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Dynamic Characteristic Simulation of Helicopter Tail Drive Shaft System

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Abstract

Helicopter with the advantage of light, flexible and hovering in the air, is widely used. In both military and civilian domain, it gets more and more attention. It becomes the main subject of research in the world. In the power transmission system of helicopter, the tail rotor shaft is an important part. It is one of the key technologies to predict the dynamic characteristics of the shaft accurately for improving the overall performance of the helicopter. Based on the theory of elastic mechanics, rotor dynamics and the finite element analysis, the former main drive shaft is taken as an example. The dynamic characteristics of the transmission shaft is calculated by the multi/few degrees of freedom finite element method. The validity of the finite element method with few degrees of freedom is determined. Then the structure characteristics of the helicopter tail drive shaft are analyzed, and the dynamic characteristics of the helicopter tail rotor shaft are calculated by using the finite element method with few degrees of freedom. The research results provide the basis and guidance for the design of the helicopter tail drive system.

Keywords: *Helicopter, propeller shaft, finite element, dynamic characteristics*

1. Introduction

Along with our country national economy in a sustained and stable development, and the acceleration of modernization of national defense construction, China's military and civilian department need more and more helicopter urgently. Air force needs a large number of armed helicopters. The Navy needs a carrier based helicopter. Public security, forestry, petroleum, telecommunications and other departments need helicopters in the rescue, disaster relief and offshore oil exploitation[1].

The transmission system is one of the three major components of the helicopter, which occupies a very important position in the helicopter. Tail drive system is an important subsystem of the helicopter transmission system, the role of which is to transfer the power from engine to the tail rotor by torque and rotating speed, balance torsional moment generated by rotor-wing and realize the steering control. If the tail drive system design exist flaws, the tail transmission shaft will produce strong vibration in high speed rotation, which may make parts damage and lead to the tail rotor control failure, threaten the security of flight[2]. At present, there is not a complete set of design method of helicopter tail transmission shaft in China. The domestic helicopter tail drive shaft has exposed many problems in the work, which limits the development of our country's helicopter.

In order to obtain the vibration characteristics of the tail drive system, and the influence of tail drive system on vibration characteristics of the whole helicopter transmission system, it is necessary to study the dynamic characteristics of the transmission shaft of the tail drive system independently. So this paper will study the tail drive shaft. The dynamic characteristics of the tail drive shaft are calculated and analyzed by using the finite element method with few degrees of freedom, in order to better obtain tail drive system

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vibration characteristics, to provide the necessary theoretical basis for future optimization of helicopter structure and improve the helicopter dynamic characteristics.

2. Dynamic Calculation Method of Helicopter Transmission Shaft

Taking the front main drive shaft part of the helicopter transmission system as an example, the dynamic characteristics of the rotor including the mode shape and the critical speed are studied by using the finite element method with multiple/ few degrees of freedom respectively. Then the two calculation methods are analyzed to determine the dynamics calculation method for helicopter transmission shafting.

2.1 Structural Characteristics of the Front Main Drive Shaft

One end of the front main drive shaft is connected with the engine, the other end is connected with the main reducer through the diaphragm coupling. Diaphragm coupling plays the role of supporting and transmission torque. In the dynamic analysis of the transmission shaft, the connection of real coupling is simulated by coupling stiffness and loading mass. Drive shaft is a hollow shaft in which torsion measuring unit is installed. The unit is just in the internal of the transmission shaft, regarded as additional mass loading to the model.

2.2 The Finite Element Method with Few Degrees of Freedom for Calculating the Characteristics of Front Main Drive Shaft

Three dimensional entity modeling was carried out by Solidworks, and then the model is introduced into ANSA to mesh grid. The two end faces of the sectional is processed by using high quality hexahedral mesh. Then introduce the grid model to the ANSYS APDL, as shown in Figure 1.

