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THE ANALYSIS OF VIBRATION CHARACTERISTIC OF COMBINATION FOUNDATION WITH COMPOSITE MATERIAL AND STEEL

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The vibration of ship power equipment is one of the main sources of the ship hull vibration, as an important part of vibration transfer media, the characteristics of the foundation directly affect the performance of vibration isolation in the whole ship. Under the condition of strength and stiffness non-decrease, part of typical steel foundation structure are instead by composite plate. Vibration characteristic of steel foundation and combined foundation made of steel and composites were analyzed. Based on the evaluation index of modal, impedance and vibration acceleration level, the influence on vibration characteristics of structure with different composite layer angles were studied under same support steel structure. Results show that vibration acceleration level of support structure of composites-steel foundation are lower than that of steel foundation under the same load. Thus, the natural frequency of composites-steel foundation could be changed by reasonable design. Based on the effect of lay angle on foundation's modal, impedance and vibration acceleration level, lay angles could be divided into three patterns, namely, 0 °, 5 °to 60 °and 90 °.

Keywords: composites; vibration characteristic; composites-steel foundation; layer angle

1. Introduction

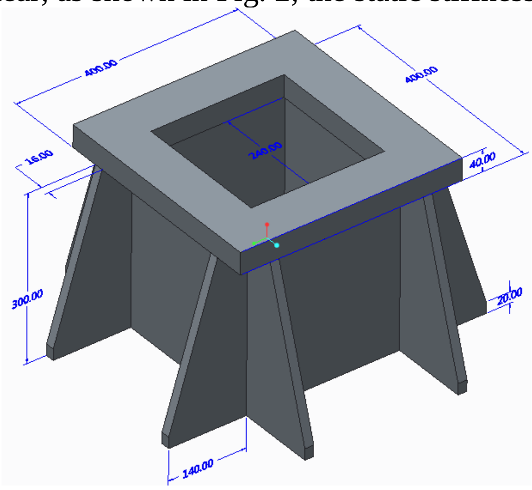
Foundation is generally used to connect equipment and hull structure, its main function is to carry equipment weight and transform force from machine equipment to hull structure. At present, steel foundation are often used on vessel, but it has disadvantage in bigger quality, small damping coefficient and less vibration suppression. Composite material has high strength ratio, modulus ratio, light quality, anisotropy and designable, also has good anti-fatigue properties and easy to form on large area overall. According to the data from the Boeing Company, composite material covers almost the entire body of Boeing 787, the mass of composites were accounted for more than 50% of the whole machine structure [1]. Piezoelectric patches bonded to a composite laminate plate and combined structure used as vibration actuators were done by Her and Lin [2], an analytical solution of the vibration response of a simply supported laminate rectangular plate under time harmonic electrical loading is obtained and compared with finite element results. Numerical studies on the vibration and acoustic response characteristics of a fiber-reinforced composite plate in a thermal environment by considering the inherent material damping property of the composite material were done by Jeyaraj et al. [3]. Zhang et al. [4] presented an improved Fourier series method for the free vibration analysis of the moderately thick laminated composite rectangular plate with non-uniform boundary conditions Two kinds of material foundations were put forward by Lang [5,6], the influences of foundation material for natural frequency and mode shapes are not obvious, but if the ballast pump foundation uses material of composite laminate, it is positive to vibration-isolation in low frequency; and based on the first-order shear deformation theory for laminated composite plate, characteristics of stiffened laminated composite plates for ships were analyzed. Vibration excitation test was carried out by Zhao et al. [7], by comparison of vibration level of steel foundation and composites-steel foundation, composites steel had better effect on vibration isolation.

Consider the advantage of composite laminate layer on vibration, part of steel foundation was instead by composite layer, the advantage and disadvantage of between two foundations were studied, and by comparison of vibration response of steel foundation and a series of composite material-steel mixed foundations, the effect of layer angle on foundation modal, impedance and vibration acceleration level analyzed as well.

