Research Article

Meshing Stiffness Parametric Vibration of Coaxial Contrarotating Encased Differential Gear Train

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1. Introduction

Due to the existence of an encased structure, the coaxial contrarotating encased differential gear train can transmit torque through multiple paths, so it has stronger load-carrying capacity, more compact structure, and wider transmission ratio range than the ordinary multistage planetary gear train. It is widely used in the fields of helicopter transmission, marine power, and aeroengine. However, it is difficult to design the parameters of the system due to the requirement of constant speed reverse output of the internal and external output shafts, and the vibration and noise caused by internal excitations such as time-varying stiffness and errors also challenge its application. Howe and Mckibbin [1, 2] studied various gear drive system configurations that can realize the coaxial counterrotating of the fan rotors, and, on this basis, the lubrication and efficiency of differential gear train configuration are analyzed.

Parametric stability of gear systems caused by time-varying meshing stiffness has been extensively studied. Lin and Parker [3, 4] used multiscale method to study the effects of meshing stiffness parameters on the instability of the two-stage gear system and planetary gear system and derived a design expression for controlling the instability region by adjusting the stiffness parameters. Liu et al. [5] used the perturbation method to derive the expression of the system parameters instability with both meshing stiffness and bearing stiffness fluctuations, which is verified by Floquet theory. Qiu et al. [6, 7] established a lumped parameter model of a planetary gear considering time-varying meshing stiffness, damping, and input speed fluctuations and studied the effects of damping and input speed fluctuations on instability by the perturbation analysis and numerical method. Canchi and Parker [8] studied the parameter excitation of the rotating ring gear under time-varying stiffness and obtained the conditions of the ring-planet mesh phasing and contact ratio, which can suppress the parameter...
instability of the flexible ring gear in the planetary gear system. Based on the hybrid continuous discrete model, Parker [9, 10] obtained the parameter expression of the instability boundary of the planetary gear system with elastic continuous ring gear by using the structural modal characteristics and multiscale method.

Scholars have carried out many studies on the dynamic characteristics of meshing forces and multipath load distribution caused by time-varying meshing stiffness and error of planetary gear system. Inalpolat and Kahraman [11] established a nonlinear dynamic model including periodic time-varying mesh stiffnesses and gear tooth separation that can predict the sidebands of planetary gear set having manufacturing errors and rotating carrier and compared the predicted meshing force spectrum with the measured meshing force spectrum. Sondkar and Kahraman [12] used a three-dimensional dynamic model of the herringbone planetary gear train to analyze the variation of the maximum meshing force amplitude with the meshing frequency under different staggering phase angles of the left and right gears. Sun et al. [13] and Dong et al. [14] established the nonlinear dynamic model of planetary gear train and studied the influence of different load-sharing assumptions are made: the planets of each planetary set are evenly arranged and have equal mass and moment of inertia. The torsional stiffness of each stepped planet is equal. The input power is transmitted to the ring gear \( r_1 \), stepped planets \( a_i \) and \( b_i \), and ring gear \( r_2 \), and the differential stage consists of the sun gear \( s_2 \), planets \( p_j \), and ring gear \( r_2 \). The input power is transmitted to the ring gear and the carrier, respectively, through the encased stage and the differential stage to realize the reverse double output. By reasonable design of system parameters, the output speeds of ring gear \( r_2 \) and carrier \( c_2 \) can be equal [15].

Define the torsional deformation of each component of the gear system as generalized coordinates:

\[
x = \begin{bmatrix} u_{s1}, u_{s2}, u_{r1}, u_{r2}, u_{a1}, \ldots, u_{a_M}, u_{b1}, \ldots, u_{b_M}, u_{p1}, \ldots, u_{pN} \end{bmatrix}^T,
\] (1)

where \( M \) and \( N \) are the numbers of stepped planet gears and planet gears, respectively. For simplicity, the following assumptions are made: the planets of each planetary set are evenly arranged and have equal mass and moment of inertia. The torsional stiffness of each stepped planet is equal. The friction and error of the system are not considered.

