the flexural-torsional coupling characteristics of NACA airfoil, and took the strain test through fiber grating (FBG). Based on the modal model of vibration and strain response, Li et al.[10-11] expounded the constitutive characteristics of the strain transfer function, the testing scheme and the four methods of identification

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Author(s): HUANG Zheng, male, born in 1989, Ph. D.. Research interest: performance of composite propeller.
E-mail: huangzheng.315@163.com
XIONG Ying (Corresponding author), male, born in 1958, professor, doctoral supervisor. Research interest: ship fluid mechanics. E-mail: ying_xiong28@126.com

of the modal parameters, and improved the strain modal measurement method by comparing the displacement modal and the strain modal of the cantilever beam. The study of strain measurement and strain modal of the specimen are worth learning, but there is no strain modal measurement and verification for the propeller model.

As for the structural vibration and noise calculation in the flow field, Xia[12] calculated and measured the vibration and sound radiation performance of single and double cylindrical shell structure. Yang[13] and Ding et al.[14] studied the vibration noise of the composite rudder wing and the composite material after optimization design is used to achieve the vibration attenuation and noise reduction, which provides a reference for the vibration frequency response analysis of the propeller model in this paper.

In the above research, there is neither modal measurement nor verification of the small-size propeller model, and there is also no analysis of vibration response to the propeller of the new material. However, exploring the propeller from the structural level is the foundation of its fluid - solid coupling study. The strain modal and natural frequency of the 240 mm metallic propeller and carbon fiber propeller are measured by means of attaching electrical resistance strain gauge. The results of the finite element analysis are verified, and the influence of the natural frequency of the wet modal and the fiber orientation on the natural frequency of the composite propeller is studied. The vibration performance of the composite propeller model are studied by using the structural vibration frequency response analysis method. In this paper, strain modal measurement method is applied to study the modals of copper propeller and composite propeller and the vibration frequency response is analyzed, which belong to exploratory work.

1 Dry modal calculation and test of propeller model

Because of the complex structure and small size of the propeller model, in order to measure the natural frequency of the propeller model, it is necessary to combine the finite element calculation with the test measurement to select the modal vibration mode more accurately and obtain the natural frequency. In the preliminary studies, the reliable modal calculation method is established and based on it, the natural frequency and modal vibration modes of copper propeller and carbon fiber propeller are forecast and verified by the strain modal measurement test in this section.

1.1 Basic principle of strain modal

Usually, the natural frequency of the structure is measured by the displacement modal measurement method with the acceleration sensor attached, and displacement frequency response function is input by hammering or sweeping excitation force. This method is very mature. Theoretically, the strain modal and displacement modal are two forms of the same energy balance state. The displacement modal represents the inherent vibration equilibrium state of the structure and the strain modal is the corresponding strain distribution state. Just as the displacement modal analysis method is used to establish the structural vibration displacement response prediction model, strain modal analysis method can also establish the vibration strain response prediction model to obtain the load-strain frequency response function which can be used to seek the strain modal corresponding to displacement modal and the relevant modal parameters.

1.2 Verification of calculation method of propeller dry modal

The modal calculation is carried out by using the ABAQUS software and the frequency extraction calculation is conducted in the modal analysis step. However, the conventional acceleration sensor of small-scale model has a large influence because of the additional mass, and the electrical resistance strain gauge measurement modal changes above it which is output as a strain value. The damping of the carbon fiber propeller is relatively large, and the input signal needs several times of percussion before screening. As for the modal test of the small-size model, the operation and the vibration mode selection are the process of repeated adjustment.

In order to establish the finite element method of the propeller modal, the calculated result is firstly compared with that of Young[1] to verify the feasibility of the algorithm. Through the theoretical prediction, the stress and strain are in good agreement with the tested results and the dry modal and wet modal natural frequencies of the propeller series are further predicted. In the test, the calculation object is 438 X series propellers with diameter of 0.305 m. The geometrical parameters of the four propellers are the same except for the skew back, trim and camber. The propellers are made of 2014-T4 aluminum with the density of 2 800 kg/m^3, Young's modulus E = 75 GPa, Poisson's ratiov = 0.33.