2. Foundation Model

2.1 Model of Steel foundation

At present, the steel foundation is typically used on vessel. Typical marine equipment foundation model was shown in Fig.1. Foundation mainly contains panel, web, bracket and so on. Panel is connected to equipment, web and bracket, which are used to connect panel and hull structure. The thickness of panel, web plate and bracket are 40 mm, 16 mm and 16 mm. The parameters of steel material model are as follows: Young's modulus E=2.1×10^{11}Pa, Poisson's ratio $\sigma = 0.3$, density $\rho_1 = 7.85\times10^{-9} t/mm^3$, the weight of the whole foundation model is 105.3 kg. One of the main functions of the foundation is carrying equipment weight, thus the bearing capacity should be analyzed. A series of different loads of weight were applied on the foundation panel, deformation, stress and static stiffness were calculated, which was present in Table 1. Static stiffness could be obtained by loading and deformation. The foundation of the maximum stress under maximum loading is 120MPa, less than the yield strength of steel, so the foundation deformation changed in linear, as shown in Fig. 2, the static stiffness of steel foundation is 1.72×10^{10} N/m.



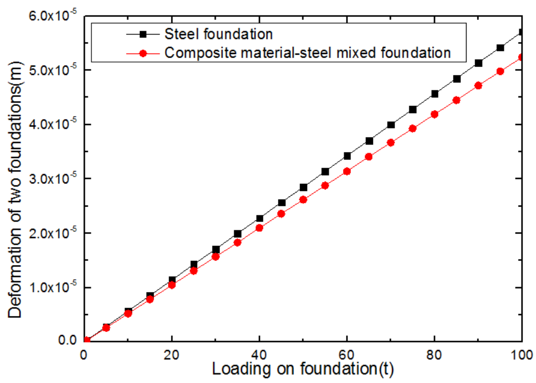


Figure 1: Foundation model. Figure 2: Deformation curves of foundation

Table 1: Deformation and stress of foundation under different loading

Loading on panel(t)	Steel foundation		Combined foundation of steel and composite materials	
	Deformation(mm)	Stress(MPa)	Deformation(mm)	Stress (MPa)
10	5.71E-03	12.0	5.24E-03	11.9
50	2.85E-02	59.8	2.62E-02	59.7
100	5.71E-02	120	5.24E-02	119

2.2 Model of composite material- steel foundation

Different from steel, composite material has the characteristic as follows: the mechanics property is anisotropic, the relative strength and modulus are high and the composite material has obvious advantage in design. The design of composite material can be divided into three levels: single-layer design, layer design and structural design. These three design levels are prerequisites, mutual influence and interdependence. Composite material-steel foundation was studied by this section, whose steel is partly substituted by composites. As a bridge between the equipment and the hull structure, craftsmanship process is first considered in the connection of equipment and the hull. The combined foundation made of steel and composites by Mei et al. [8], web of combined was steel, the best way of connection of panel of foundation and ship hull is steel welding. According to the foundation style of section 2.1, the web and the brackets connected to hull could not be changed, only the panel can be replaced by composites in whole or partly. In order to ensure a good connection between panel and the web and brackets, steel plate is still used by the lower panel of the panel sandwich, which ensures good welding of panel and the web brackets. Steel plate is still used by lower panel, the foundation can be simplified as a combined structure made of laminates and steel. The material properties are as follows: E_1=128.8GPa, E_2=E_3=8.3GPa, G_{12}=G_{13}=4.1GPa, G_{23}=4.1GPa, v=0.355, ρ=1578kg/m^3 [9]. Under the guarantee that the stiffness and strength are not reduced, and laying angle is in a specific direction of 0° along the edge of foundation, the number of layers should be increased. Deformation and stress of the composite foundation were calculated and described in Table 1. The total weight of composite foundation was 99.33kg. Comparing the static stiffness of the composites-steel foundation with the pure steel foundation, seen from Fig. 2.

