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Performance Margin Modeling and Reliability Analysis for Harmonic Reducer Considering Multi-Source Uncertainties and Wear

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ABSTRACT The harmonic reducer of the space drive mechanism is one of the critical components of the satellite remote sensing system and its reliability is always required strictly in practice. During the manufacturing and usage processes of the harmonic reducer, uncertainties are ubiquitous and performance degradation is inevitable, which is mainly caused by the wear between the meshed tooth surfaces. They influence the reliability of harmonic reducer. In this paper, a performance margin modeling and reliability analysis for harmonic reducer considering multi-source uncertainties and wear is proposed. Firstly, based on the functional principle and the influence of wear, the performance margin model is established using hysteresis and transmission errors as key performance parameters. Then multi-source uncertainties are analyzed and quantified, including manufacturing errors, uncertainties in operational and environmental conditions, and uncertainties in performance thresholds. Finally, the reliability model is constructed based on the performance margin. A case study of a harmonic reducer is applied and the reliability sensitivity analysis is implemented to show the practicability of the proposed method. The results show that the proposed method can provide some suggestions to the design and manufacturing phases of the harmonic reducer.

INDEX TERMS Performance margin, reliability, harmonic reducer, uncertainty quantification, wear.

NOTATION

B	Hysteresis error of the harmonic reducer
m	Module of the gear
Z_G	Number of the Circular Spline teeth
J_I	Circumferential backlash of the gear pair
$J_I(E_M)$	Backlash caused by the gear tooth-thickness deviation
α	Pressure angle of the gear
E_M	Measurement error of the gauge pin distance
$J_I(\Delta e)$	Backlash caused by the center pitch error of gears
Δe	Center pitch error of the gears
φ	Transmission error of the harmonic reducer
$\Delta T_{\Sigma K}$	Composite error of the circular spline
ΔF_t	Coaxial error of the gear pair

ΔF_r	Radial runout of the gear
Δf_{pb}	Basic pitch deviation of the gear
$\Delta \rho_n$	Radial error of the wave generator
d_R	Reference diameter of the flex spline
ω_0	Max radial deformation quantity of the flex spline
z_{Σ}	Number of the meshed gear teeth
K_B	Coefficient of the measurement error
u	Wave number of the wave generator
i	Transmission ratio
e_1	Radial circle run-out of the hole
e_2	Radial circle run-out of the shaft
e_3	Radial error in the major axis of the wave generator
e_4	Radial circle run-out of the flexible bearing
e_5	Radial backlash of the flexible bearing
b	Tooth width of the harmonic gear
h_0	Tooth thickness of the harmonic gear

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b_z	Width of the flexible bearing
$W(t)$	Accumulated wear amount with time
a	Wear rate
ξ	Wear amount during the running phase
N	Number of Monte Carlo simulation
$R_B(t)$	Reliability of hysteresis error
$R_\varphi(t)$	Reliability of transmission error
$R(t)$	Reliability of harmonic reducer

I. INTRODUCTION

The harmonic reducer is one of the important components in the space drive mechanism. It can provide high transmission accuracy and support a high ratio reduction compared with traditional gearing systems such as helical gears or planetary gears [1]. In order to make harmonic reducers operate with high transmission accuracy and stability, it is usually required with excellent transmission characteristics in practical applications, among which the hysteresis and transmission errors are usually selected as two key performance parameters of transmission. Large hysteresis errors and transmission errors can cause the unbalanced rotation, shocks and short-term output interrupt during the operation of harmonic reducers, and further affect the function of the space drive mechanism [2]. During the long-time operation of harmonic reducers, hysteresis errors and transmission errors degrade due to the increase in the backlashes between tooth surfaces caused by the accumulated wear damage, and further, the reliability of harmonic reducers degrades. Meanwhile, the uncertainties during the manufacturing and usage processes of the harmonic reducer are various and inevitable, which also affect the reliability of harmonic reducers. In order to guarantee the harmonic reducer to operate with high transmission accuracy and stability, it is necessary to model its reliability based on its functional principles under the consideration of wear and multi-source uncertainties.

A. LITERATURE REVIEW

The harmonic reducer is composed of a circular spline, a flexspline, and a wave generator. The motion of harmonic reducer is based on elastic dynamics and utilizes the flexibility of metal. In the manufacturing process of the harmonic reducer, manufacturing errors inevitably exist in each part, which causes hysteresis and transmission errors during the movement of the harmonic reducer. Many scholars have modeled the hysteresis and transmission errors of harmonic reducers from the perspective of errors in the manufacturing process. Zhao *et al.* [3] considered the harmonic hysteresis phenomenon and established a dynamical model for the hysteresis error of a harmonic reducer in a space manipulator according to its structure. Zhang *et al.* [4] presented a new approach to model the hysteresis behavior in harmonic drives derived by the compliance behavior of the flexspline and the wave generator. Gravagno *et al.* [5] discussed the influence of the wave generator shape on the pure transmission error of a harmonic reducer and evaluated its transmission error

quantitatively. Yamamoto *et al.* [6] focused on the positioning performance of harmonic drive gearings and investigated the effects of the synchronous component on the transmission error. H. D. Taghirad and P. Be'linger [7] proposed linear and nonlinear regression models for hysteresis errors of harmonic drives considering friction and estimated the model parameters by using a least-squares approximation. Tong *et al.* [8] analyzed the harmonic transmission mechanism according to the thin shell elastics deformation theory and gave a transmission error model of the harmonic reducer considering gear backlashes and stiffness. Sha and Fan [9] proposed a transmission error model for a harmonic drive according to the analysis of the instantaneous transmission ratio, manufacturing and installation errors, and backlashes. In the current research, most of the research focuses on the construction of theoretical models for the hysteresis and transmission errors of harmonic reducers, seldom taking the uncertainties in the manufacturing and usage phases into account.