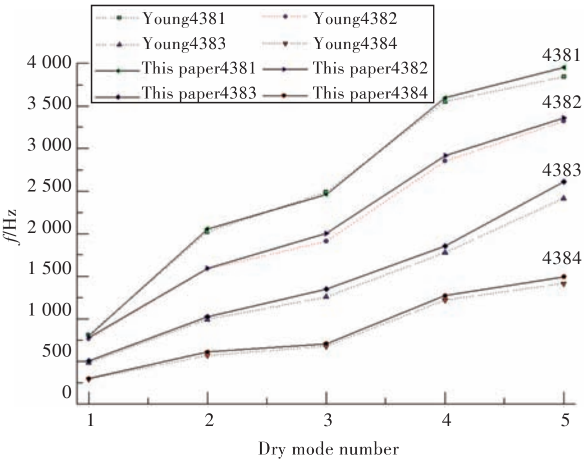


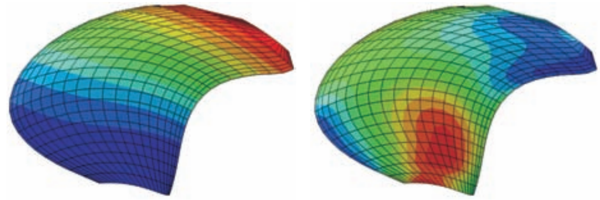
Fig.1 Comparation of 438X's dry modal natural frequencies with Young's[1] research

It can be known from the results shown in Fig. 1 that the differences of natural frequencies of different orders which are calculated by the dry modal method and Young[1] are all within 6%, which proves that the test has a good accuracy. With the skew back and elasticity of blade increased, the natural frequency decreases.

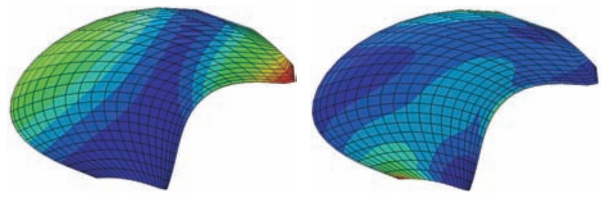
1.3 Dry modal calculation and test of copper propeller

The tested copper propeller model has a diameter of 240 mm, which is made of nickel-aluminum bronze. Its Young's modulus is 150 GPa and Poisson's ratio is 0.3. The weight of the propeller model is 1.98 kg and the density of the nickel-aluminum bronze is calculated to be 8.41×10^3 kg/m^3. The propeller model has 5 blades which are divided into 400 C3D8I grids by using the programming rule of surface element method and the propeller hubs are divided into 10620 C3D10 grids. The bolts at propeller hub center are set to be fixed boundaries, which means that inner cylindrical surface of the hub is rigid fixation. It is calculated that the resonance between the blades lead to the similar natural frequency of each fifth-order modal, and the vibration modes are distributed on different blades which can be regarded as the same order modal.

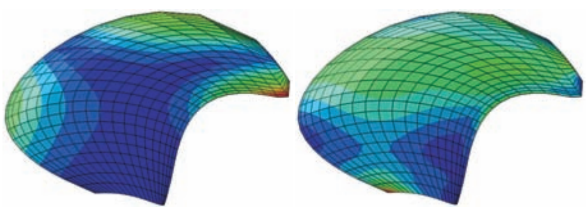
The displacement modal and strain modal vibration mode are shown in Fig. 2. The first-order displacement modal is the radial bending deformation; the second-order displacement modal is chordwise torsion deformation; and the third-order displacement modal is the bending and torsional deformation. The first three order natural frequencies are shown in Table 1.



(a) First order



(b) Second order



(c) Third order

Fig.2 Copper propeller model's first three displacement modal vibration mode (left) and strain modal vibration mode (right)

Table 1 Comparation of first three natural frequencies of copper propeller between calculation and test

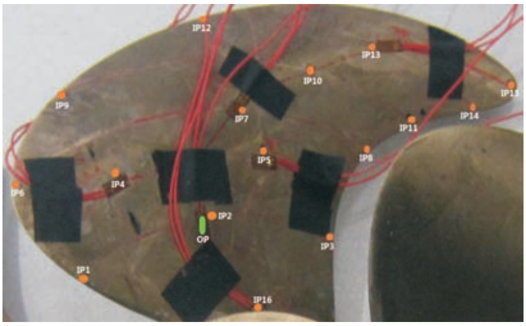
	Order			Damping/%
	1	2	3	
Calculated value/Hz	744.16	1 176.26	1 731.24	
Test value/Hz	751	1 185	1 702	0.98

Two methods are used to measure the modal:

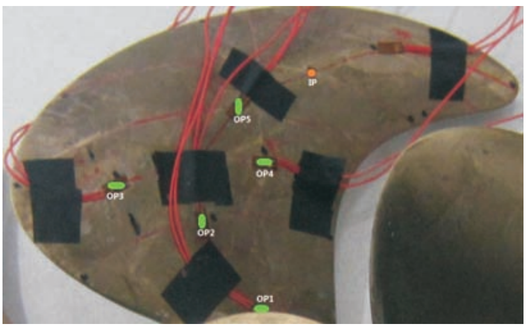
1) Method 1: Measurement points of 0.5R as the response output point (OP) and mobile incentive points (IP1-IP15) are fixed, which belong to multi inputs and single output (MISO). The natural frequency and strain modal vibration mode are determined through the measurement of each row of strain frequency response function matrix.

