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ORIGINAL ARTICLE

Load Sharing Behavior of Star Gearing Reducer for Geared Turbofan Engine

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Abstract Load sharing behavior is very important for power-split gearing system, star gearing reducer as a new type and special transmission system can be used in many industry fields. However, there is few literature regarding the key multiple-split load sharing issue in main gearbox used in new type geared turbofan engine. Further mechanism analysis are made on load sharing behavior among star gears of star gearing reducer for geared turbofan engine. Comprehensive meshing error analysis are conducted on eccentricity error, gear thickness error, base pitch error, assembly error, and bearing error of star gearing reducer respectively. Floating meshing error resulting from meshing clearance variation caused by the simultaneous floating of sun gear and annular gear are taken into account. A refined mathematical model for load sharing coefficient calculation is established in consideration of different meshing stiffness and supporting stiffness for components. The regular curves of load sharing coefficient under the influence of interactions, single action and single variation of various component errors are obtained. The accurate sensitivity of load sharing coefficient toward different errors is mastered. The load sharing coefficient of star gearing reducer is 1.033 and the maximum meshing force in gear tooth is about 3010 N. This paper provides scientific theory evidences for optimal parameter design and proper tolerance distribution in advanced development and manufacturing process, so as to achieve optimal effects in economy and technology.

Keywords Geared turbofan engine · GTF engine · Aero-turbofan engine · Star gearing reducer · Load sharing behavior

1 Introduction

Gear and gearing system are most important objects in mechnical enginerring, so many scholars from both home and abroad have been constantly exploring and studying many different type gearing transmission systems, and many important research findings are as followed. HIDAKA T, et al. of Japan studied the relationship between error and load sharing, built a model for processing manufacture errors and assemble errors, almost the first time reveal the scientific problem behind the load distribution uniformity, which is commonly used by many scholars [1, 2]. MA P, et al. probed into the effects of gear errors on planetary gear transmission system, especially focusing on eccentricity error and misalignment, revealed some internal properties between different type errors and load sharing coefficient(LSC) [3]. National Aeronautics and Space Administration(NASA) of American has studied some new type power-split gear transmission systems of helicopter and aero-engine for many years, developed many advanced gearing transmission technology. KRANTZ T L, et al. of NASA discussed the characteristics

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of load sharing for two path power-split transmission [4, 5]. KAHRAMAN A, et al. of Ohio State University in American continuously explored characteristics of load sharing and meshing errors for planetary transmission from the perspective of statics, obtained numerous important academic results and also got some classical and useful conclusions [6–9]. SINGH A established the analysis model on characteristics of load sharing for planetary gear transmission and gave physical explanation. Compared with traditional ones built before, this model is much refined, considering more factors and using generalized formulation to describe the system [10, 11]. CARLOS H W, et al. elaborated the solutions to meshing force, which can be precisely used in calculating the meshing force action on gear tooth in both internal gear pair and external gear pair, and also very useful for calculating LSC and studying the load sharing behavior [12]. ZHU Rupeng, et al. of Nanjing University of Aeronautics and Astronautics in China did many research works in gear transmssion system, discussed the characteristics of load sharing for planetary and encased differential herringbone gearing systems, worked on load sharing of power-split gearing system, especially for helicopter gearbox and aero-engine [13, 14]. FANG Zongde, et al. of Northwestern Polytechnical University studied the LSC of planetary and two-way power-split gear system for many years, developed a new method to calculated LSC, which involved deformation compatibility of the power-split gear system [15]. LIU Geng, BU Zhonghong, et al. of Northwestern Polytechnical University proposed a new modal analysis method for planetary gearing system with journal bearings, and also considering the supporting stiffness of sliding bearing, proposed a dynamic model of planetary gearing system in energy method [16]. CHEN Binkui, et al. of Chongqin University conducted a further research on many types of planetary gearing system, especially in double enveloping cycloid drive and obtained many useful conclusions [17].

