Structure Design and Modal Analysis for a New Type of Cycloidal Drives

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***Abstract* — Cycloidal drives have been widely used in various fields of common transmission. They have also had great potential for application in the field of mechatronic system. In the cycloidal drives, the turning arm bearing parts is the weakest. Especially in specific conditions such as high torque, peak impulsive load, strong repeated fluctuating load, high and low temperature alternation etc. This results in turning arm bearing being easily destroyed and producing vibration and noise. In order to solve this situation, a new type of cycloidal drives with a rubber ring was proposed and produced using modal analysis. According to the analysis results, the same order natural frequency has a tendency to grow gradually with increasing hardness of rubber material. A new type of cycloidal drives with rubber whose Shaw's hardness is 80° has better modal characteristics than traditional cycloidal drives by more effectively avoiding resonance region. This study has provided an effective optimizing design method for the new type of cycloidal drives.**

Keywords - a new type of cycloidal drives; finite element method; modal analysis

I. INTRODUCTION

Cycloidal drives have the characteristics of large transmission ratio, small volume, high reliability, light-weight, high efficiency, long service life and so on. Not only are cycloidal drives widely used in general transmission field, but also they have extremely extensive application potentiality in high-tech equipment. However, the size of the turning arm bearing is limited by the width of the cycloid gear and the root radius, and the speed of turning arm bearing is higher than that of the input shaft. Therefore, turning arm bearing become the weakest link for cycloidal drives. Especially in the specific conditions, such as high torque, peak impulsive load, strong repeated fluctuating load, high and low temperature alternation and so on, turning arm bearing is destroyed more easily, and produce vibration and noise. Therefore, many scholars have studied the cycloidal drives.

A modified torsional model of 2K-H epicyclic gearing is developed and used to identify unique properties of natural frequencies and vibration modes [1]. The natural frequency and free vibration of 2K-V cycloid-pin-annulus reducer was obtained by modal analysis technology [2]. Analyzing the natural frequencies and vibration modes of 2K-H planetary gear system in a coal shearer is helpful for designing and monitoring the planetary gear system [3].

The natural frequencies and mode shapes of double-circular-arc modified cycloid gears are extracted, which provide the reference for this gear dynamic design [4]. The stress and strain distribution of main load bearing parts like cycloidal gear and pin gear were obtained by finite element method [5]. Dynamic simulation analysis of output-pin-wheel cycloid drives and finite element modal analysis were done in both of the no-load and full load conditions [6].

The inherent characteristics of the cycloids are analyzed with unrestricted and physical constraint modal, resulting in the first ten natural frequencies and its corresponding vibration form, which will be the dynamic analysis foundation of the whole reducer system [7]. The modal analysis of shearer's cycloid gear was carried to determine its low-order vibration characteristics to avoid resonance in the structural design [8]. Modal analysis of epicycloidal sprocket was carried to determine the sprocket's natural frequencies and mode shapes to avoid resonance during the transmission process [9]. The modal analysis of cvcloidal gear pump is carried out, the modes, natural frequency and mode shapes participation factor of cycloid gear pump are acquired to ensure in the design of cycloid gear pump can avoid resonance model [10].

However, as the robot, precision machinery, aerospace, high-tech equipment and other industries' requirements are improved continuously, cycloidal drives are facing more stringent demands in terms of vibration and noise. This article makes use of the buffer action produced by the elastic deformation of rubber material to invent a new type of cycloidal drives with a rubber ring, and carries out the modal analysis.

II. STRUCTURE OF THE NEW TYPE OF CYCLOIDAL DRIVES

The new type of cycloidal drives has four major components including eccentric driving input mechanism, damping component, cycloidal meshing mechanism and output transmission mechanism. Their structures are shown in Figure.1.

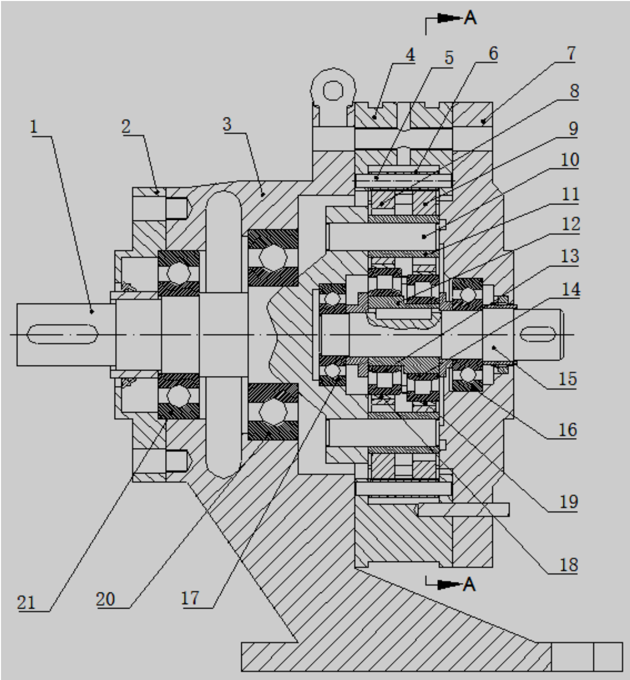

Figure 1. The structure of new type of cycloidal drives.