Method 2: Incentive points (IP) of 0.8R and mobile measurement points (OP1-OP5) are fixed, i.e., single input and multi outputs (SIMO). By measuring the columns of the strain frequency response function matrix to determine the natural frequency, the accuracy of the natural frequency measurement is verified again on the basis of the determination of vibration mode in 1), as shown in Fig. 3.

The output value of data acquisition instrument is the strain value, and the signal need to be cleared each time before percussion. The percussion needs appropriate intensity and instantaneity, and every percussion needs to meet that signal is within the ef-



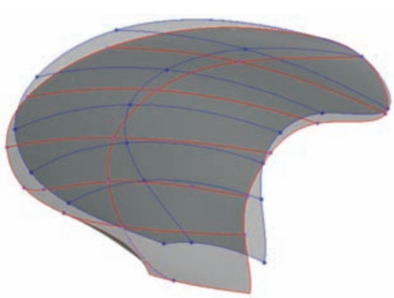
(a) Method 1



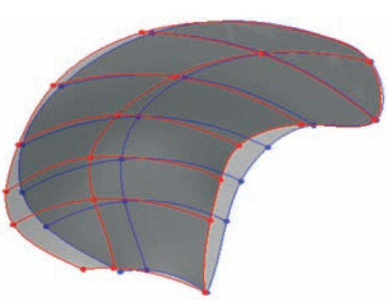
(b) Method 2

Fig.3 The distributions of IP and OP of copper propeller model

fective value and only has one peak value. If there is an adjoint peak, it is needed to knock again. The average value of the two excitation signals is calculated and both methods need to be measured for three times to ensure the reliability of test. The selected first two order strain modal vibration modes are shown in Fig. 4, and the modal vibration modes are similar to the calculated strain diagram (Fig. 2). After averaging for three times, the calculated first three order natural frequencies of copper propeller



(a) First order



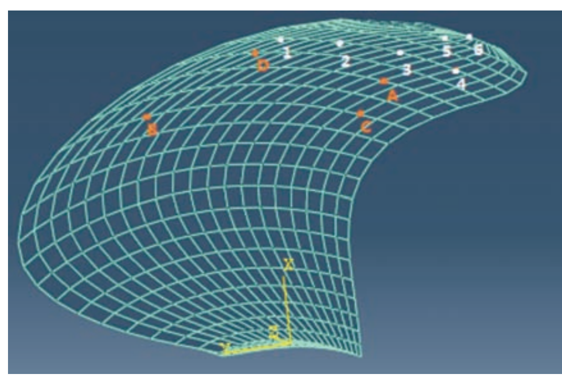
(b) Second order

Fig.4 The first two test strain modal's vibration mode of copper propeller model

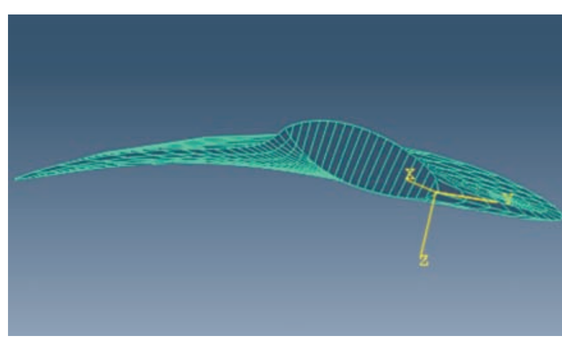
are shown in Table 1, which shows that the measured natural frequencies are in good agreement with the calculated values, and the errors are all within 3%.