By using the form of the input command stream program in ANSYS APDL, the dynamic characteristics of transmission shaft model are calculated, including natural frequencies, mode shapes and critical speed (Campbell diagram). The function of the program is mainly as follows:

1) Define the material properties of the input model. The material for the drive shaft is 30Ni4CrMoA. Its elastic modulus is set to 2.05e11, Poisson's ratio is 0.3, the density is 7800kg/m3.
2) Define the rotation axis through the two end node coordinates.
3) Couple all nodes of drive shaft end face to the center point.
4) A reference point is defined beyond the end faces. Matrix27 element is added where the reference point and the end point is connected. Figure 2 shows the connection between coupling point and reference point of the calculation model.

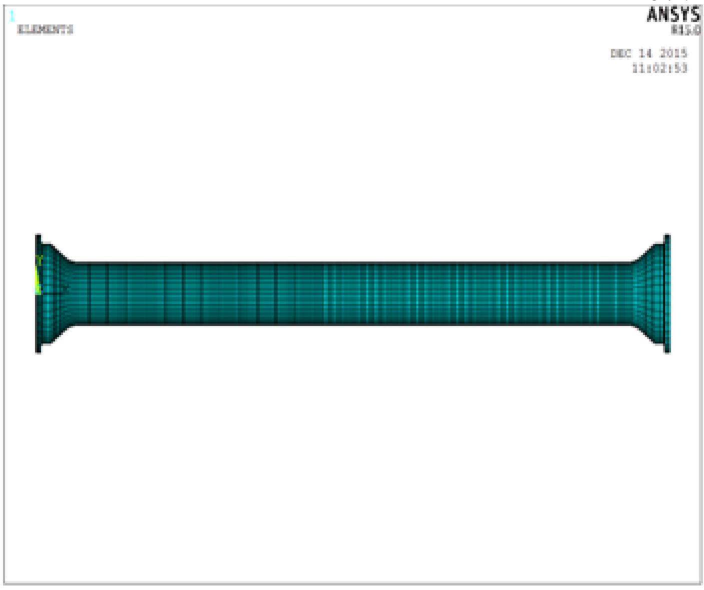


Figure 1. Mesh Model of Front Main Drive Shaft

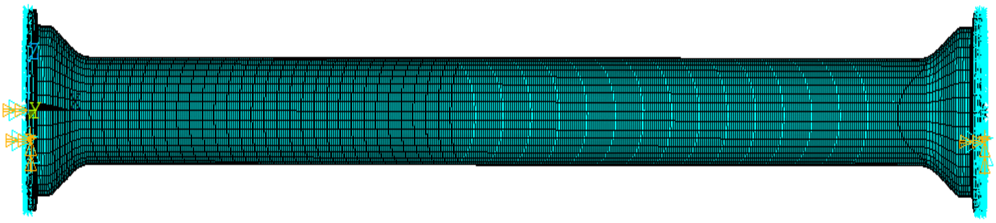
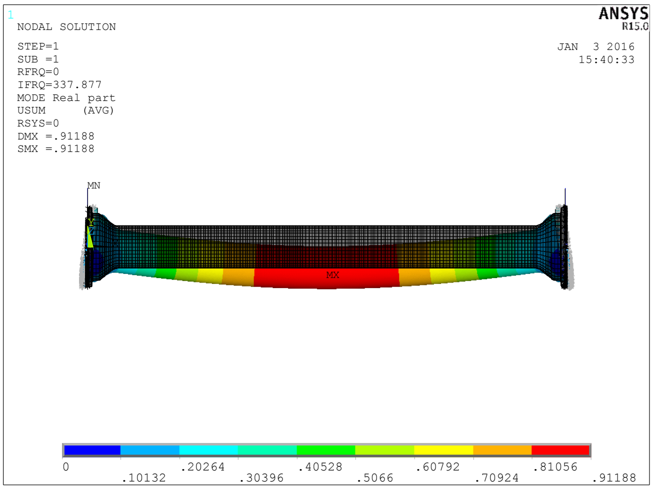