The torsional dynamic model of the coaxial contrarotating gear system is shown in Figure 2. In the figure, \( k_s \) and \( k_r \) represent the torsional stiffness of the sun gear shaft and the stepped planet gear shaft, respectively, and \( k_{s1s1} \), \( k_{s1a1} \), \( k_{r1b1} \), \( k_{r1p1} \), and \( k_{r2p2} \) are the meshing stiffnesses between the sun \( s_1 \) and the stepped planets \( a_i \), the ring \( r_1 \) and the stepped planets \( b_i \), the sun \( s_2 \) and the planets \( p_j \), and the ring \( r_2 \) and the planets \( p_j \), respectively. Damping symbols are similar.

2.1. Stiffness. The Fourier series expression of the time-varying meshing stiffness considering the mesh phasing is [4]

\[
k_m(t) = k_m^d + 2k_m^e \sum_{l=1}^{\infty} \left( a_m^{(l)} \cos \omega_mt + b_m^{(l)} \sin \omega_mt \right),
\] (2)

where
In the formula, $a_m$ and $b_m$ are the mean component and fluctuation value of the mesh stiffness of the gear pair $m$, $\omega_m$ is the meshing frequency, $\epsilon_m$ is the contact ratio, and $c_m$ is the mesh phasing.

2.2. Damping. The meshing damping of gear pair $m$ is [16]

$$
\epsilon_m = 2\xi_m \frac{I_{m1}r_{m2}^2 + I_{m2}r_{m1}^2}{K_m} \tag{4}
$$

In the formula, $K_m$ and $2k_m^r$ are the mean component and fluctuation value of the mesh stiffness of the gear pair $m$, $\omega_m$ is the meshing frequency, $\epsilon_m$ is the contact ratio, and $c_m$ is the mesh phasing.

2.2. Damping. The meshing damping of gear pair $m$ is [16]

$$
\epsilon_m = 2\xi_m \frac{I_{m1}r_{m2}^2 + I_{m2}r_{m1}^2}{K_m} \tag{4}
$$

The torsional damping of the shaft $z$ is

$$
c_z = 2\xi_z k_z I_z \frac{I_{z1}I_{z2}}{I_{z1} + I_{z2}} \tag{5}
$$

where $\xi_z$ is the relative torsional damping coefficient of the shaft $z$, $k_z$ is the torsional stiffness, and $I_{z1}$ and $I_{z2}$ are the moments of inertia of the components connected to the shaft.

3. The Equations of Motion for the Gear Train

According to Newton’s law, the equations of motion for the encased differential gear train are obtained as follows:

$$
\frac{I_{z1}}{r_{bz1}^2} \ddot{u}_{z1} + \sum_{j=1}^{M} \left( k_{z1ai} \delta_{z1ai} + c_{z1ai} \dot{\delta}_{z1ai} \right) + \frac{k_z}{r_{bz1}^2} \left( \frac{u_{z1}}{r_{bz1}} - \frac{u_{z2}}{r_{bz2}} \right) + \frac{c_z}{r_{bz1}^2} \left( \frac{\dot{u}_{z1}}{r_{bz1}} - \frac{\dot{u}_{z2}}{r_{bz2}} \right) = \frac{T_{in}}{r_{bz1}}, \tag{6}
$$

$$
\frac{I_{z2}}{r_{bz2}^2} \ddot{u}_{z2} + \sum_{j=1}^{N} \left( k_{z2pj} \delta_{z2pj} + c_{z2pj} \dot{\delta}_{z2pj} \right) - \frac{k_z}{r_{bz2}^2} \left( \frac{u_{z1}}{r_{bz1}} - \frac{u_{z2}}{r_{bz2}} \right) + \frac{c_z}{r_{bz2}^2} \left( \frac{\dot{u}_{z1}}{r_{bz1}} - \frac{\dot{u}_{z2}}{r_{bz2}} \right) = 0, \tag{7}
$$

$$
\frac{I_{z1}}{r_{br1}^2} \ddot{u}_{z1} - \sum_{j=1}^{M} \left( k_{z1bi} \delta_{z1bi} + c_{z1bi} \dot{\delta}_{z1bi} \right) + \frac{k_z}{r_{br1}^2} \left( \frac{u_{z1}}{r_{br1}} - \frac{u_{z2}}{r_{br2}} \right) + \frac{c_z}{r_{br1}^2} \left( \frac{\dot{u}_{z1}}{r_{br1}} - \frac{\dot{u}_{z2}}{r_{br2}} \right) = 0, \tag{8}
$$