1.4 Dry modal calculation and test of composite propeller

In this paper, the tested composite propeller is made of orthogonal carbon fiber cloth. According to the static loading test, the material parameters are determined as follows: elastic modulus, $E_1 = E_2 =$ 75 GPa, $E_3 = 9$ GPa; shear modulus, $G_{12} = 4.5$ GPa, $G_{13} = G_{23} = 3.5$ GPa; Poisson´s ratio, $\nu_{12} = 0.038$, $\nu_{13} = \nu_{23} = 0.3$; $\rho = 1\ 650$ kg/m^3; ply angle combinations, [60, −30, 60, −30]. The intersection angle between composite propeller and X−axis is the main direction and the value in first quadrant is positive. The fiber cloth is laid on the XY plane determined by the central surface of blades, as shown in Fig. 5.



(a) Main direction and coordinate system of the blade fiber



(b) Blade and fiber cloth on the same plane

Fig.5 The coordinate system of fiber stacking

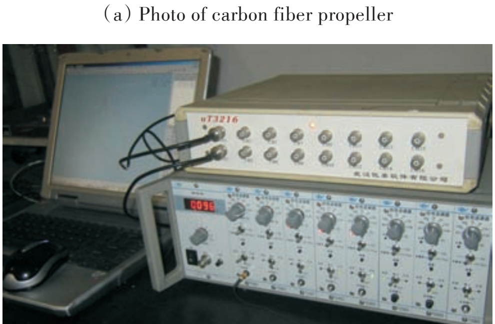
The verified modal calculation method and determined material parameters are adopted to calculate the natural frequencies and modal vibration modes of integrated model of composite propeller, and the natural frequencies are shown in Table 2. The displacement modal and strain modal vibration modes are similar to those of the metal propeller and only the amplitudes of vibration mode at diverse locations are different.

Table 2 Comparation of first three natural frequencies of composite propeller between calculation and test

	Order			Damping/%
	1	2	3	
Calculated value/Hz	676.16	1 085.20	1 925.54	
Test value/Hz	727	1 080	1 690	4.0

The carbon fiber propeller strain modal measurement steps are the same to those of copper propeller. The test procedure is shown in Fig. 6. The peak value of frequency response function of the carbon fiber propeller is less obvious than that of the copper propeller because of the vibration attenuation caused by high damping characteristics of carbon fiber propeller. When the natural frequency is extracted, the average of peak frequency is used to ensure the rationality of the test data. The strain modal vibration mode of carbon fiber propeller is similar to that of the copper propeller measured through the test, and first three order natural frequencies are shown in Table 2. Due to the precision of the equipment and complexity of structure, the deviations between calculation value and test value of the first two order natural frequencies are within 8%, and the deviation of third-order natural frequency is 12%. The natural frequency of each order of the carbon fiber propeller is smaller than that of the copper propeller which is due to the small stiffness and small density of the carbon fiber propeller, as well as its small ratio.

(a) Photo of carbon fiber propeller



(b) Test instrument

Fig.6 The test scene of composite propeller

2 Wet modal calculation of propeller model

Propeller operates in flow field and the inherent characteristics of its structure are different in the air. The attached water mass in the flow field affects the natural frequency and vibration mode of the propeller, which thus changes the vibration response of the propeller. Due to fluid influence on the electrical resistance strain gauge, the wet modal is not measured, which is only compared and verified with the results of Reference[1]. Based on previous dry modal study of propeller in the air, the wet modal natural frequency and vibration mode are forecast, which lays a foundation for further research of vibration response.

Based on the finite element method, the fluid-solid coupling wet modal vibration of composite propeller blades is regarded as an acoustic fluid-solid coupling problem. The coupling vibration equation of the model is as follows:

$$\begin{bmatrix} \boldsymbol{M}_s & 0 \\ \rho_f \boldsymbol{R} & \boldsymbol{M}_f \end{bmatrix} \begin{Bmatrix} \ddot{u} \\ \ddot{p} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{C}_s & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} \dot{u} \\ \dot{p} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K}_s & -\boldsymbol{R}^T \\ 0 & \boldsymbol{K}_f \end{bmatrix} \begin{Bmatrix} \boldsymbol{u} \\ \boldsymbol{p} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{F}_s \\ 0 \end{Bmatrix}$$

The nodal displacement and pressure on the structure surface can be obtained by solving the equation. If the damping and the external force are neglected, the matrix equation of free vibration can be obtained:

$$\begin{bmatrix} \boldsymbol{M}_s & 0 \\ \rho_f \boldsymbol{R} & \boldsymbol{M}_f \end{bmatrix} \begin{Bmatrix} \ddot{u} \\ \ddot{p} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K}_s & -\boldsymbol{R}^T \\ 0 & \boldsymbol{K}_f \end{bmatrix} \begin{Bmatrix} \boldsymbol{u} \\ \boldsymbol{p} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix}$$

where $\boldsymbol{M}_s$ and $\boldsymbol{M}_f$ are respectively the mass matrix of solid and fluid; $\boldsymbol{K}_s$ and $\boldsymbol{K}_f$ are respectively the stiffness matrix of solid and fluid; $\boldsymbol{C}_s$ is the damp matrix of solid; $\boldsymbol{F}_s$ is the force matrix of solid; $\boldsymbol{R}$ is the resistance; $\boldsymbol{u}$ is the displacement; $\boldsymbol{p}$ is the pressure.