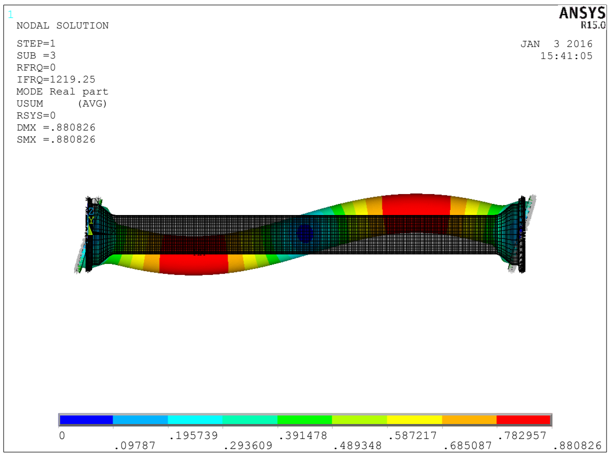
Figure 2. Connection between Coupling Point and Reference Point of the Calculation Model

5) Stiffness and mass of the diaphragm coupling are loaded on the Matrix27 element. Quality includes half quality of the diaphragm coupling and the quality of the torque meter assembly at this point (the left end and right end of the coupling point is loaded with 0.98kg and 1.52kg respectively).
6) The mode of vibration is calculated and the Cabell diagram is drawn.
7) Input the program to the APDL, to solve the dynamic characteristic of the main drive shaft, that is, the mode shapes and the Cabell diagram (critical speed).

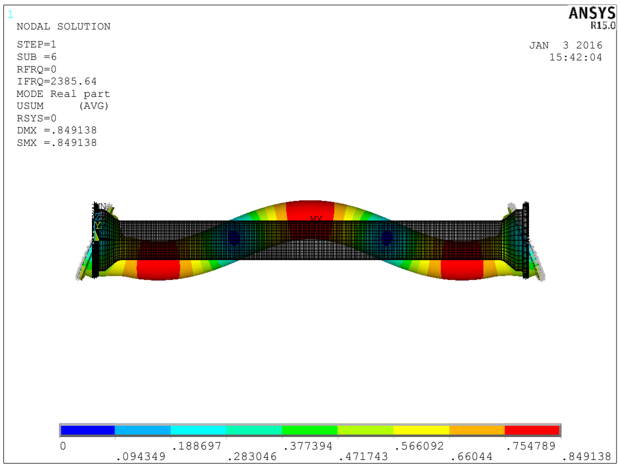
The static frequency mode characteristic is the natural frequency and vibration mode of the power transmission shaft in the non-rotating state. In the calculation of static frequency modal characteristics, according to the transmission characteristics and working conditions, the calculation of the first 3 modes can meet actual needs. The first three modes are shown in Figure 3.



(a) First-order bending vibration (First-order frequency)



(b) Second-order bending vibration (Second-order frequency)



(c) Third-order bending vibration (Third-order frequency)

The Cabell diagram of the front main drive shaft is shown in Figure 4.

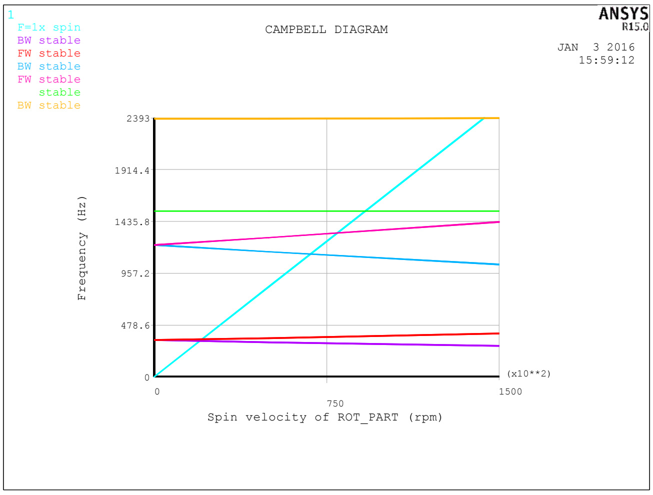


Figure 4. Cabell Diagram of the Front Main Drive Shaft

From Figure 4 we can see that, the horizontal axis represents rotating speed and the vertical axis represents the frequency. When the speed is 150000r/min, there are only 6 intersections. The critical speed of the first three order is calculated, as shown in Table 1 below.