3. Vibration frequency, impedance and vibration level of foundations

3.1 Modal

Under installation state, the foundation not only need to meet the static strength and deformation requirements, but also to avoid the local vibration amplification, the modal frequency and the work frequency have a certain margin. Once the local coupling vibration occurs, not only affects the vibration of the entire equipment, but also results in the whole hull vibration through equipment feet. Modal analysis is also known as the analysis of the inherent characteristics of structure, modal analysis is always used to determine the natural frequency and vibration modal shape. Typical vibration equation for free motion without damp is as follows:

$$[M]\{\ddot{X}\}+[K]\{X\}=\{0\} \tag{1}$$

Where [M] is mass matrix, [K] is stiffness matrix, $\{\ddot{X}\}$ is the acceleration vector, $\{X\}$ is the displacement vector. Eq. (1) can be rewritten as:

$$([K]-\omega^2[M])\{\phi\}=\{0\} \tag{2}$$

Table 2: Modal analysis of steel foundation and composites-steel foundation

Frequency	Steel foundation	Composites-steel foundation (layer direction was in 0°)	Frequency difference	Vibration shape description
1	1026.7	1035.4	0.85%	foundation torque
2	1085.1	1107.8	2.09%	foundation torque
3	1299.6	1346.4	3.60%	foundation torque

Modal analysis of two kinds of foundation without support structure were carried on, see Table 2 and Fig. 3. Frequency and vibration modal of Table 2 could be explained as follows: The foundation panel is thicker and resulted in bigger stiffness, leading to that the main vibration of foundation is in the form of torsional vibration. When the composites lay direction is 0°, the steel foundation and composites-steel foundation have certain difference in natural frequency. With the increase of frequency, the difference increases gradually. The mass of foundation is smaller relative to support structure. The change of foundation panel have less effect on natural frequency of the overall foundation with support structure.

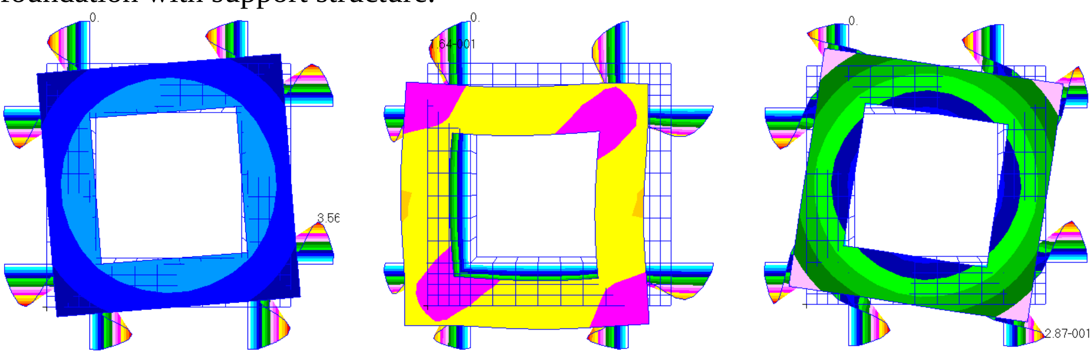


Figure 3: Vibration modal of foundation

3.2 Impedance

Ship foundation is an elastic structure, whose mechanical impedance function is complex. The input impedance is also known as origin impedance. The condition of the single-point excitation is considered only, the F_i excitation is applied on point i, speed response V_i of the point i is obtained. The origin resistance is obtained by the division of excitation and speed response.

$$Z_i = F_i / V_i \quad (3)$$

Where Z_i indicates the impedance of point i, whose unit is N s/m. The F_i indicates exciting force of point i, whose unit is N. The V_i indicates the speed response of point i, the unit is m/s.

For the convenience of data processing, the impedance could be transformed into decibel (dB):

$$Z_{i,dB} = 20\log_{10}(\frac{Z_i}{Z_0}) \quad (4)$$

Where $Z_{i,dB}$ is the impedance, whose unit is dB. The Z_i is impedance, the unit is N s/m. The Z_0 is benchmark impedance and equal to 1 N s/m.

Response was calculated after the excitation on foundation with support structure, the impedance data of points at calculated frequency range were described in Table 3. Impedance of steel foundation is significantly smaller than impedance of composites–steel foundation. Within the frequency range of 10Hz to 200Hz, the difference is about 10dB. Within the frequency range of 200Hz to 315Hz, the difference is about 4dB. The impedance is similar that when the frequency is close to 500Hz. It could be explained that the stiffness of the composites was lower than those of steel, its response is bigger under the same load.