Figure 2: Torsional dynamic model for the coaxial contrarotating gear train.
\[
\frac{I_{c2}}{r_{br2}} \ddot{u}_{c2} - \sum_{j=1}^{N} \left( k_{c2pj} \delta_{c2pj} + c_{c2pj} \dot{\delta}_{c2pj} \right) - \frac{k_r}{r_{br2}} \left( \frac{u_{r1}}{r_{br1}} - \frac{u_{c2}}{r_{br2}} \right) - c_r \left( \frac{u_{r1}}{r_{br1}} - \frac{u_{c2}}{r_{br2}} \right) = - \frac{T_{ou1}}{r_{br2}},
\]

\[
\left( I_{c2} + NI_p \right) \ddot{u}_{c2} - \sum_{j=1}^{N} \left( k_{c2pj} \delta_{c2pj} + c_{c2pj} \dot{\delta}_{c2pj} \right) \cos \alpha_{c2} - \sum_{j=1}^{N} \left( k_{c2pj} \delta_{c2pj} + c_{c2pj} \dot{\delta}_{c2pj} \right) \cos \alpha_{c2} = - \frac{T_{ou2}}{r_{c2}}.
\]

\[
\left( \frac{I_a}{r_{ba}} \right) \ddot{u}_{ai} - k_{s1ai} \delta_{s1ai} - c_{s1ai} \dot{\delta}_{s1ai} + \frac{k_x}{r_{ba}} \left( \frac{u_{ai}}{r_{ba}} - \frac{u_{bi}}{r_{bb}} \right) + \frac{c_x}{r_{ba}} \left( \frac{u_{ai}}{r_{ba}} - \frac{u_{bi}}{r_{bb}} \right) = 0,
\]

\[
\left( \frac{I_b}{r_{bb}} \right) \ddot{u}_{bi} - k_x \left( \frac{u_{ai}}{r_{ba}} - \frac{u_{bi}}{r_{bb}} \right) - c_x \left( \frac{u_{ai}}{r_{ba}} - \frac{u_{bi}}{r_{bb}} \right) + k_{s1bi} \delta_{s1bi} + c_{s1bi} \dot{\delta}_{s1bi} = 0,
\]

\[
\left( \frac{I_c}{r_{cb}} \right) \ddot{u}_{pj} - k_{s2pj} \delta_{s2pj} - c_{s2pj} \dot{\delta}_{s2pj} + k_{r2pj} \delta_{r2pj} + c_{r2pj} \dot{\delta}_{r2pj} = 0.
\]

In the above equations, the relative displacement of gear mesh is

\[
\delta_{s1ai} = u_{s1} - u_{ai},
\]

\[
\delta_{s2pj} = u_{s2} - u_{pj} - u_{c2} \cos \alpha_{c2} ',
\]

\[
\delta_{s1bi} = u_{bi} - u_{s1},
\]

\[
\delta_{s2pj} = u_{pj} - u_{c2} \cos \alpha_{c2} '.
\]

where \( I_h \) (h = 1, 2, 3, 4, 5, 6, 7, 8) are the moments of inertia of the component \( h \), \( r_{bh} \) is the base circle radius of the gear \( h \), \( r_{c2} \) is the distance from the center of planet to the center of the carrier, \( m_p \) is the mass of planet, \( \alpha_{c2} ' \) and \( \alpha_{r2} ' \) are the working pressure angles of the sun-planet and ring-planet mesh, \( T_{in} \) is the input torque, and \( T_{ou1} \) and \( T_{ou2} \) are the load torques applied to the carrier and ring gear, respectively.

Substituting equation (14) into (6)–(13), the matrix form of the system equations can be obtained as follows:

\[
M \ddot{x} + C \dot{x} + K x = Q.
\]

where \( M \), \( C \), \( K \), and \( Q \) are generalized mass matrix, damping matrix, stiffness matrix, and external load array, respectively, as shown in Appendix A.