Table 1. The Critical Speed of the First Three Order

Order	1	2	3
Critical speed（r/min）	20761.87	79700.20	143580

2.3 Finite Element Calculation of the Dynamic Characteristics of the Front Drive Shaft with Few Degrees of Freedom

When the Newmark method is applied to solve large nonlinear rotor dynamics differential equations, it has high computational stability and efficiency, and its accuracy can completely meet the needs of practical engineering. In this paper, the finite element method is used to analyze the dynamic characteristics of the rotor system by Newmark iterative method.

According to the structure characteristic of the front main drive shaft of helicopter, we simplified the structure of the transmission shaft to a hollow shaft tube structure, and omitted the flange structure at both ends of shaft. We adopted the finite element method of few degrees of freedom, the drive shaft is divided into 10 axis, 11 nodes, 44 different degrees of freedom, and the quality of shaft focus on each node acquiescently. As shown in figure 5.

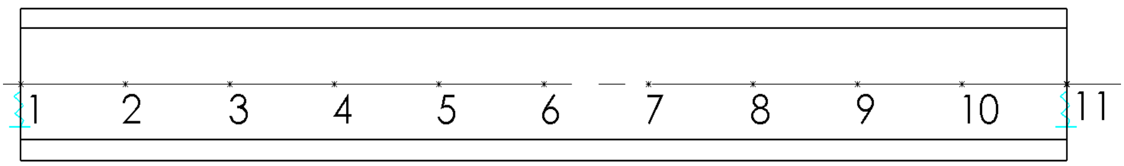


Figure 5. Schematic Diagram of the Front Main Drive Shaft Model Node

The both ends of the main drive shaft respectively connected with the diaphragm coupling, and play the supporting function, and it adds additional quality lateral stiffness and angle stiffness in node 1 and 11. The structural parameters of the transmission shaft are shown in table 3.

Table 2. Table of Structural Parameters of Finite Element Analysis of the Front Main Drive Shaft

Segment number	Segment length	External diameter	Inner diameter	Node number	Added mass	Shaft segment quality	Total mass of node	Jd
	(m)	(m)	(m)		(kg）	(kg）	(kg）	kg•m^2
				1	0.65	0.118	0.768	0
1	0.07	0.0631	0.0586	2	0	0.236	0.236	0
2	0.07	0.0631	0.0586	3	0	0.236	0.236	0
3	0.07	0.0631	0.0586	4	0	0.236	0.236	0
4	0.07	0.0631	0.0586	5	0	0.236	0.236	0
5	0.07	0.0631	0.0586	6	0	0.236	0.236	0
6	0.07	0.0631	0.0586	7	0	0.236	0.236	0
7	0.07	0.0631	0.0586	8	0	0.236	0.236	0
8	0.07	0.0631	0.0586	9	0	0.236	0.236	0
9	0.07	0.0631	0.0586	10	0	0.236	0.236	0
10	0.0725	0.0631	0.0586	11	0.65	0.118	0.768	0
sum	0.7025				1.3	2.37	3.67	0

According to the above parameters, write the rotor dynamics program, and it can be used to solve the dynamic characteristics of the front main drive shaft of the helicopter transmission system.

Figure 6 shows the first third-order mode shapes diagram of the front main drive shaft by the finite element method with few degrees of freedom.

Table 3 shows the calculative first third-order critical speed of positive precession

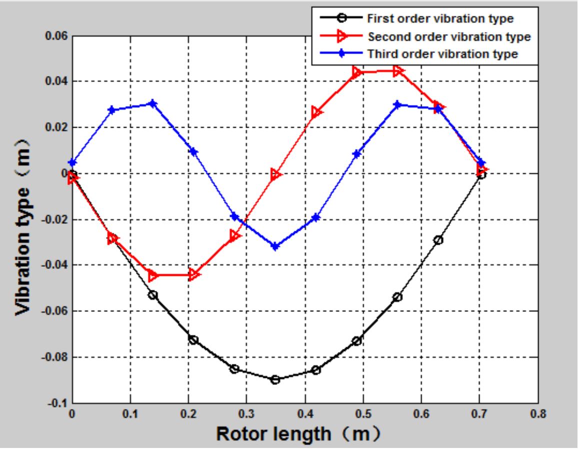


Figure 6. The Third-Order Modal Shapes Diagram of the Front Main Drive Shaft by the Finite Element Method with Few Degrees of Freedom