1 output shaft, 2 output shaft end cap, 3 speed reducer base, 4 reducer main box, 5 gear pin, 6 wheel roller, 7 input shaft end cap, 8 cycloidal gear(I), 9 cycloidal gear (II), 10 pin, 11 roller, 12 eccentric sleeve, 13 turning arm bearing (I), 14 turning arm bearing(II), 15 input shaft, 16 input shaft bearing (I), 17 input shaft bearing(II), 18 flexible rubber ring (I), 19 flexible rubber ring (II), 20 output shaft bearing(I), 21 output shaft bearing (II).

The new type of cycloidal drives is the key transmission parts. Their detailed structures are shown in Figure.2. Rubber ring 18 is installed between turning arm bearing 22 and cycloidal gear 8. To prevent the rubber ring 18 sliding out between turning arm bearing and the cycloidal gear, there is larger roughness in internal surface of cycloidal gear center hole, external surface of turning arm bearing and internal and external surfaces of rubber ring. Rubber ring was stuck by superglue pressed between the turning arm bearing and cycloidal gear.

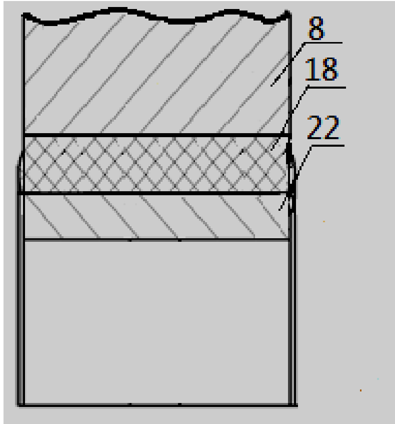

Figure 2. Structure of damping component of the new type of cycloidal drives: 8 cycloidal gear, 18 flexible rubber ring (I), 22 turning arm bearing.

III. CALCULATION OF ENGAGE FREQUENCY

Work conditions of the new type of cycloidal drives as follows: speed of input shaft $n_H = 1440 r/\min$, input power $P = 4kW$, transmission ratio $i = 29$, efficiency $\eta = 0.92$, working 8 hours a day.

The main frequency of vibration caused by meshing of cycloidal gear and pin wheel is called meshing frequency of gear, denoted by $f_m(nz/60)$. Rotating frequency of gear shaft is called shaft frequency, denoted by $f_s(n/60)$. If a angular velocity which rotates with equal speed in opposite directions of turning arm is added to cycloidal drives, the relative motion relationship between the parts of cycloidal drives still remains the same. Cycloidal drives become to planetary transmission whose input shaft is fixed. According to the principle of relative motion, meshing frequency of cycloidal drives can be calculated according to the method of fixed shaft rotating. It is equal to the product of rotating cylinder number of cycloidal gear in unit time and number of teeth of cycloidal gear. The parameters of new type of cycloidal drives is shown in TABLE I.

TABLE I PARAMETERS OF NEW TYPE OF CYCLOIDAL DRIVES

parts	Z	Speed n(rpm)	equivalent speed n(rpm)	rotation frequency fs(Hz)	Meshing frequency fm(Hz)	Meshing cycle T(ms)
the eccentric input shaft		1440	0			
Pin gears	30	0	-1440	24	720 24.8	1.39 40.32
Cycloid gear	29	49.7	-1489.7	0.8276		
Output mechanism		49.7	-1489.7	□□□□□□		

Theory for modal analysis

By the finite element method of elastic mechanics, the equation of motion of reducer system is shown,

$$M\ddot{X} + C\dot{X} + KX = F(t) \tag{1}$$

In this equation, X, $\dot{X}$, $\ddot{X}$ indicate in order node displacement vector, speed vector and acceleration vector. $F(t)$ indicates node dynamic load vector. M, C, K

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indicate in order overall quality of system matrix, damping matrix and stiffness matrix.

Ignoring exogenous excitation, so $F(t)=0$. Because of influence of damping is small, damping coefficient can be ignored, then

$$M\ddot{X} + KX = 0 \tag{2}$$

In modal analysis, structure is supposed to be linear, so corresponding solution can be supposed to be harmonic response , and the formula of the solution can be supposed to be :

$$X = \Phi e^{jwt} \tag{3}$$

In this formula, Φ is amplitude array; w is simple harmonic vibration frequency; t is time variable. Let formula(3) substitute into formula(2), eliminate factor e^{jwt}, and get basic equation of undamped modal analysis.

$$K\Phi_i = \omega_i^2 M\Phi_i \tag{4}$$

In this formula, Φ_i is ith step modal mode vectors(eigenvector); ω_i is ith step modal natural frequency(ω_i^2 is eigenvalue).