Disregarding damping and external forces, the equation for the free vibration of the system is

\[
M \ddot{x} + \left( K_a + K_n \right) x = 0.
\]

4. Dynamic Equations Decoupled and Stability Analysis

Let \( K_n \) in equation (16) be zero; then the derived system equation is

\[
M \ddot{x} + K_a x = 0.
\]

The eigensolutions can be obtained by solving formula (17).

\[
K_a \Phi^{(i)} = \omega_i^2 M \Phi^{(i)},
\]

where \( \Phi^{(i)} \) are the vibration modes of the derived system and \( \omega_i \) are natural frequencies. Let

\[
x = \Phi q.
\]

where \( \Phi = [\phi^{(1)}, \phi^{(2)}, \ldots, \phi^{(n)}] \) is the main modal matrix; \( q = [q_1, q_2, \ldots, q_n]^T \). Substituting equation (19) into equation (16) and multiplying \( \Phi^T \) by left, the regular modal equation can be obtained as

\[
\Phi^T M \Phi q + \Phi^T \left( K_a + K_n \right) \Phi q = 0.
\]

Expansions of equation (20) are

\[
\dot{q}_n + \omega_n^2 q_n + 2 \sum_{l=1}^{L} \sum_{k=1}^{p} \left[ \varepsilon_{s3nt} A_{mr}^{(n)} \cos \omega_{s3nt} t + B_{mr}^{(n)} \sin \omega_{s3nt} t \right] + \varepsilon_{r3nt} C_{mr}^{(n)} \cos \omega_{r3nt} t + D_{mr}^{(n)} \sin \omega_{r3nt} t
\]

\[
+ \varepsilon_{s2p} E_{mr}^{(n)} \cos \omega_{s2pt} t + F_{mr}^{(n)} \sin \omega_{s2pt} t \right) + \varepsilon_{r2p} G_{mr}^{(n)} \cos \omega_{r2pt} t + H_{mr}^{(n)} \sin \omega_{r2pt} t \right] q_r = 0, \quad n = 1, 2, \ldots, L.
\]
where $L = 5 + 2M + N$ and $e_m = k_m^c/k_m^a$. The expressions of coefficient terms $A_{nr}^{(l)}, B_{nr}^{(l)}, C_{nr}^{(l)}, D_{nr}^{(l)}, F_{nr}^{(l)}, G_{nr}^{(l)}$, and $P_{nr}^{(l)}$ are shown in Appendix B.

Using multiscale method, time variables representing different scales are introduced:

$$T_0 = t, \quad T_1 = \epsilon t.$$  

The solution of equation (21) is expressed as

$$q_n(t, \epsilon) = q_{n0}(T_0, T_1) + \epsilon q_{n1}(T_0, T_1), \quad n = 1, 2, \ldots, L.$$  

(23)

Substituting equation (23) into equation (21), collecting terms of the same power in $\epsilon$ on both sides of the equation yields

$$q_n = A_n(T_1)e^{i\omega_n T_0} + \text{cc},$$  

$$D_0^3 q_n + \omega_n^2 q_n = -2i\omega_n e^{i\omega_n t} D_1 A_n$$

$$- 2 \sum_{r=1}^L \sum_{l=1}^\infty \left\{ \frac{\omega_{1r}}{\epsilon} \left( A_{nr}^{(l)} \cos \omega_{1r} t + B_{nr}^{(l)} \sin \omega_{1r} t \right) + \frac{\omega_{2r}}{\epsilon} \left( C_{nr}^{(l)} \cos \omega_{2r} t + D_{nr}^{(l)} \sin \omega_{2r} t \right) + \frac{\omega_{s2}}{\epsilon} \left( E_{nr}^{(l)} \cos \omega_{s2} t + F_{nr}^{(l)} \sin \omega_{s2} t \right) + \frac{\omega_{r2}}{\epsilon} \left( G_{nr}^{(l)} \cos \omega_{r2} t + H_{nr}^{(l)} \sin \omega_{r2} t \right) \right\} q_{r0},$$

where $A_n(T_1)$ is the amplitude in complex form, $\epsilon = \max\{\epsilon_{s1a}, \epsilon_{r1b}, \epsilon_{s2p}, \epsilon_{r2p}\}$, and cc is the complex conjugate of preceding items. Substitution of equation (24) into equation (25) yields