Since star gearing system has many special advantages, so the newest geared turbofan (GTF) engine in the world adopts star gearing reducer as its main transmission system which is expected to be full-time life without any additional maintenance outside normal maintenance periods [18]. MATSUMURA S, HOUJOH H, et al. of Tokyo Institute of Technology in Japan have done much groundbreaking research work in gear dynamic and noise, mostly using different kinds of transmission experiments to investigate the dynamic, lubrication and noise characteristic of gearing system [19, 20]. WU Qiong, et al. deduced a new staging white noise mathematical model according launch environment, the model si applied for pseudo excitation method to calculate the specific structure of time flight counter [21]. MO Shuai, et al. of Beihang University focusing on different types of gear transmission, developed a load sharing model based on transmission error and multiple meshing error, and also put forward a precisely modeling method for spiral bevel gear considering machine adjustment parameters [22–24].

All these researches had important effects on planetary gearing trains, but targeted other transmission types and focused on different key points. Most of the models established did not consider meshing clearance variation caused by the simultaneous floating of center gears, tooth thickness error, base pitch error, and bearing error. To the best knowledge of the authors, up to now few published papers are available on the characteristics of load sharing for star gearing reducer in GTF aero-turbofan engine. This paper established a refined model of LSC, in consideration of multiple gear manufacturing errors(eccentricity error, gear thickness error, base pitch error), assembly error, bearing manufacturing errors, and meshing clearance variation caused by the simultaneous floating of center gears. The research findings can provide scientific theoretical basis for the LSC identification, tolerance control, as well as gear machining and assembly of star gearing reducer for GTF aero-engine.

2 Star Gearing Reducer of GTF Engine

As a new type engine, GTF engine has low emissions, low noise, low fuel consumption and low maintenance costs recognized by market and technology, Pratt & Whitney company thinks it will become the next generation commercial aero-engine. GTF engine in China belongs to predevelopment stage. Fan drive gear system (FDGS) is the most complicated difference between ordinary turbofan engine and GTF engine, and load sharing design is one of the key technologies for GTF engine, for FDGS in particular.

Figure 1 illustrates the 3D model of GTF engine, which is so far the most advanced and newest engine in the world [18]. The diagram of star gearing reducer for GTF engine is shown in Fig. 2. Star gearing reducer is the core part in newest engine and also is a new transmission type. Sun gear is the input shaft, angular gear is the output shaft,

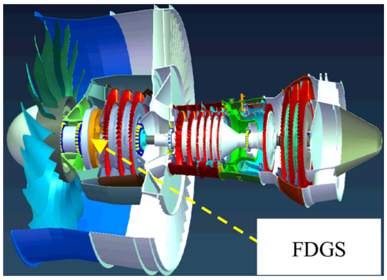

Fig. 1 Geared turbofan (GTF) engine

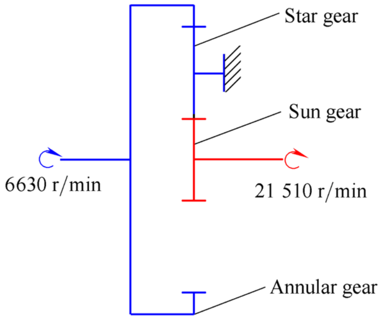

Fig. 2 Kinematic diagram for star gearing reducer

carrier is fixed, and the support function of carrier is integrated in the housing of reducer. However, in tradition 2K-H(NGW) planetary gear transmission system, angular gear is fixed and carrier is the output shaft.

The parameters of the star gearing reducer are as below, $Z_S = 32$, $Z_P = 35$, $Z_I = 103$. Module of gear is 2.12 mm, the input speed is 21 510 r/min, output speed is 6630 r/min, and the input power is 641 kW. In star gearing reducer, center gears (sun gear, annular gear) usually worked as the floating component in engineering.