The complex eigenvalue analysis is used to solve the natural frequency and modal of free vibration caused by the interaction of the structure and the fluid.

Because the wet modal is difficult to measure, the propeller wet modal calculation method is verified by the comparison with Reference[1]. The calculation results shown in Fig. 7 indicate that the deviation of the natural frequency of each order obtained by the wet modal calculation method is within 8% compared with that of Young[1], thus the wet modal calculation method has a good accuracy.

quency and has little effect on the high-order natural frequency. The calculation results of first four order wet modal natural frequencies are shown in Table 3. The reduction ratio is 18%–33%, and vibration mode of each order is similar to the corresponding vibration mode of the dry modal.

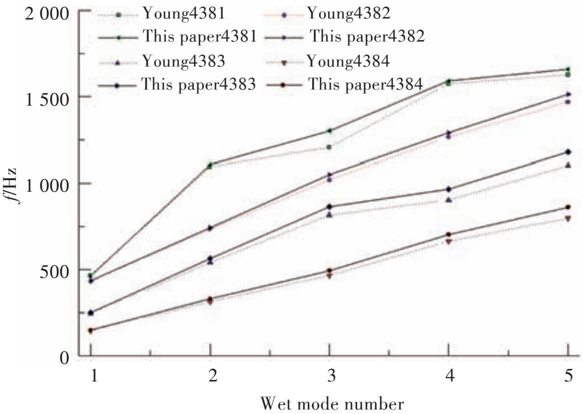


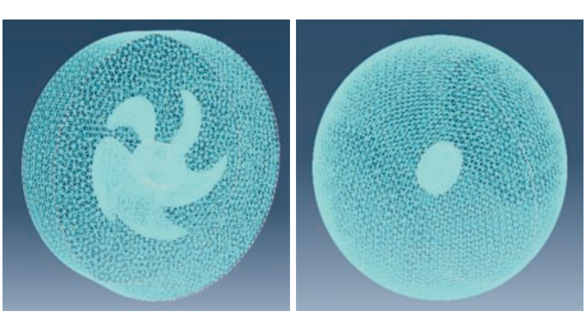
Fig.7 Comparation of 438X's wet modal natural frequencies with Young's research[1]

Table 3 Comparation of the first four dry and wet modal frequencies of copper propeller

	Order			
	1	2	3	4
Dry modal/Hz	744.16	1 176.26	1 731.24	2 611.24
Wet modal/Hz	498.95	843.14	1 340.12	2 139.34
Decrease proportion/%	32.95	28.32	22.59	18.07

2.1 Wet modal natural frequency of copper propeller

The water area diameter of wet modal calculation model of copper propeller is 2 000 mm which is 8.3 times the scale of the propeller model. This is determined by reference to the grid division method that the diameter of the water area is 6 times the size of the model and the result which has little change after encryption in Reference[13]. The grid division of propeller blades and hubs is the same to that of the dry modal calculation model, and the fluid domain is modeled by acoustic unit AC3D4 with 183 876 inner domain grids and 469 853 outer domain grids. The copper propeller and the fluid domain model are bound through the coupling surface to achieve the coupling calculation, and the inner and outer domain grid model of fluid-solid coupling wet modal is shown in Fig. 8. The bulk modulus of the fluid material is 2.13 GPa and the density is 1×10^3 kg/m^3.



(a) Inner domain (b) Outer domain

Fig.8 The inner (a) and outer (b) domain of wet modal

It is calculated that the natural frequency of wet modal of the copper propeller is smaller than corresponding natural frequency of the dry modal and the degree of reduction decreases with the increase of the order, which shows that the attached water mass has a great influence on the low-order natural fre-

2.2 Wet modal natural frequency of composite propeller

The calculation model setting of the composite propeller is the same as that of the copper propeller's wet modal, and only the material is different. The attached water mass also makes the low-order natural frequency decrease more and the high-order natural frequency decrease less. The calculation results of first four order wet modal natural frequencies are shown in Table 4. The reduction ratios are 54%–64%, and vibration mode of each order is similar to the corresponding vibration mode of the dry modal.