Table 3: Impedance data of steel foundation and composites-steel foundation

Frequency	Steel foundation	Composites-steel foundation (layer direction was in 0 °)
10	172.7	160.0
12.5	170.9	158.2
16	169.4	156.7
20	167.5	154.8
25	165.5	152.8
31.5	163.2	150.5
40	161.2	148.5
50	159.1	146.5
63	157.1	144.5
80	154.9	142.4
100	152.7	140.3
125	150.2	138.1
160	147.0	135.5
200	141.9	131.9
250	120.9	116.6
315	122.9	118.8
400	111.7	110.7
500	109.2	108.9

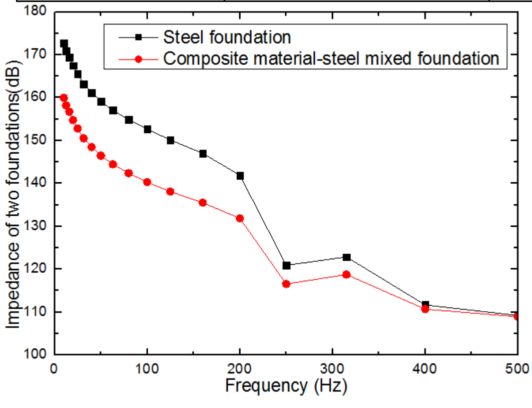


Figure 4: Impedance curves of foundations

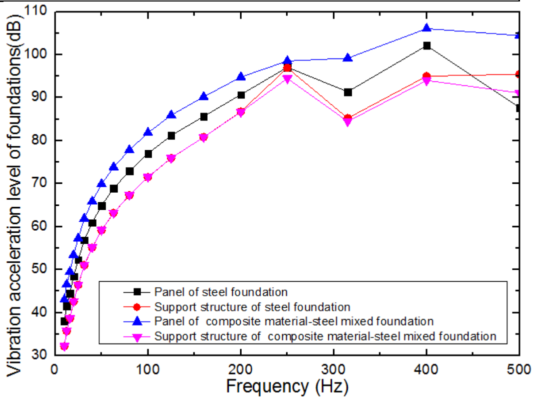


Figure 5: vibration acceleration level of foundations

3.3 Vibration level difference

The impedance of steel foundation is smaller than that of composites in section 3.3, which means that more equipment vibration energy will be transformed from foundation panel to web and bracket, and ultimately to support structure. The damping of composite material is bigger than steel, the vibration energy finally transmitted to supporting structure were analyzed in this section.

Acceleration level of vibration is defined as:

$$L_i = 20\lg \frac{a}{10^{-6} m/s^2} (dB) \tag{5}$$

Where a is the acceleration, whose unit is m/s^2.

Vibration level difference is defined as the ratio of the vibration response of up elastic support and low elastic support. Vibration acceleration level is expressed as:

$$L_r = 10\lg \left(\frac{\sum_{i=1}^{N} 10^{0.1 L_{upi}} / N}{\sum_{i=1}^{N} 10^{0.1 L_{downi}} / N} \right) (dB) \tag{6}$$

Frame ship and foundation support is not perfectly rigid, could be treat as elastic structure. The insertion loss can be the most appropriate evaluation index. The models of steel foundation and composite-steel foundation with support structure are built up respectively. Vibration level difference of two foundations in the low and medium frequency were calculated, shown in Table 4.