$$D_0^3 q_n + \omega_n^2 q_n = -2i\omega_n e^{i\omega_n t} D_1 A_n - \sum_{r=1}^L \sum_{l=1}^\infty \left\{ \frac{\omega_{1r}}{\epsilon} \left( A_{nr}^{(l)} + iB_{nr}^{(l)} \right) \left( A_{r} e^{i(\omega_{s1a} + \omega_{r1b})t} + \overline{A}_{r} e^{i(-\omega_{s1a} + \omega_{r1b})t} \right) + \frac{\omega_{2r}}{\epsilon} \left( C_{nr}^{(l)} + iD_{nr}^{(l)} \right) \left( A_{r} e^{i(\omega_{s2p} + \omega_{r2p})t} + \overline{A}_{r} e^{i(-\omega_{s2p} + \omega_{r2p})t} \right) + \frac{\omega_{s2}}{\epsilon} \left( E_{nr}^{(l)} + iF_{nr}^{(l)} \right) \left( A_{r} e^{i(\omega_{s2p} + \omega_{r2p})t} + \overline{A}_{r} e^{i(-\omega_{s2p} + \omega_{r2p})t} \right) + \frac{\omega_{r2}}{\epsilon} \left( G_{nr}^{(l)} + iH_{nr}^{(l)} \right) \left( A_{r} e^{i(\omega_{s2p} + \omega_{r2p})t} + \overline{A}_{r} e^{i(-\omega_{s2p} + \omega_{r2p})t} \right) \right\} + \text{cc}.$$

It can be seen from the above that, in addition to the fact that the meshing frequency is close to the natural frequency of the system to excite the main resonance, when the frequency $\omega_n$ is close to the natural frequency combination $\omega_n \pm \omega_r$, there will be a secular term in the equation and an unstable region of parameter vibration in the gear system.

5. Meshing Stiffness Parametric Vibration

The parameters of the coaxial contrarotating encased differential gear train are shown in Table 1. The meshing frequency of each gear pair of the system is [15]
Table 1: Encased differential gear train parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of planets</td>
<td>$M = N = 3$</td>
</tr>
<tr>
<td>Number of teeth</td>
<td>$z_1 = 57$, $z_2 = 54$, $z_3 = 18$, $z_4 = 107$, $z_5 = 38$, $z_p = 25$, $z_{r2} = 88$</td>
</tr>
<tr>
<td>Modulus (mm)</td>
<td>$m_{s1} = 2.75$, $m_1 = 3.5$, $m_{s2} = 4$, $m_{r2} = 4$</td>
</tr>
<tr>
<td>Pressure angle (°)</td>
<td>$\alpha_s = 20$, $\alpha_p = 20$, $\alpha_b = 20$, $\alpha_{s2} = 20$, $\alpha_{r2} = 20$, $\alpha_p = 20$</td>
</tr>
<tr>
<td>Planet mass (kg)</td>
<td>$m_p = 2.156$</td>
</tr>
<tr>
<td>Moment of inertia (kg·m²)</td>
<td>$I_{s1} = 0.0423$, $I_4 = 0.011$, $I_b = 0.00076$, $I_{s1} = 1.1475I_{s2} = 0.0223$, $I_p = 0.0037$, $I_{r2} = 2.059$, $I_{s1} = 0.3413$</td>
</tr>
<tr>
<td>Base radius (mm)</td>
<td>$r_{s1} = 73.62$, $r_{s2} = 69.77$, $r_{s2} = 29.6$, $r_{p1} = 175.96$, $r_{p1} = 71.42$, $r_{p2} = 46.98$, $r_{n2} = 165.39$, $r_{n2} = 126$</td>
</tr>
<tr>
<td>Mesh stiffness $k_{s1}$ (N/m)</td>
<td>$k_{s1} = 4.20 \times 10^6$, $k_{s1} = 3.70 \times 10^8$, $k_{r2p} = 3.53 \times 10^8$, $k_{s2p} = 3.93 \times 10^8$</td>
</tr>
<tr>
<td>Mesh stiffness $k_{s2}$ (N/m)</td>
<td>$k_{s2} = 0.81 \times 10^6$, $k_{s2} = 0.73 \times 10^8$, $k_{r2p} = 0.66 \times 10^8$, $k_{s2p} = 0.71 \times 10^8$</td>
</tr>
<tr>
<td>Torsional stiffness (N·m/rad)</td>
<td>$k_t = 2.4 \times 10^5$, $k_\gamma = 8.6 \times 10^5$, $k_\gamma = 5.7 \times 10^5$</td>
</tr>
<tr>
<td>Damping coefficient</td>
<td>$\xi_{s1} = 0.07$, $\xi_{s2} = 0.075$</td>
</tr>
<tr>
<td>Working pressure angles (°)</td>
<td>$a_{r2p} = 20$, $a_{r2p} = 20$</td>
</tr>
<tr>
<td>Mesh phasing</td>
<td>$\gamma_{s1} = [0, 0, 0]$, $\gamma_{s2} = [0.1246, 0.4579, 0.7913]$, $\gamma_{s2} = [0.1978, 0.8645, 0.5311]$, $\gamma_{s2} = [0.0432, 0.7099, 0.3765]$</td>
</tr>
</tbody>
</table>