Table 4 Comparation of the first four dry and wet modal frequencies of carbon fiber propeller

	Order			
	1	2	3	4
Dry modal/Hz	676.16	1 085.20	1 925.54	2 735.84
Wet modal/Hz	247.06	440.366	852.5	1 237.82
Decrease proportion/%	63.46	59.42	55.73	54.76

Compared with the copper propeller, the natural frequency of the wet modal of carbon fiber propeller reduces more, because the density of carbon fiber propeller is much smaller than that of copper propeller and is only 1.65 times the density of the water. The influence of fluid domain is bigger. This conclusion is consistent with the paper of Young [1] in which the wet modal natural frequency of the elastic propeller is reduced by 50%.

3 Study on the structural vibration performance of the propeller model

When rotating in the flow field, the propeller bears certain pressure load which is regarded as excitation force with a certain frequency characteristic in the study of structural vibration, and the vibration of the blade can be caused in the relevant frequency band. Analyzing the propeller vibration performance is the basis of the noise characteristic study. Wet modal calculation and the vibration response calculation in flow field take long time, so blade vibration in air is calculated here. Although there is difference between blade vibration in the flow field and in the air, from the perspective of comparative research, the comparison of vibration performance in the air of blades made by different materials can reflect their vibration performance differences in the flow field. Therefore, meaningful conclusion can be drawn by the study of law.

In this section, the effect of fiber ply angle on natural frequency is first studied, and then the vibration frequency response between copper propellers and carbon fiber propellers with different fiber orientations is explored under the assumption of the same unit pressure load, and the fiber orientation beneficial for vibration attenuation is obtained.

3.1 Influence of fiber orientation on natural frequency

Composite propeller is composed of resin matrix and reinforced fiber material, and fiber material is the main support body which determines the overall performance of the material. The difference of fiber ply angle has a great impact on the propeller structure performance. According to the fiber materials selected in the previous stage, the dry modal natural frequency of the composite propeller is calculated within an angle range of 180° to study the influence of the ply angle on the structure performance of the blade.

The calculation results of natural frequencies of composite propeller with different fiber orientations are shown in Fig. 9. The composite material is orthogonal carbon fiber cloth, and the natural frequency has 2 periods in the range of 180° which is because the elastic modulus, shear modulus and Poisson's ratio at main direction and secondary direction of orthogonal fiber cloth are the same. It can be found that after 90° rotation of ply angle, the natural frequency of the blade is equal. At the same time, the natural frequency of first-order bending vibration mode shows the same change law with that of third-order bending and torsional vibration mode and inverse change law with that of second-order torsional vibration mode, which indicates that the bending vibration and torsional vibration of the carbon fiber cloth can not be obtained simultaneously.

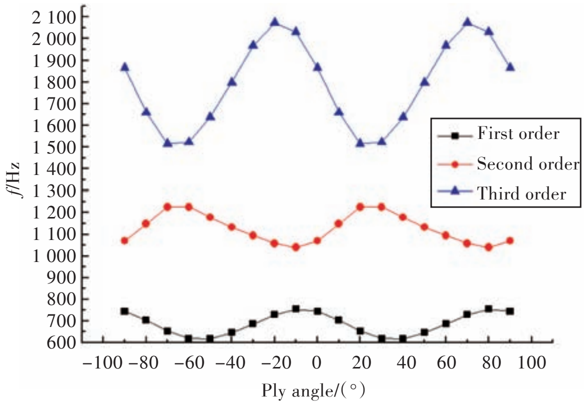


Fig.9 The first three natural frequencies of composite propeller with different fiber orientations

3.2 Structural vibration response of composite propeller

As for the study of the vibration performance of the propeller, the vibration frequency response under the same excitation conditions is studied. Under the assumption that the surface of the blade is subject to a unit excitation load of 1 Pa, with the excitation frequency of 10–5 000 Hz and the step length of 10 Hz, a point i in the middle of the blade is selected as the measuring point, and the vibration acceleration level is calculated to carry out the quantitative analysis. The effective value of this point in the test frequency band is calculated by linear spectrum of acceleration frequency response. The calculation formula is as follows:

$$a_i = \sqrt{\frac{1}{m}\sum_{i=1}^{m} {a_k}^2}$$

where a_k is the amplitude value of the acceleration response at the k^{th} frequency point; m is the number of frequency points within the range of the analysis frequency. The total acceleration level (TAL) of the measuring point is often used in the project and its calculation formula is as follows:

$$TAL = 20\log_{10}\left(\frac{a_i}{a_0}\right)$$

where a_0 is the standard value 10^{-6} m/s^2.