Table 3. The First Third-Order Critical Speed of the Front Main Drive Shaft by the Finite Element Method with Few Degrees of Freedom with Positive Precession

Order	1	2	3
Critical speed with positive precession (r/min)	21400	85980	194480

2.4 Comparative Analysis and Method Validation of the Dynamic Characteristics of the Front Main Drive Shaft

The dynamic characteristics of the front main drive shaft of the helicopter transmission system are calculated respectively by using finite element method of multiple degrees of freedom and few freedoms, the calculation results of the two critical speeds are shown in Table 4.

Table 4. The Calculative First Third-Order Critical Speed with Positive Precession by Two Methods

Order	1	2	3
Critical speed by using finite element method of multiple degrees of freedom（r/min）	20761	79700	143580
Critical speed by using finite element method of few degrees of freedom（r/min）	21400	85980	194480
Error	3％	7％	26％

The results are as follows:

1) According to the modal shape result of the figure 3 and figure 6 which using two kinds of methods calculate. The first three order modal shape of the front main transmission shaft are respectively the first-order bending vibration, the second-order bending vibration and third-order bending vibration. The two methods calculate the same mode of vibration;
2) According to the result of critical speed by two kinds of calculation method in the table 4.The first-order critical speed are 20761r/min and 21400r/min respectively. The relative error is 3%, the second-order critical speed were 79700r/min and 85980r/min. The relative error is 7%. The third-order critical speed of two methods to calculate are above more than one hundred thousand turn per minute, and the calculation result is no longer accurate, so it is no longer considered.
3) In the working process of the helicopter transmission system, it should avoid the rotational speed of the front main drive shaft to the critical speed. Avoid causing resonance, resulting in trouble or even greater harm. The data shows that the normal operating speed of main transmission shaft is 6057.9r/min, and it’s far below the first critical speed, and can work normally.
4) The contrast of results calculated by the two methods above, two kinds of calculative methods within the effective range have few influence on the results. Considering the computational model, time, calculation simply and other factors, choosing the finite element method few degrees of freedom to calculate the dynamic characteristics of helicopter tail transmission shafting.

3. The Structural Characteristics of the Helicopter Tail Drive Shaft

The helicopter tail drive system mainly consists of the main reducer, multi pivot level transmission shaft, intermediate reducer, two fulcrum of tail transmission inclined shaft, tail deceleration device, a diaphragm coupling, etc. Among them, the level of transmission shaft of the fulcrum through the main reducer and intermediate reduction power device transfer power in the helicopter, the hin-walled cylindrical form generally used in structure, so greatly reduces the system of the bending stiffness and the overall quality, at the same time on the one hand reduces the critical speed of the system, on the other hand drive shaft become flexible shaft, the increase in the speed of automatic centering effects [3], as shown in Figure 7.

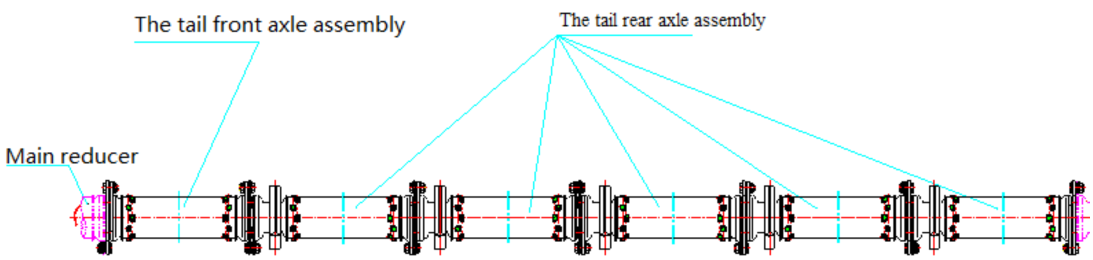


Figure 6. Helicopter Tail Drive System Structure Schematic Diagram

Tail transmission shafting of the horizontal transmission shaft system from a root of the tail front axle assembly, 5 root tail transmission rear axle assembly composed, with the tail horizontal transmission shafting span longer, in order to improve the critical speed, lest the resonate. At the end of the pass on the rear axle is provided with a support and the bearing. Its structure as follows:

(1) The tail front axle is composed of a aluminum hollow tube, flange plate. The flange plate and aluminum hollow tube connected by six hexagon head screw type rivet, in order to improve the connection reliability and strength.