Table 4: Acceleration levels of two foundation up and down

Frequency (Hz)	Steel foundation (dB)			Composites-steel foundation (layer direction was in 0 °) (dB)		
	Panel	Support structure	Vibration level difference	Panel	Support structure	Vibration level difference
10	38.1	32.2	5.9	43.1	32.3	10.8
12.5	41.6	35.7	5.9	46.6	35.8	10.8
16	44.5	38.7	5.8	49.5	38.8	10.7
20	48.5	42.6	5.9	53.4	42.7	10.7
25	52.3	46.5	5.8	57.3	46.5	10.8
31.5	56.9	51.1	5.8	61.9	51.1	10.8
40	61.0	55.1	5.9	65.9	55.2	10.7
50	65.0	59.2	5.8	69.9	59.2	10.7
63	68.9	63.2	5.7	73.9	63.3	10.6
80	73.0	67.3	5.7	77.9	67.4	10.5
100	77.0	71.5	5.5	81.9	71.6	10.3
125	81.2	76.0	5.2	85.9	76.0	9.9
160	85.7	80.8	4.9	90.2	80.8	9.4
200	90.7	86.8	3.9	94.8	86.7	8.1
250	97.1	96.9	0.2	98.5	94.5	4.0
315	91.4	85.3	6.1	99.2	84.5	14.7
400	102.1	95.0	7.1	106.1	94.0	12.1
500	87.7	95.5	-7.8	104.5	91.1	13.4
Total level (10~500)	104.0	101.0	3	109.5	98.8	10.7

Seen from Fig. 5, under the same load, acceleration response of steel foundation panel have better level in composites-steel foundation. With the increase of frequency, difference is gradually increased, which is 5.0dB at the frequency of 10Hz, but the difference is 16.8dB at the frequency of 500Hz. The total level of composite foundation panel are respectively in 2.4dB and 4.4dB, which are little less than steel foundation at the frequency of 250Hz and 500Hz. Total level of composites-steel foundation is 2.2dB less than that of steel foundation. It is demonstrated that composites-steel foundation has certain effect on reducing the vibration transmission. Vibration level difference of two foundation panel and support structure were described in Fig. 6. Vibration level difference curve is relatively consistent within the frequency range of 10Hz to 300Hz. But the difference becomes little obviously within the frequency range of 300Hz to 500Hz, furthermore, vibration level difference is negative. It indicates that the vibration of the support structure is greater than foundation panel. It is concluded that composites-steel foundation is better in damping loss than steel foundation. Vibration isolation of composites-steel foundation is better at frequency of 300Hz to 500Hz, eventually leading that vibration level of composites-steel foundation is 2.2dB less.

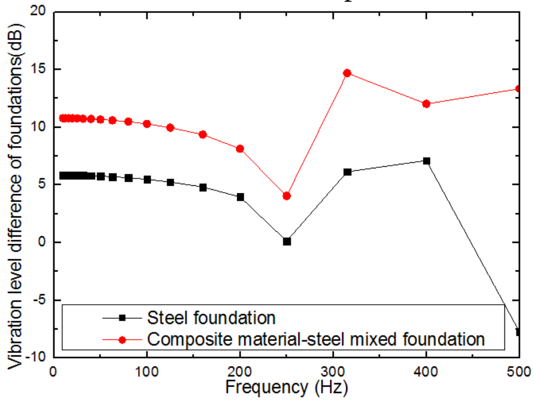


Figure 6: Vibration level difference of foundations

4. Layer angle analysis of composites-steel foundation

By changing its performance, composite laminated structure was designed to meet the given design requirements with the minimum mass in this section. Except for composites lay angle, the material performance and the model method in current section were consistent with that in the section 2. In practical engineering, the laminated plate thickness of each layer and layer angle can't be in an arbitrary value, the thickness of single layer must be a single integer times of the thickness of the material. However, every layer order of composites can be changed arbitrarily, -90 °、 -75 °、 -60 °、 -45 °、 -30 °、 -15 °、 0 °、 15 °、 30 °、 45 °、 60 °、 75 °、 90 ° and other standard angles are usually selected as layer angle, the specific calculation cases are as follows: Case 1: all the layer angle is 0 °; Case 2: the first layer angle is 0 °, the subsequent layer angle is 5 °; Case 3 to Case 9 are 0 °/ 10 °, 0 °/ 15 °,0 °/ 20 °, 0 °/ 30 °, 0 °/ 45 °, 0 °/ 60 °, 0 °/ 90 °, respectively.

4.1 The effect on foundation vibration modal of layer angle

For steel foundation, when the style and the dimensions of size and thickness are determined, the modal frequency is obtained correspondingly. But composites-steel foundation is different with steel materials, according to the requirements, the layer design is carried out to achieve the required performance. From the modal analysis of foundation with support structure, the layer has less effect on the vibration modal in section 3.2. In this section, only the modal of composites-steel foundation without support structure was analyzed. The effect of the lay angle on modal of foundation was shown in Table 5. It was demonstrated that the influence on modal of foundation with different layer angles were different. When the layer angle is between 50 ° and 60 °, the modal results of composites-steel foundation is the same. Therefore the case of composites-steel foundation could be divided into three case, namely 0 °, 5 ° to 60 °, 90 °.