Table 2: Natural frequencies for the system (Hz).

<table>
<thead>
<tr>
<th>Order</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>0</td>
<td>473</td>
<td>1167</td>
<td>2246</td>
<td>2246</td>
<td>2300</td>
<td>3117</td>
<td>3356</td>
<td>3356</td>
<td>4015</td>
<td>4490</td>
<td>6413</td>
<td>6413</td>
<td>6439</td>
</tr>
</tbody>
</table>

Figure 3: Dynamic meshing force of gear pair.
Figure 4: Spectrum of meshing forces ($n_{s1} = 4000$ r/min).

Figure 5: Continued.
5.1. Natural Frequency. Natural frequencies of the encased differential gear train are obtained from equation (17), as shown in Table 2. It can be divided into three types according to its multiplicity: eight natural frequencies always have multiplicity 1, two groups of $M-1$ multiples ($f_{1,b_1}f_{n_1}, f_{1,b_1}f_{13}$), and one group of $N-1$ multiples ($f_{1,b_1}f_{n_1}$), which, respectively, correspond to the torsional vibration mode, stepped planet mode, and planet mode of the system. Frequency of 0 represents the rigid body motion of the system, and the magnitude of multiple frequencies is independent of the number of planets [17].

5.2. Dynamic Characteristics of Elastic Meshing Force. The elastic meshing force of gear pair $m$ in the encased differential gear train is expressed as $F_{em}(t) = k_{em}(t) \delta_m$. It is defined that input torque $T_{in} = 1283.5 \text{N\cdot m}$ is constant, and the

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**Figure 5:** Spectrum of meshing forces ($n_{i1} = 3000 \text{ r/min}$).

**Figure 6:** Spectrum of meshing forces ($n_{i1} = 2000 \text{ r/min}$).
output torque $T_{ou1} = T_{ou2} = iT_{in}/2$, where $i$ is the gear system transmission ratio. The Runge-Kutta method is used to solve the numerical solution of the differential equations.

5.2.1. Time-Domain Analysis of Meshing Force. When the torque is constant and the input speed is $n_{s1} = 4000 \text{ r/min}$, the meshing force of gear pairs is shown in Figure 3. It can be seen from the figure that the dynamic meshing force fluctuates around the static meshing force value shown by the dotted line. The meshing force $F_{s1a1}$ fluctuates with its own meshing period. The meshing forces $F_{s1b1}$, $F_{s2p1}$, and $F_{s2p3}$ mainly fluctuate in their own periods, and they also have high-frequency fluctuations of small amplitude. This is caused by the excitation of the time-varying stiffness parameters such as mesh phasing and contact ratio.

5.2.2. Frequency-Domain Analysis of Meshing Force. The frequency spectrum of system meshing force at different input speeds and constant torque is shown in Figures 4–6. It can be seen from the figures that, in addition to the meshing frequency of its own planetary set, the meshing frequency of other planetary sets and natural frequencies $f_2$ and $f_3$ also appear in the meshing force, which indicates that the system has multifrequency coupling vibration.

As shown in Figure 4, when the input speed is $n_{in} = 4000 \text{ r/min}$, the meshing frequency $f_{s1b1}$ appears in the frequency spectrum of the meshing force $F_{s1a1}$ of the encased stage, and the encased stage meshing frequency $f_{1a1}$ appears in the spectrum of differential stage meshing forces $F_{s2p1}$ and $F_{s2p3}$, but there is no differential stage meshing frequency in the encased stage meshing force spectrum, which indicates that the meshing frequency
coupling relationship between the meshing forces of different planetary sets is not equal. As shown in Figures 5 and 6, when the rotating speed is \( n_{in} = 3000 \text{ r/min} \) and \( n_{in} = 2000 \text{ r/min} \), in addition to the above coupling effect, there is also coupling of differential stage meshing frequency in the encased stage meshing force spectrum.