The solvable conditions of the previous formula is:

$$\det(K - \omega^2 M) = 0 \tag{5}$$

Formula (5) is called characteristic equation of structure. solution of the equation can get n eigenvalues ω_1^2 、 ω_2^2 、 …、 ω_n^2 and n linearly independent eigenvectors.

IV. MODAL ANALYSIS

The hardness and elastic modulus The performance of rubber used by the flexible rubber ring is closely related to its formula. Damping property of rubber is closely related to fillers, such as carbon black, which are added to raw material. Carbon black and other fillers can change the shear modulus of damping rubber. The measurement procedure of static shear modulus is very complicated and difficult to control, so there is rarely direct measurement of shear modulus in engineering. It is calculated by measuring the hardness. The hardness of different formula of damping rubber is different. The scope of frequently-used rubber is shore hardness 60° ～ 80° . The hardness of rubber can be measured by using durometer directly. The shear modulus of rubber can be calculated according the following formula [11].

$$G = \frac{0.7554H_A + 5.53}{100 - H_A} \tag{6}$$

H_A indicates the number of degrees of Shore durometer, G indicates shear modulus of rubber.

Supposing the rubber is a kind of incompressible material, and its material property is same in all respects. The relation of shear modulus G, Young's modulus E and Poisson's ratio ν is shown,

$$G = \frac{E}{2(1+\nu)} \tag{7}$$

Supposing Poisson's ratio of rubber is ν =0.47, the elasticity modulus of rubber with different hardness is shown in Table 2.

TABLE II ELASTICITY MODULUS OF DIFFERENT HARDNESS OF RUBBER

hardness (HA°)	60	65	70	75	80
elasticity modulus E(Mpa)	3.7379	4.5890	5.7239	7.3130	9.6964

Modeling of modal analysis. Definition of material property is the precondition of modal analysis by finite element method. The materials of gear pin, wheel roller, cycloidal gear, pin and pin roller are all GCr15 in the model. Supposing its Young's elasticity modulus is 2.06E+11(Pa), and Poisson's ratio is 0.30, and density is 7850(kg/m3). The elasticity modulus of rubber with different hardness is shown in Table 2, and density is 930(kg/m3).

The finite element modal analysis of cycloidal drives mainly is adopted by free meshing method. This method can determine the density of grid according to the complexity of model structure, and reduce artificial disturbance to meshing. For complex loading and simple structure parts (pin, gear pin, turning arm bearing sleeve, rubber ring, etc.), it is supposed to proceed local mesh refined and improve the accuracy of analysis. Meshing model of cycloidal drives is shown in Figure.3.

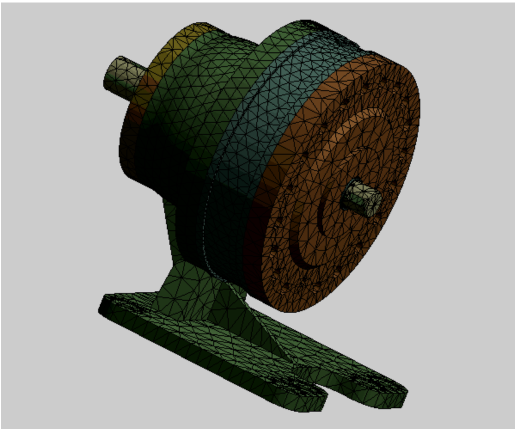

Figure 3. Meshing model of cycloidal drives

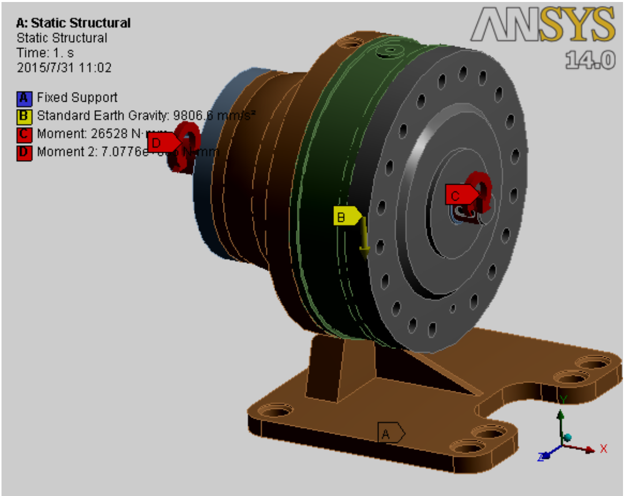

Figure 4. Force and constraint model of cycloidal drives.