Table 5: Modal analysis of foundation with different layer angles

Cases	Modal frequency (Hz)		
1	1035.4	1107.8	1346.4
2	1040.7	1129.8	1357.3
3	1040.7	1129.8	1357.3
4	1040.7	1129.8	1357.3
5	1040.7	1129.8	1357.3
6	1040.7	1129.8	1357.3
7	1040.7	1129.8	1357.3
8	1040.7	1129.8	1357.3
9	1036.9	1114.5	1346.6

4.2 Effect on impedance of different layer angles

The response of composites-steel foundation with different layer angles after motivation were calculated. Impedance characteristics and modal characteristics are similar with the data from Table 6, so there are only three patterns in the calculation, namely 0°, 5° to 60° and 90°. If the thickness of panel is the same, the impedance is higher, the property is better. From the data in Table 6, impedance of foundation with layer angle in 0° is the best, impedance of foundation with layer angle 90° is the second.

Table 6: Impedance data of points on foundation with different layer angles

Frequency(Hz)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
10	160.0	159.7	159.7	159.7	159.7	159.7	159.7	159.7	159.6
12.5	158.2	158.0	158.0	158.0	158.0	158.0	158.0	158.0	157.9
16	156.7	156.5	156.5	156.5	156.5	156.5	156.5	156.5	156.4
20	154.8	154.5	154.5	154.5	154.5	154.5	154.5	154.5	154.4
25	152.8	152.6	152.6	152.6	152.6	152.6	152.6	152.6	152.5
31.5	150.5	150.3	150.3	150.3	150.3	150.3	150.3	150.3	150.2
40	148.5	148.3	148.3	148.3	148.3	148.3	148.3	148.3	148.2
50	146.5	146.2	146.3	146.3	146.3	146.3	146.3	146.3	146.2
63	144.5	144.3	144.3	144.3	144.3	144.3	144.3	144.3	144.2
80	142.4	142.2	142.2	142.2	142.2	142.2	142.2	142.2	142.1
100	140.3	140.1	140.1	140.1	140.1	140.1	140.1	140.1	140.0
125	138.1	137.9	137.9	137.9	137.9	137.9	137.9	137.9	137.8
160	135.5	135.3	135.3	135.3	135.3	135.3	135.3	135.3	135.3
200	131.9	131.7	131.7	131.7	131.7	131.7	131.7	131.7	131.6
250	116.6	116.5	116.5	116.5	116.5	116.5	116.5	116.5	116.5
315	118.8	118.7	118.7	118.7	118.7	118.7	118.7	118.7	118.7
400	110.7	110.9	110.9	110.9	110.9	110.9	110.9	110.9	110.8
500	108.9	107.6	107.6	107.6	107.6	107.6	107.6	107.6	108.3

4.3 Effect on vibration level of different layer angles

Vibration could be transmitted from equipment machine feet to foundation panel, then transmitted from the foundation web plate and bracket to support structure. The main role of the foundation is to support equipment and keep the equipment in normal work, moreover, to reduce the vibration from equipment to support structure. Therefore the final evaluation of foundation performance is the vibration of the support structure. Known from Table 7, when the layer angle are in 5° to 60° and 90°, acceleration level of support structure are the same, which are greater than acceleration level of the support structure when layer angle is in 0°. So the vibration level of support structure is minimal when lay angle is in 0°.