First, the vibration frequency response acceleration levels of copper propeller and carbon propeller model are compared and their tested values of structural damping coefficient are 1% and 4% respectively, and then the direct modal damping coefficient is input in ABAQUS software to perform simulation. As shown in Fig. 10, the vibration acceleration response is related to the natural frequency of the propeller, and the peak value appears at the natural frequency, which reflects the magnitude of the provoked acceleration of the modal vibration of each order. The natural frequencies of the copper propeller and carbon fiber propeller are different, so are the peak frequencies of acceleration. But in general, the carbon fiber propeller shows greater vibration acceleration than the copper propeller due to large elasticity of the former, and the TAL is 136 dB, also higher than 127.16 dB of the copper propeller. It can be seen that when the carbon fiber propeller model with the material parameters determined above is subject to the unit pressure load, its vibration performance is worse than that of the copper propeller model.

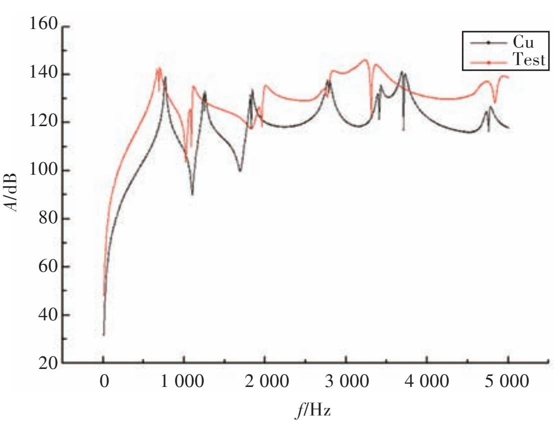


Fig.10 The vibration response of copper propeller and carbon fiber propeller tested

In the study of the different vibration acceleration level of carbon fiber propeller with different fiber orientations, because the period of the natural frequency of the orthogonal carbon fiber cloth is 90°, only the vibration acceleration level of orthogonal carbon fiber with orientations of −30°−+ 60° is calculated here. As mentioned above, the fiber orientation has a great influence on the natural frequency of the carbon fiber propeller and also affects its vibration performance. In order to compare the vibration frequency response of carbon fiber propeller with different fiber orientations, the structure damping coefficient is decreased to 0.5% to reduce the damping attenuation effect.

It can be seen from Fig. 11 that the fiber ply angle has a great influence on the vibration acceleration level. The TAL value of 142.11 dB of carbon fiber propeller is the minimum when the ply angle is −10°, which is 3.25 dB lower than the TAL value of 145.36 dB at ply angle of 60°, and the specific results are shown in Table 5.

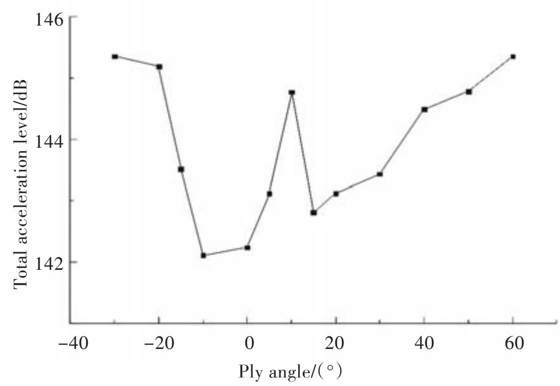


Fig.11 The total acceleration level of composite propeller with different fiber orientations

Table 5 The total acceleration level of composite propeller with different fiber orientations

Ply angle/(°)	TAL/dB	Ply angle/(°)	TAL/dB
−30	145.4	20	143.1
−20	145.2	30	143.4
−10	142.1	40	144.5
0	142.2	50	144.8
10	144.8	60	145.4

Finally, the tested carbon fiber propeller model and the optimized carbon fiber propeller are assigned with structural damping coefficients to reflect their true material damping characteristics. Since the damping of the former is truly measured through test and that of the latter is the vibration−reduction fiber ply angle calculated by comparative analysis and both of them are assigned with the same structural damping coefficient of 4%, the calculation results, as shown in Fig. 12, show that after assignment of the damping characteristics for the carbon fiber propeller, the peak clipping phenomenon of vibration response at natural frequency is obvious, which is due