3 Equivalent Mesh Error in Meshing Line

E and A are manufacture error and assembly error; β and γ are directions of manufacture error and assembly error; ω_S, ω_P and ω_I are the angular velocities of sun gear, star gear, and annular gear respectively; α_w and α_n are working pressure angles for external gearing and internal gearing; ϕ_i refers to the position angle for star gear i to the first star gear. In $\phi_i = 2\pi(i-1)/n$, n stands for the number of star gears; t indicates time; ε_t is gear thickness; ε_{bp} shows base pitch error. Subscripts S, Pi and I refer to sun gear, star gear i and annular gear.

3.1 Meshing Error Caused by Manufacturing Error

Make an equivalent meshing error analysis in meshing line, and define equivalent meshing error deviating from meshing line is positive. Manufacture errors which affect load distribution of star gear mainly include eccentricity error, tooth thickness error, base pitch error, and bearing error.

Equivalent meshing error in meshing line is caused by eccentricity error of gears:

$$\begin{cases} e_{EIi} = E_I \sin(-\omega_I t + \beta_I - \alpha_n - \phi_i), \\ e_{EPiI} = E_{Pi} \sin(-\omega_P t + \beta_{Pi} - \alpha_n), \\ e_{ESi} = -E_S \sin(\omega_S t + \beta_S + \alpha_w - \phi_i), \\ e_{ESPi} = -E_{Pi} \sin(-\omega_P t + \beta_{Pi} + \alpha_w). \end{cases} \tag{1}$$

Equivalent meshing error in meshing line is caused by eccentricity error of bearings:

$$\begin{cases} e_{EbIi} = E_{bI} \sin(-\omega_I t + \beta_I - \alpha_n - \phi_i), \\ e_{EbPiI} = E_{bPi} \sin(-\omega_P t + \beta_{Pi} - \alpha_n), \\ e_{EbSi} = -E_{bS} \sin(\omega_S t + \beta_S + \alpha_w - \phi_i), \\ e_{EbSPi} = -E_{bPi} \sin(-\omega_P t + \beta_{Pi} + \alpha_w). \end{cases} \tag{2}$$

Equivalent meshing error in meshing line is caused by base pitch error and thickness error of gears:

$$\begin{cases} \varepsilon_{bpS} = E_{bpS}, \\ \varepsilon_{bpPi} = E_{bpPi}, \\ \varepsilon_{bpI} = E_{bpI}, \\ \varepsilon_{tS} = E_{tS}, \\ \varepsilon_{tPi} = E_{tPi}, \\ \varepsilon_{tI} = E_{tI}. \end{cases} \tag{3}$$

3.2 Meshing Error Caused by Assembly Error

Assembly errors come from sun gear, star gear, and annular gear. Equivalent meshing error in meshing line is caused by assembly error of gears:

$$\begin{cases} e_{AIi} = A_I \sin(\gamma_I - \alpha_n - \phi_i), \\ e_{APiI} = A_{Pi} \sin(\gamma_{Pi} - \alpha_n), \\ e_{ASi} = -A_S \sin(\gamma_S + \alpha_w - \phi_i), \\ e_{ASPi} = -A_{Pi} \sin(\gamma_{Pi} + \alpha_w). \end{cases} \tag{4}$$

3.3 Meshing Error Caused by Floating Error

v_{Si} is the variation in meshing backlash caused by sun gear floating; v_{Ii} is the variation in meshing backlash caused by annular gear floating; x_S and y_S are displacements of the center for sun gear in x and y directions; x_I and y_I are displacements of the center for annular gear in x and y directions. A_i is direction angle in meshing line between sun gear and star gear i, and B_i is direction angle in meshing line between star gear i and annular gear:

$$\begin{cases} v_{Si} = -(x_S \cos A_i + y_S \sin A_i), \\ v_{Ii} = -(x_I \cos B_i + y_I \sin B_i), \\ A_i = \pi/2 - \alpha_w + \phi_i \quad (i = 1, 2, \cdots, n), \\ B_i = \pi/2 + \alpha_n + \phi_i \quad (i = 1, 2, \cdots, n). \end{cases} \tag{5}$$