According to the kinematic principle of cycloidal drives, applying clockwise revolute pair on the input shaft, applying anticlockwise revolute pair on the cycloidal gear and the output shaft. According to the force situation of cycloidal drives, setting reducer's own gravity B. The input shaft's clockwise torque C=26286. The output shaft anticlockwise torque D = 707760. The basic constraints is A. The force and constraint model of cycloidal drives are shown in Figure.4.

Discussion: Using ANSYS software to complete free modal analysis for the traditional cycloidal drives and the new type of cycloidal drives that adopt five different hardness rubber ring. Their each order natural frequency are shown in Figure.5.

It is shown that the natural frequency of traditional cycloidal drives is higher these new type of cycloidal drives obviously in Fig.5. To Make five different kinds of new type of cycloidal drives be locally enlarged, they are shown in Figure.6.

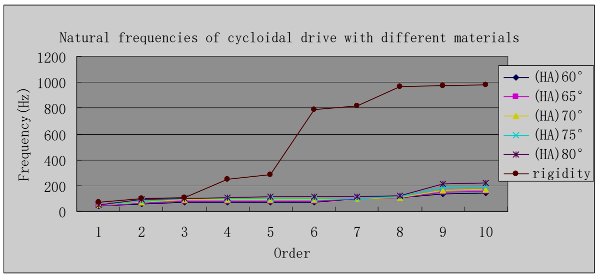

Figure 5. Natural frequencies of cycloidal drives with different materials

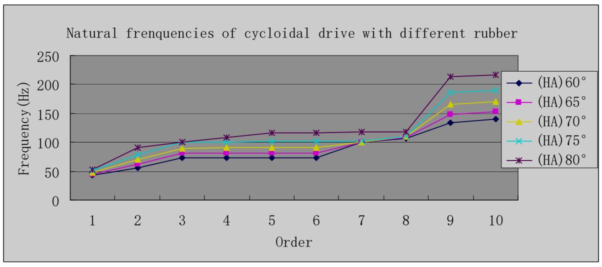

Figure 6. Natural frenquencies of cycloidal drives with different rubber

The Fig.6 shows that the new type of natural frequencies of cycloidal drives will increase with the increase of hardness of rubber ring.

According to analysis, the new cycloidal drives with different hardness rubber ring and traditional cycloidal drives are equal at 1 ~ 10 order vibration modes. The order of vibration modes (cycloid gear swing perpendicular to the axis) which cause drives' damage easily increase gradually with the increase of hardness of rubber ring. So let the rubber ring be 80° .

In order to further study cycloidal drives with rubber ring whose Shaw's hardness is 80° , 11 ~ 20 th order frequencies are shown in TABLE III.

TABLE III. 11 ~ 20TH ORDER FREQUENCIES OF NEW TYPE OF CYCLOIDAL DRIVES

Order	11	12	13	14	15	16	17	18	19	20
Frequency(Hz)	246	284	397	411	419	428	441	885	960	1115

To analyze by contrasting with meshing frequency of cycloidal drives, it is shown that the speed of motor is 1440 r/min. The rotational frequency of corresponding input eccentric shaft is 24 Hz. Rotational frequency of cycloidal gear is 0.8276 Hz and the rotational frequency of output gear is 0.8276 Hz. These numerical values are far less than the lowest frequency (53.14 Hz) of new type of cycloidal drives with rubber ring whose Shaw's hardness is 80° . With the order of vibration increasing, the top natural frequency will gradually increased. The 17th order natural frequency is 441.2 Hz, and the 18th order natural frequency is 885.52 Hz. The meshing frequency between cycloidal gear and pin gear is 720 Hz. The minimum difference is 165.52 Hz. The 6th order natural frequency (788.66 Hz) of traditional cycloidal drives is the closest to meshing frequency. Their difference is 68.66 Hz. As a result, when the new type of cycloidal drives run in normal working condition, resonance phenomenon with will not occurs. And the new type of cycloidal drives own better modal characteristics compared with traditional cycloidal drives. This study provide an effective method for optimization design for new type of cycloidal drives.

V. CONCLUSION

Based on 3D model and structure modal analysis theory, the free modal analysis of a new type of cycloidal drives are carried. According to the analysis results, with the hardness of rubber material increasing, the same order natural frequency has a tendency to increase gradually. The order of vibration modal that damage cycloidal drives and influence vibration greatly also has a tendency to increase gradually. The new type of cycloidal drives with rubber whose Shaw's hardness is 80° of the new type cycloidal drives has better modal characteristics than traditional cycloidal drives. It can more effectively avoid resonance region.

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