This is because the torsional internal force of the connecting shaft couples the vibration displacements of different frequencies together and then acts on the two connected parts in the form of acting force and reaction force, respectively. The connected coupling parts will return back the vibration displacement with new frequency to the meshing force of the planetary set in the form of equivalent meshing line deformation, resulting in the intercoupling between the meshing forces of different planetary sets [18].

5.3. Analysis of the Dynamic Load Characteristics. In the compound planetary gear transmission, different meshing states will cause difference between the multiple external and internal meshing forces of the same planetary set and will also form the different dynamic characteristics of the meshing forces of each planetary set. In this paper, the dynamic load factor is used to evaluate the dynamic characteristics of meshing forces.

The dynamic load factor \( G_m \) is the ratio of the maximum dynamic load to the static load on the gear teeth during a meshing period; that is [19],

\[
G_m = \max \left( \frac{F_m(t)}{F_m^s} \right), \quad (28)
\]

where \( F_m^s \) is the static meshing force.

It can be seen from Figure 7 that, in the range of the speed variation, the dynamic load factor of the gear pair \( s1ai \) is significantly larger than that of other meshing pairs, which is because the gear pair \( s1ai \) is a high-speed gear train and its vibration is relatively severe. The load distribution among the planets in each planetary set of the system is very uniform.

According to Figures 7(a) and 7(b), the system has a strong main resonance response when the meshing frequency \( f_{s1ai} \) is close to the natural frequency \( f_2 \), and the dynamic load factors \( G_{s1ai} \) and \( G_{r1b} \) of the encased stage gear pair are very large. Due to the time-varying meshing stiffness, the meshing frequency \( f_{s1ai} \) causes the superharmonic responses and 1/2 subharmonic response of the encased stage, and the meshing frequencies \( f_{r1b} \) and \( f_{2p1} \) also cause the superharmonic responses.

From Figures 7(c) and 7(d), in addition to the main resonance response, superharmonic response, and sub-harmonic response, the dynamic load factor of the differential stage also peaks at \( f_{2p1} = f_2 + f_3 \), corresponding to the combined resonance of the additive type.

6. Conclusions

In this paper, the torsional dynamic characteristics of the coaxial contrarotating encased differential gear system are studied, and the natural frequency of the system is obtained. The time-domain and frequency-domain characteristics of the elastic meshing force are analyzed, and the variation of dynamic load factor with the input rotating speed is studied.

(1) Natural frequencies of the encased differential gear train can be divided into 3 types according to its multiplicity, which correspond to the torsional vibration mode, stepped planet mode, and planet mode.

(2) The dynamic meshing force fluctuates around the static meshing force value. The meshing force of the gear pair \( s1ai \) fluctuates with its own meshing period. The meshing forces of gear pairs \( s1b1, s2p1, \) and \( r2p1 \) fluctuate mainly in their own periods, and they also have high-frequency fluctuations of small amplitude.

(3) In addition to the meshing frequency of its own planetary set, the meshing force spectrum also includes the meshing frequency of other planetary sets and the natural frequency of the system.

(4) The dynamic load factor of the gear pair \( s1ai \) is significantly larger than those of the other meshing pairs. The dynamic load factor of the gear pair of the system peaks not only at the main resonance response but also at the superharmonic response, subharmonic response, and combined resonance response.
Appendix