3.4 Comprehensive Meshing Error

e_{SPi} and e_{PiI} are cumulate equivalent meshing error for different kinds of manufacture error and assembly error. Composition meshing errors are derived from the superposition of cumulate equivalent meshing error and equivalent meshing error caused by floating error.

$$\begin{cases} e_{SPi} = e_{ESi} + e_{ASi} + e_{EbSi} + e_{ESPi} + e_{ASPi} \\ \qquad + e_{EbSPi} + \varepsilon_{bpS} + \varepsilon_{bpPi} + \varepsilon_{tS} + \varepsilon_{tPi}, \\ e_{PiI} = e_{EIi} + e_{AIi} + e_{EbIi} + e_{EPiI} + e_{APiI} \\ \qquad + e_{EbPiI} + \varepsilon_{bpI} + \varepsilon_{bpPi} + \varepsilon_{tI} + \varepsilon_{tPi}. \end{cases} \tag{6}$$

Comprehensive meshing error between sun gear and star gear i is u_{SPi}, and comprehensive meshing error between star gear i and annular gear is u_{PiI}.

$$\begin{cases} u_{SPi} = e_{SPi} + v_{Si}, \\ u_{PiI} = e_{PiI} + v_{Ii}. \end{cases} \tag{7}$$

4 Calculation Model of Load Sharing

Figure 3 displays the calculation model of LSC for reducer, with sun gear and annular gear as floating components, ignoring the little floating in axial z, and assuming that the center of star gear 1 is on the axial x. Using equivalent stiffness as the elastic deformation in mesh pair, revolute pair and support pair; K_{SP} and K_{PI} are the mesh stiffness for S-Pi and Pi-I meshing pair; K_S and K_I are the support stiffness for sun gear and annular gear. Meshing force between sun gear and star gear i is F_{SPi}, and that between star gear i and annular gear is F_{PiI}. r_{bS} and r_{bP} are the base radials for sun gear and star gear. T is the input torque; W_{Pi} is the LSC for star gear i; and W_P is the LSC for reducer.

Static and dynamic models can be both used to study the LSC of gearing system, but precise dynamic model needs to consider damping, which is very difficult to accurately confirmed in conceptual phase of GTF engine. The process to obtain really time-varying stiffness is complicated and tedious. Time-varying mesh stiffness approximates to rectangular wave function, and most of the time in one cycle approximates to stable value. Thus, variation is not very big. So in the statics research, adopting equivalent stiffness can satisfy calculation accuracy, and compared with dynamic model. This method is relatively simple with small amount of calculation and fast solution speed, which can be used as a fast solving method for conceptual design.

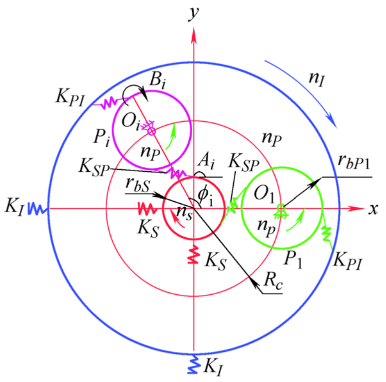

Fig. 3 Calculation model of LSC

Meshing force in the S-Pi and Pi-I gear meshing pair is

$$\begin{cases} F_{SPi} = K_{SP}(r_{bS}\theta_S - r_{bP}\theta_{Pi} - u_{SPi}), \\ F_{PiI} = K_{PI}(r_{bP}\theta_{Pi} - u_{PiI}). \end{cases} \tag{8}$$

Equation of static equilibrium for sun gear is

$$T - r_{bS}\sum_{i=1}^{n} F_{SPi} = 0. \tag{9}$$

Equations of static equilibrium for star gear is

$$F_{SPi} - F_{PiI} = 0 \quad (i = 1, 2, \cdots, n). \tag{10}$$

Some equations of static equilibrium are caused by the simultaneous floating of sun gear and annular gear:

$$\begin{cases} \sum_{i=1}^{n} F_{SPi}\cos A_i + K_S x_S = 0, \\ \sum_{i=1}^{n} F_{SPi}\sin A_i + K_S y_S = 0, \\ \sum_{i=1}^{n} F_{PiI}\cos B_i + K_I x_I = 0, \\ \sum_{i=1}^{n} F_{PiI}\sin B_i + K_I y_I = 0. \end{cases} \tag{11}$$