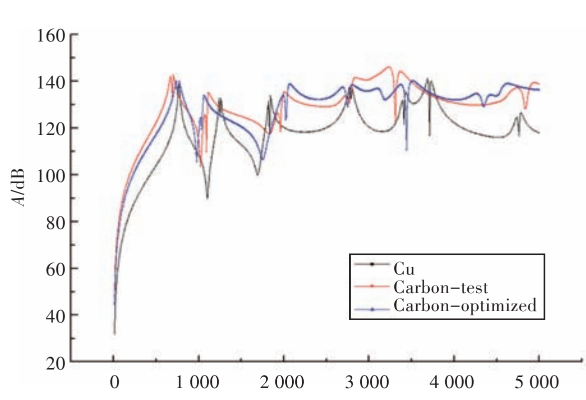


Fig.12 The vibration response of optimized and tested carbon fiber propeller with damp

to the vibration attenuation caused by the damping material. The vibration performance of carbon fiber propeller with optimized material is improved, and its TAL value of 134.01 dB is 2 dB lower than that of tested carbon fiber propeller, but is still 7 dB higher than that of metal propeller.

It is worth to note that the vibration acceleration level calculated here cannot be used as a numerical calculation basis of the vibration response, and it is just the qualitative analysis under the assumption that the propeller is subject to unit pressure load. It can be seen that if the carbon fiber material is selected, the change of the fiber orientation can effectively improve the vibration performance of carbon fiber propeller and reduce its vibration response. However, the vibration acceleration level of carbon fiber propeller is still bigger than that of copper propeller, which is because the elasticity of carbon fiber propeller is two times that of copper propeller, and the high damping characteristics of carbon fiber propeller can not hide its vibration defect caused by high elasticity.

After analysis and reasoning, because of the fluid-solid coupling effect, the decibel difference of vibration acceleration between carbon fiber propeller with optimized fiber orientation and copper propeller in the fluid domain is lower than that in the air. If the elasticity of carbon fiber propeller is reduced properly, its high damping and low density characteristics may reduce the vibration response effectively.

4 Conclusions

The strain modal of propeller is more suitable to be measured by electrical resistance strain gauge due to the small size of the model. In order to study the structural vibration performance, the strain modal test of metal propeller and carbon fiber propeller is carried out and the proved finite element modal algorithm is adopted to calculate their natural frequency and displacement, strain modal vibration mode and the deviation of tested and calculated first three order natural frequencies of copper and carbon fiber propeller are within 3% and 12% respectively. The carbon fiber propeller has small natural frequency of each order, similar strain modal and four times structure damping compared with copper propeller.

On this basis, wet modals of copper propeller and carbon fiber propeller are calculated, and the first four order wet modal natural frequencies of copper propeller reduce by 18%-33% compared with that of dry modal, while the carbon fiber propeller's reduction is 54%-64% which is more than that of the copper propeller because the density of the carbon fiber propeller is much smaller than that of the copper propeller and is only 1.65 times the density of water, and the attached water mass of fluid domain has a greater impact.

Finally, the vibration performances of copper propeller and carbon fiber propeller with different fiber orientations are studied, and the fiber orientation beneficial for vibration attenuation is obtained. The TAL of optimized carbon fiber propeller is 2 dB less than that of the tested carbon fiber propeller, but is still 7 dB higher than that of metal propeller.

In this paper, the inherent and vibration performances of copper propeller and carbon fiber propeller are researched, which provides the basis for the further calculation of fluid-solid coupling vibration noise and lays a foundation for the research and design of vibration attenuation and noise reduction of the composite propeller.

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复合材料螺旋桨模型的应变模态与振动特性

黄政, 熊鹰, 杨光

海军工程大学 舰船工程系,武汉 430033

摘　要: 采用有限元模态算法和应变模态测量试验对比金属桨和碳纤维桨模型的固有频率、位移和应变模态振型,试验测得铜桨和碳纤维桨的前三阶固有频率与计算值相差分别在3%和12%以内。碳纤维桨各阶固有频率均比铜桨要小,应变模态振型相似,前者结构阻尼是后者的4倍左右。计算二者在流域中的湿模态,铜桨的前四阶湿模态固有频率比干模态减小18%~33%,碳纤维桨减小54%~64%。研究铜桨和不同铺层碳纤维桨之间的振动特性,得出有利于减轻振动的纤维铺层方式,优选出的碳纤维桨总振动加速度级(TAL)比试验用碳纤维桨降低2 dB。

关键词: 复合材料螺旋桨; 应变模态; 固有频率; 振动响应; 振动加速度级