Table 7: Vibration acceleration level of support structure with different layer angles

Frequency(Hz)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
10	32.3	32.2	32.2	32.2	32.2	32.2	32.2	32.2	32.2
12.5	35.8	35.8	35.8	35.8	35.8	35.8	35.8	35.8	35.8
16	38.8	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7
20	42.7	42.6	42.6	42.6	42.6	42.6	42.6	42.6	42.6
25	46.5	46.5	46.5	46.5	46.5	46.5	46.5	46.5	46.5
31.5	51.1	51.1	51.1	51.1	51.1	51.1	51.1	51.1	51.1
40	55.2	55.2	55.2	55.2	55.2	55.2	55.2	55.2	55.2
50	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2	59.2
63	63.3	63.2	63.2	63.2	63.2	63.2	63.2	63.2	63.2
80	67.4	67.3	67.3	67.3	67.3	67.3	67.3	67.3	67.3
100	71.6	71.5	71.5	71.5	71.5	71.5	71.5	71.5	71.5
125	76.0	75.9	75.9	75.9	75.9	75.9	75.9	75.9	76.0
160	80.8	80.8	80.8	80.8	80.8	80.8	80.8	80.8	80.8
200	86.7	86.7	86.7	86.7	86.7	86.7	86.7	86.7	86.7
250	94.5	94.5	94.5	94.5	94.5	94.5	94.5	94.5	94.5

Frequency(Hz)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
315	84.5	84.5	84.5	84.5	84.5	84.5	84.5	84.5	84.5
400	94.0	94.2	94.2	94.2	94.2	94.2	94.2	94.2	94.3
500	91.1	93.2	93.2	93.2	93.2	93.2	93.2	93.2	93.0
Total level (10 to 500)	98.8	99.3	99.3	99.3	99.3	99.3	99.3	99.3	99.3

5. Conclusion

For composite sandwich plate is good in vibration characteristics and design, the typical steel foundation was treated as research object in the paper. On the premise of strength and stiffened of foundation was relatively suitable, the steel foundation was substituted by composites-steel foundation. By comparison of vibration characteristic differences of steel foundation and composite material-steel foundation, the vibration effect on foundation with different composite layer angles were analyzed, the following conclusion could be obtained:

It was demonstrated that the natural frequency of steel foundation are almost constant, the natural frequency of composites-steel foundation could be changed by reasonable design. Under the same load, vibration acceleration level at machine feet of support structure of composites-steel foundation are lower than that of steel foundation. Based on the effect on foundation modal, impedance and acceleration level, the lay angle could be divided into three patterns, namely, 0°, 5° to 60°, 90°, this three kinds of patterns have advantage and disadvantage in intensity, modal, impedance and acceleration level, according to specific needs in engineering practice, the compatible scheme of composites layer can be selected.

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REFERENCES

1 Cao, C. One generation of material technology, one generation of large aircraft, *Hangkong Xuebao/acta Aeronautica Et Astronautica Sinica*, **29**(3), 701-706, (2008).

2 Her, S. C. and Lin, C. S. Vibration Analysis of Composite Laminate Plate Excited by Piezoelectric Actuator, *Sensors*, **13**(3), 2997-3013, (2013).

3 Jeyaraj, P., Ganesan, N. and Padmanabhan, C. Vibration and acoustic response of a composite plate with inherent material damping in a thermal environment, *Journal of Sound & Vibration*, **320**(1–2), 322-338, (2009).

4 Zhang, H,. Shi, D., Y. and Wang, Q. An improved Fourier series solution for free vibration analysis of the moderately thick laminated composite rectangular plate with non-uniform boundary conditions, *International Journal of Mechanical Sciences*, **121**, 1-20, (2016).

5 Lang, Y. and Hong, M. Mobility characteristics analysis of stiffened laminated composite plates for ships, *Chinese Journal of Ship Research*, **2**(4), 1-6, (2007).

6 Lang, Y. Research on dynamical characteristics of composite laminate foundation of shipboard, Dalian University of Technology, (2007).

7 Zhao, S., L., Guo, W., T. and Wu, Y., B. Experimental study on vibration reduction of composite stand, *Development and Application of Materials*, **24**(4), 8-13, (2009).

8 Mei, Z., Y., Yang, K. and Qiu, J., B. Damping mechanism of sandwich panel on cylindrical foundation, *Journal of Vibration and Shock*, **31**(9), 149-153, (2012).

9 Qi, W., K., Cheng, B. and Liu, L. Research of vibration modal experiment for composite laminates, *Aeroengine*, **39**(6), 53-58 (2013).