(2) The tail rear axle, including the aluminum hollow tube, flange plate, supporting bearing, flange, and spline joint. Both ends of the aluminum hollow tube respectively with flange and spline flange using high strength hexagon head screw type rivet connection. Spline flange and spline joint connected by internal and external spline engagement; bearing assembly on the spline flange.

(3) Each transmission shaft is connected through the diaphragm coupling, which can compensate the misalignment caused by the processing and the assembly.

The horizontal transmission shaft system of the helicopter tail drive system, the transmission chain is longer, drive shaft, spline, bearing is the main moving parts. The transmission shaft assembly is much, the link is much, so the dynamics of the transmission system is complex. Therefore, this paper studies the helicopter tail drive shaft system of the front axle and rear axle by the diaphragm coupling are connected with each other to calculate the dynamic characteristics.

4. Finite Element Modeling with Few Degrees of Freedom of the Helicopter Tail Drive Shaft

According to the structural characteristics of the horizontal transmission shaft system of the helicopter tail transmission shaft system, simplified tail front/rear transmission shaft were the hollow shaft pipe structure, omitted at the two ends of the shaft flange structure; Due to the tail transmission axle spline connection main torque transfer function and spline connection dynamics is very complex, non-linear. So here the default is the fixed connected, thus simplifying the calculation. Use the less degree of freedom finite element method, the tail transmission shafting division for 24 shaft section, 25 nodes, a total of 100 degrees of freedom, the shaft segment mass default to each node, as shown in Figure 8. The structure parameters of data segments are given in table 5. Among them, at the two ends of the shaft coupling default for bearings, the stiffness of bearing applied in node 1 and 25, 5 tail rear axle of the rolling bearing are located at node 6, 10, 14, 18, and 22, between the shaft and the diaphragm couplings connected to lateral stiffness and torsional stiffness coupling to connect nodes 5, 9, 13, 17, 21 (because the inertia of the diaphragm coupling is very small, so here is omitted).

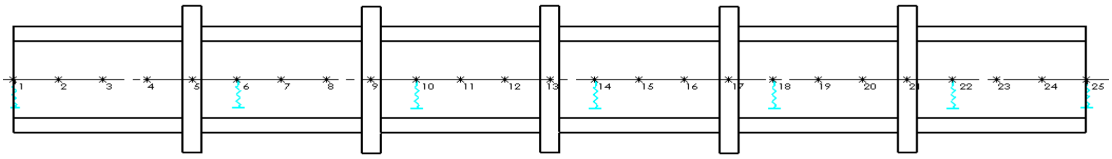


Figure 8. The Tail Drive Shaft System Schematic Diagram of the Node

Table 5. Structural Parameters of the Finite Element Analysis of the Main Drive Shaft

Segment number	Segment length	External diameter	Inner diameter	Node number	Added mass	Shaft segment quality	Total mass of node	Jd
	(m)	(m)	(m)		(kg)	(kg)	(kg)	kg•m^2
				1	0.65	0.248	0.898	0
1	0.369	0.090	0.0864	2	0	0.497	0.497	0
2	0.369	0.090	0.0864	3	0	0.497	0.497	0
3	0.369	0.090	0.0864	4	0	0.497	0.497	0
4	0.369	0.090	0.0864	5	1.3	0.305	1.605	0
5	0.0645	0.090	0.0864	6	0	0.476	0.476	0
6	0.6432	0.090	0.0864	7	0	0.866	0.866	0
7	0.6432	0.090	0.0864	8	0	0.866	0.866	0
8	0.6432	0.090	0.0864	9	1.3	0.866	2.166	0
9	0.0645	0.090	0.0864	10	0	0.476	0.476	0
10	0.6432	0.090	0.0864	11	0	0.866	0.866	0
11	0.6432	0.090	0.0864	12	0	0.866	0.866	0
12	0.6432	0.090	0.0864	13	1.3	0.866	2.166	0
13	0.0645	0.090	0.0864	14	0	0.476	0.476	0
14	0.6432	0.090	0.0864	15	0	0.866	0.866	0
15	0.6432	0.090	0.0864	16	0	0.866	0.866	0
16	0.6432	0.090	0.0864	17	1.3	0.866	2.166	0
17	0.0645	0.090	0.0864	18	0	0.476	0.476	0
18	0.6432	0.090	0.0864	19	0	0.866	0.866	0
19	0.6432	0.090	0.0864	20	0	0.866	0.866	0
20	0.6432	0.090	0.0864	21	1.3	0.866	2.166	0
21	0.0645	0.090	0.0864	22	0	0.476	0.476	0
22	0.6432	0.090	0.0864	23	0	0.866	0.866	0
23	0.6432	0.090	0.0864	24	0	0.866	0.866	0