The LSC of star gear and reducer are given as below:

$$\begin{cases} W_{Pi} = F_{SPi} n r_{bS}/T \quad (i = 1, 2, \cdots, n), \\ W_P = \max(W_{Pi}). \end{cases} \tag{12}$$

At the instant startup of gearing system, assume the resistant torque on the output shaft is big enough, so annular gear can be regard as stationary. Input torque is gradually applied to sun gear, so one of the n star gears will first enter meshing during loading process. Due to manufacture error, assemble error and floating error, backlashes exist between the n-1 star gears and sun gear. The meshing pair and support pair began deformation with the increasing of input torque, and the deformation will make the former backlashes disappear gradually. When the input torque equals to rated toque, the backlashes will disappeared and the star gears are all in working state. The deformations in meshing pair and support pair result in micro rotation angle θ_S in sun gear and micro rotation angle θ_{Pi} in star gear i during these loading process.

5 Load Sharing Characteristics (LSC)

5.1 Co-Effects of Component Errors

Referring to the error of position to ideal center form and location tolerance (GB1182-1184-80), phase position is 15’, the assembly error and manufacturing error are 6 μm respectively, and gear thickness error and base pitch error are also 6 μm. Based on the above design parameters, manufacturing error and assembly error, the LSC of the star gearing reducer is shown in Fig. 4. Load of F_{SPi} and F_{PiI} change as in Fig. 5. LSC of star gears change at regular intervals. $W_{P1} = 1.0206$, $W_{P2} = 1.033\ 1$, $W_{P3} = 1.011\ 7$ for each star gear; coefficient for the reducer is $W_P = 1.033\ 1$.

5.2 Single Action of Each Error

In order to study the single action of each error (removing other errors) on LSC for reducer, Fig. 6 to Fig. 11 show changes of LSC under the single action of each error and detailed values refer to Table 1 and Table 2.

LSC will change in different cycles under single effect of gear eccentricity error and bearing manufacture error. Eccentricity error and bearing manufacture error affect the coefficient in the same way. Single actions of E_I and E_{bI}, which belong to dynamic error, lead to the longest cycle for LSC respectively. Eccentricity error of sun gear, annular gear and their bearing manufacturing error have a notable influence on LSC. LSC in Fig. 6 is 1.014 4 and the same in Fig. 7, but the oscillation periods of LSC are not the same. Eccentricity error of star gear has smaller influence on LSC, which is 1.0064 in Fig. 8.

While single actions of assembly error, base pitch error and gear thickness error; which belong to static error, all keep LSC unchanged with time. Gear thickness error and base pitch error exert the same influence on system LSC.

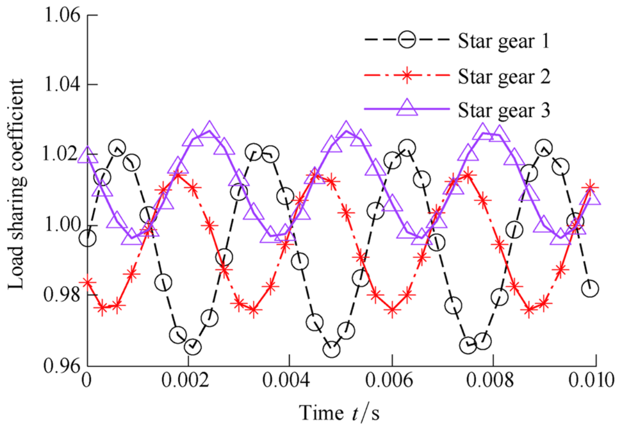

Fig. 4 Variation of W_P under the action of all errors

As the influence of assembly errors to LSC, the influence of A_I, A_{Pi}, and A_S to LSC are from strong to weak. The LSC of A_S in Fig. 9 is 1.0042, the LSC of A_{Pi} in Fig. 10 is 1.0062, and the LSC of A_I in Fig. 11 is 1.0073.