A. Expression of Dynamic Parameter Matrix

\[
M = \text{diag}\left[ \frac{I_{s1}}{r_{b1}}, \frac{I_{s2}}{r_{b2}}, \frac{I_{r1}}{r_{br1}}, \frac{I_{r2}}{r_{br2}}, \frac{I_{c1} + NI_{p}}{r_{c1}}, \frac{I_{aM}}{r_{ba}}, \frac{I_{bM}}{r_{bb}}, \ldots, \frac{I_{p1}}{r_{bp1}}, \ldots, \frac{I_{p1}}{r_{bp}} \right],
\]

\[
Q = \begin{bmatrix} T_{in} & 0 & 0 & -\frac{T_{ou1}}{r_{br2}} & \frac{T_{ou2}}{r_{c2}} & \frac{M}{M} & \ldots & 0 & 0 & 0 & \ldots & 0 \\ \frac{M}{r_{b1}} & 0 & 0 & 0 & 0 & 0 & \ldots & 0 & 0 & 0 & \ldots & 0 \end{bmatrix}^T,
\]

\[
K = [K_1, K_2],
\]

\[
K_1 = \begin{bmatrix} \sum_{i=1}^{M} k_{s1ai} + \frac{k_s}{r_{b1}r_{b2}} & -\frac{k_s}{r_{b1}r_{b2}} & 0 & 0 & 0 \\ -\frac{k_s}{r_{b1}r_{b2}} & \sum_{j=1}^{N} k_{s2pj} + \frac{k_s}{r_{b2}} & 0 & 0 & -\sum_{j=1}^{N} k_{s2pj} \cos \alpha'_{s2p} \\ 0 & 0 & \sum_{i=1}^{M} k_{r1bi} + \frac{k_r}{r_{br1}r_{br2}} & -\frac{k_r}{r_{br1}r_{br2}} & 0 \\ 0 & 0 & \frac{k_r}{r_{br1}r_{br2}} & \sum_{j=1}^{N} k_{r2pj} & \sum_{j=1}^{N} k_{s2pj} \cos \alpha'_{s2p} \\ 0 & -\sum_{j=1}^{N} k_{s2pj} \cos \alpha'_{s2p} & 0 & \sum_{j=1}^{N} k_{r2pj} \cos \alpha'_{s2p} & \sum_{j=1}^{N} (k_{s2pj} \cos \alpha'_{s2p} + k_{r2pj} \cos \alpha'_{r2p}) \end{bmatrix},
\]
B. Expression of Coefficient Term

\[
\begin{align*}
A_{nr}^{(l)} &= \sum_{i=1}^{M} k_{s_{1a}a} a_{s_{1a}a}^{(n)} g_{s_{1a}a}^{(r)} \delta_{s_{1a}a}^{(r)}, \\
B_{nr}^{(l)} &= \sum_{i=1}^{M} k_{r_{1b}a} b_{r_{1b}a}^{(n)} g_{r_{1b}a}^{(r)} \delta_{r_{1b}a}^{(r)}, \\
C_{nr}^{(l)} &= \sum_{i=1}^{M} k_{s_{1b}r} a_{s_{1b}r}^{(n)} g_{s_{1b}r}^{(r)} \delta_{s_{1b}r}^{(r)}, \\
D_{nr}^{(l)} &= \sum_{i=1}^{M} k_{r_{1b}r} b_{r_{1b}r}^{(n)} g_{r_{1b}r}^{(r)} \delta_{r_{1b}r}^{(r)}, \\
E_{nr}^{(l)} &= \sum_{j=1}^{N} k_{s_{2p}p} a_{s_{2p}p}^{(n)} g_{s_{2p}p}^{(r)} \delta_{s_{2p}p}^{(r)}, \\
F_{nr}^{(l)} &= \sum_{j=1}^{N} k_{s_{2p}p} b_{s_{2p}p}^{(n)} g_{s_{2p}p}^{(r)} \delta_{s_{2p}p}^{(r)}, \\
G_{nr}^{(l)} &= \sum_{j=1}^{N} k_{s_{2p}p} a_{s_{2p}p}^{(n)} g_{s_{2p}p}^{(r)} \delta_{s_{2p}p}^{(r)}, \\
H_{nr}^{(l)} &= \sum_{j=1}^{N} k_{s_{2p}p} b_{s_{2p}p}^{(n)} g_{s_{2p}p}^{(r)} \delta_{s_{2p}p}^{(r)}, \\
K_2 &= \begin{bmatrix}
-k_{s_{1a}l} & \cdots & -k_{s_{1a}M} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{s_{2p}1} & \cdots & -k_{s_{2p}N} \\
0 & 0 & 0 & -k_{r_{1b}l} & \cdots & -k_{r_{1b}M} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -k_{r_{2p}1} & \cdots & -k_{r_{2p}N} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\end{align*}
\]

(A.1)

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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