24	0.6432	0.090	0.0864	25	0.65	0.433	1.083	0
sum	8.764				7.8	16.981	24.781	0

According to the above parameters, input the rotor dynamics program which can be used to solve the dynamic characteristics of the tail transmission shaft system of the helicopter transmission system.

5. Dynamic Characteristic Calculation of Helicopter Tail Drive Shaft System

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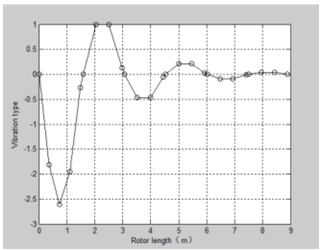
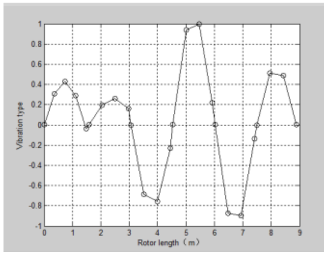
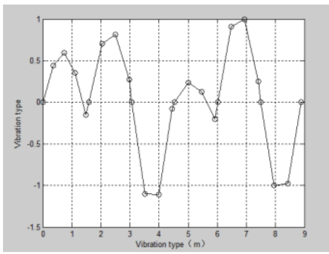


（a）first order vibration type



（b）second order vibration type



（c）third order vibration type

Figure 9. The Third-Order Modal Shapes Diagram of the Tail Rear Shaft System by the Finite Element Method with Few Degrees of Freedom

Table 6. The Third-Order Critical Speed of the Tail Rear Shaft System by the Finite Element Method with Few Degrees of Freedom with Positive Precession

Order	1	2	3
Critical speed with positive precession (r/min)	6614	7065	7423

From Figure 9 and table 6 know, tail transmission shafting in first order two drive shaft vibration is large, and shows the second flexural vibration; Second order for three drive shaft vibration is big. It showed that the three order bending vibration; Three order tail transmission shafting overall vibration. The first order critical speed is 6614 r/min, and one to three order critical speed little difference, It is possible that the lateral stiffness of the diaphragm coupling is larger, and the reason of the difference between the bearing stiffness and the bearing stiffness is not great. The tail drive rear axle shaft working speed is 3579.42 r/min, so in a safe speed range.

6. Conclusion

By the finite element method with multiple/few degrees of freedom, the dynamic characteristics of the helicopter's tail transmission shaft system are calculated. The effectiveness of the rotor dynamics program is determined by the finite element method with few degrees of freedom. Then the dynamic characteristics of the tail transmission shafting system of helicopter are calculated. The first third order modal and critical speed are obtained. The conclusions are as follows:

(1) The correctness and effectiveness of the finite element method with multi degrees of freedom (by ANSYS APDL command) and the self-programmed finite element method with few degrees of freedom to calculate of the dynamic characteristics of the rotor are verified. The error of the first two order critical speed of single rotor is less than 7%.

(2) By the finite element method with few degrees of freedom, dynamic characteristics of the helicopter tail transmission shafting are calculated, and the first third order modal and critical speed are obtained. The work speed of tail transmission shaft is below the first order critical speed, providing a basis and guidance for the design and vibration prediction of the helicopter transmission system structure.

Acknowledgments

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