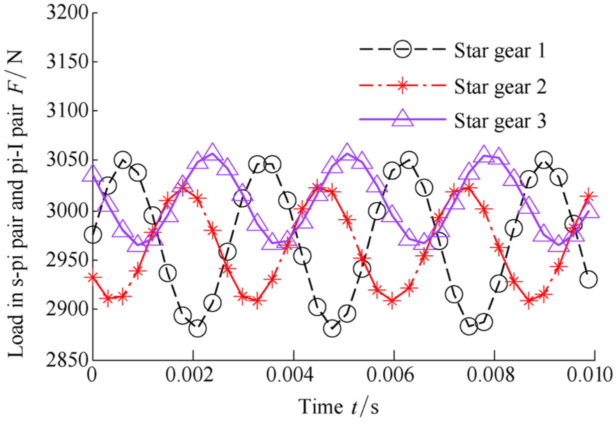

Fig. 5 Variation of F_{SPi} and F_{PiI} under the action of all errors

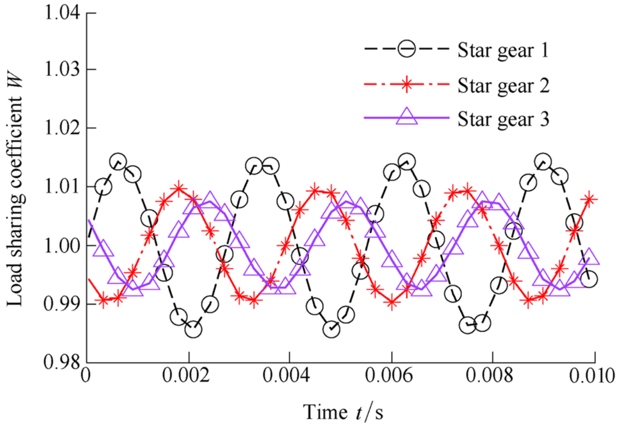

Fig. 6 Single action of E_S (eccentricity error of sun gear)

Table 1 LSC (under single action of dynamic error)

	E_S	E_{bS}	E_{Pi}	E_{bPi}	E_I	E_{bI}
W_{P1}	1.014	1.014	1.006	1.006	1.014	1.014
W_{P2}	1.010	1.010	1.004	1.004	1.010	1.010
W_{P3}	1.008	1.008	1.002	1.002	1.008	1.008
W_P	1.014	1.014	1.006	1.006	1.014	1.014

Table 2 LSC (under single action of static error)

	A_S	A_{Pi}	A_I	ε_{tS}	ε_{tPi}	ε_{tI}
W_{P1}	1.001	1.006	0.992	0.981	0.995	1.013
W_{P2}	0.994	0.996	1.001	1.013	1.009	0.997
W_{P3}	1.004	0.998	1.007	1.006	0.996	0.990
W_P	1.004	1.006	1.007	1.013	1.009	1.013

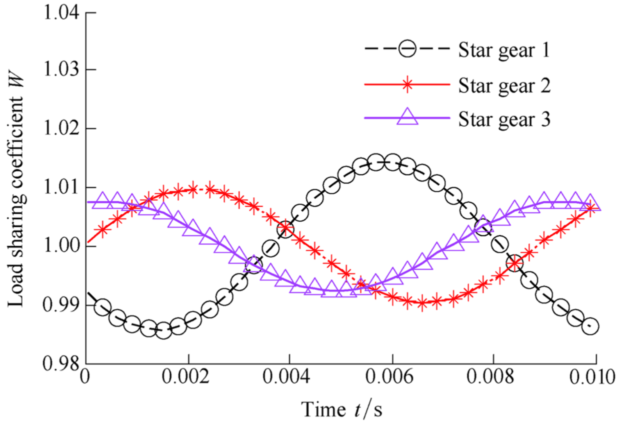

Fig. 7 Single action of E_I (eccentricity error of annular gear)

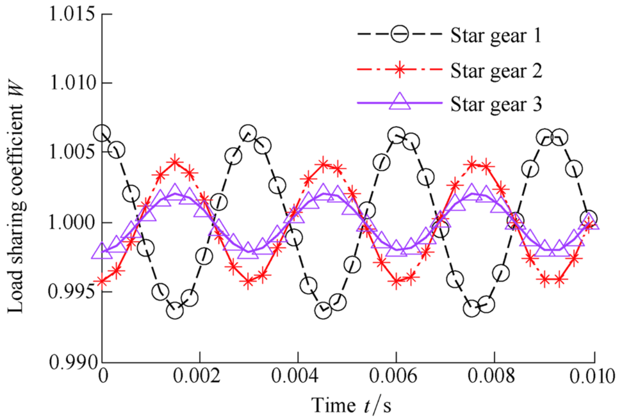

Fig. 8 Single action of E_{Pi} (eccentricity error of star gear)

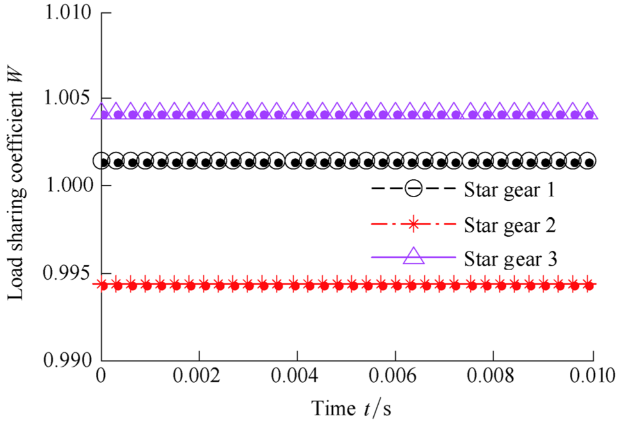

Fig. 9 Single action of A_S (assembly error of sun gear)

5.3 Single Variation of Each Error

To study the influence of single error's variation(keep other errors constant) on LSC for the system, Fig. 12, Fig. 13 and Fig. 14 show the changes of LSC under the single variation of each error.

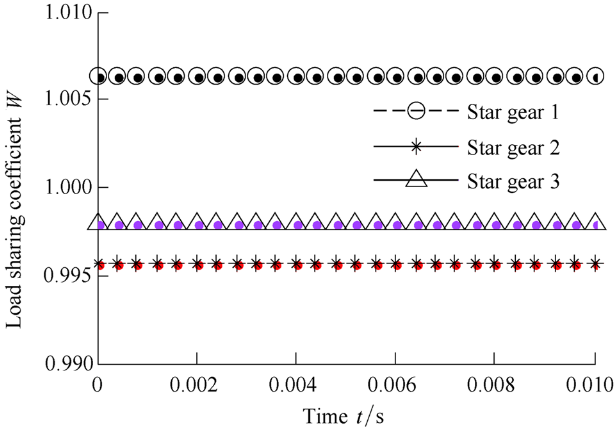

Fig. 10 Single action of A_{Pi} (assembly error of star gear)

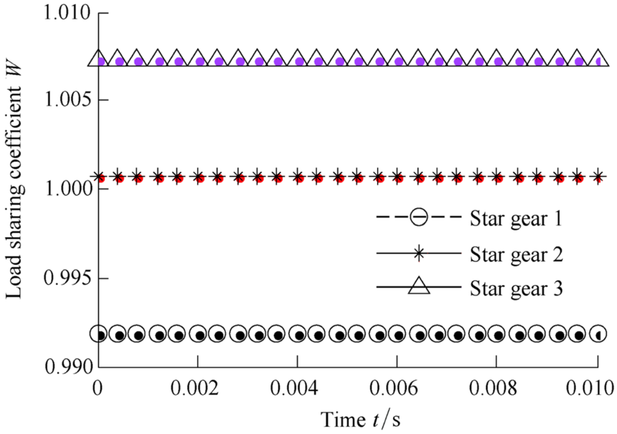

Fig. 11 Single action of A_I (assembly error of angular gear)

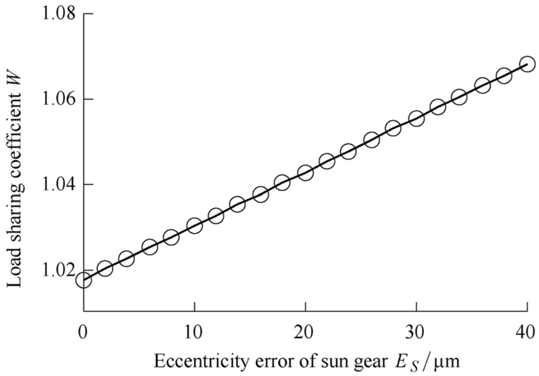

Fig. 12 Single variation of E_S (eccentricity error of sun gear)

For most types of errors, LSC of the system gradually grows with error value increasing and they are in evident positive correlation. The slope of line reflects the sensitivity between LSC and errors. But for ε_{tS}, ε_{tI}, ε_{bpS}, and ε_{bpI}; these type of errors, which varied independently, have a little influence on LSC. Because these types of errors all belong to center gears (sun gear, annular gear), during the

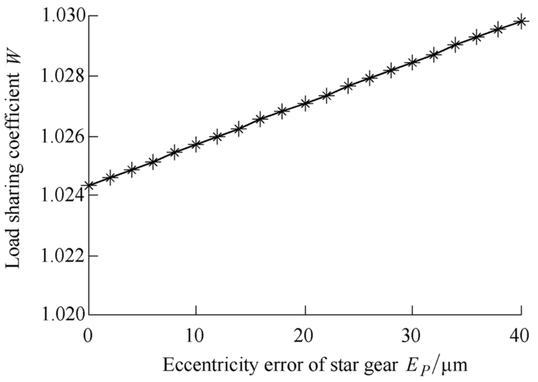

Fig. 13 Single variation of E_P (eccentricity error of star gear)

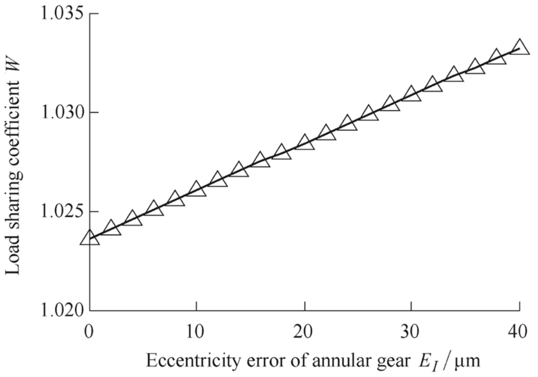

Fig. 14 Single variation of E_I (eccentricity error of angular gear)

rotating, their will have the some influence on all star gears, instead of one star gear. In addition, these errors all have no nothing to do with time and phase in mathematical expression. LSC is highly sensitive to A_I, E_S, E_{bS}, ε_{tPi}, and ε_{bpPi}. In order to weaken their influence on system LSC, the five types of errors should be minimized.

6 Conclusions

(1) Without regard for dynamic load factor, gear thickness error, base pitch error and assembly error all belong to static errors, which only change load distribution of star gears. Under the fixed distribution ratio, the load and LSC of various star gears will not change with time.

(2) Gear eccentricity error and bearing manufacturing error belong to dynamic errors, which change not only load distribution of various gears, but also the distribution ratio. Therefore, the load and LSC of star gears will change with time according to varied circles.

(3) LSC of system and most of the component errors are directly related. LSC of star gearing reducer is sensitive to the eccentricity error and bearing manufacturing error of sun gear and annular gear, assembly error of annular gear, tooth thickness error and base pitch error of star gear. The above errors should thus be controlled.

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