In the long-term operation of the harmonic reducer, the backlashes between the tooth surfaces increase due to the wear accumulation, which further leads to the increase in the hysteresis and transmission errors of the harmonic reducer. Recently, some scholars have studied the influence of wear on harmonic reducers. Ma *et al.* [10] investigated the friction behavior of the harmonic drive at low speed and established a Coulomb-viscous-Stribeck friction model to replicate the friction behavior of the harmonic drive at low speed. Kennedy *et al.* [11] stated that the friction in the harmonic drive mainly came from the teeth meshing region, which strongly depended on the motor position because of the transmission error. Zhao *et al.* [12] modeled the total friction of the harmonic drive operating in a temperature-varying environment based on a Cascaded fuzzy friction model. Gao *et al.* [13] proposed a comprehensive friction model for a harmonic reducer in collaborative industrial robot joints which takes the effects of velocity, temperature, and load torque into account. However, most of the research results focus on the wear amount during the friction phase rather than the influence of the wear on the transmission performance parameters such as hysteresis and transmission errors.

Reliability is an important parameter of harmonic reducers, which describes the capability of harmonic reducers to perform a specified function for a given period of time under stated operating conditions. Recently, many scholars have conducted reliability analysis for strength failures of harmonic reducers. For example, Yoo *et al.* [14], and Johnson *et al.* [15] predicted the lifetime of harmonic reducers and conducted reliability evaluations on the strength failures of harmonic reducers through accelerated life testing; Zou *et al.* [16], Sun *et al.* [17], and Ma *et al.* [18] focused on the structural failures of flexspline and flexible bearing and modeled the reliability of harmonic reducers using Monte Carlo simulation. Such fields have been studied a lot from both reliability testing and mechanism modeling. Besides, some scholars began to evaluate the reliability of harmonic reducers focusing on the transmission performance

related failures. Zhang *et al.* [19] considered the dynamic stresses at the critical position of the flexspline and proposed a time-dependent reliability evaluation method to predict the time-to-failure of the harmonic reducer using accelerated life tests. Zhao *et al.* [3] conducted a reliability testing on the hysteresis errors for a harmonic reducer and analyzed its dynamic reliability using a response surface method. H. D. Taghirad and P. Be'linger [7] conducted reliability evaluation for hysteresis errors under different operating conditions through the simulation for a harmonic reducer. Yang *et al.* [20] proposed a Bayesian reliability framework for a satellite-equipped harmonic gear drive considering the transmission error, output power, and transmission efficiency. Guan [21] analyzed the failure mechanisms for lubricated harmonic reducers and conducted reliability analysis for hysteresis errors using the Monte Carlo and AFOSM methods. Li [22] carried out an accelerated life testing for a lubricated harmonic reducers where the transmission error, hysteresis error, and transmission efficiency were measured, and conducted reliability evaluation. From the state of art reliability modeling and analysis on harmonic reducers, as for the strength failures of harmonic reducers, the related reliability has been studied a lot from the perspectives of theoretical mechanism modeling and statistical analysis from reliability tests. However, as for the failures focusing on the transmission characteristics of harmonic reducers, such as hysteresis and transmission errors, the existing research mainly conducted the reliability evaluation through the statistical analysis using observations from reliability tests, but did not bridge the gap between the theoretical mechanism modeling and reliability modeling.

B. CURRENT PROBLEMS

Though existing studies have contributed a lot focusing on the hysteresis and transmission errors of the harmonic reducer, as well as its reliability, there are still some problems:

- 1) Though the theoretical modeling for the hysteresis and transmission errors of harmonic reducers has been studied a lot, their degradation caused by wear is seldom studied, since current studies mainly aim at the wear modeling between the gear teeth in the friction phase rather than the influence of wear on hysteresis and transmission errors.
- 2) The uncertainties in hysteresis and transmission errors of harmonic reducers have not been studied comprehensively.
- 3) Focused on the hysteresis and transmission errors of harmonic reducers, the reliability evaluation is mainly carried out through reliability tests, and the gap between theoretical mechanism modeling and reliability modeling has not been filled up.

C. CONTRIBUTION

Aiming at the harmonic reducer using in the space drive mechanism, we choose the hysteresis and transmission errors as key parameters to describe the transmission performance of harmonic reducers and propose a performance margin

modeling and reliability analysis method considering the wear and multi-source uncertainties during the manufacturing and usage processes. Some aspects are highlighted in this paper:

- 1) Considering the functional principle of harmonic reducers and the influence of wear on hysteresis and transmission errors, the mechanism model considering degradation for hysteresis and transmission errors is constructed, and the margin degradation models for hysteresis and transmission errors are constructed by introducing their thresholds, respectively;
- 2) As for margin degradation models for hysteresis and transmission errors, multi-source uncertainties in the manufacturing and usage processes are considered and quantified separately including manufacturing errors, uncertainties in operational and environmental conditions, and uncertainties in performance thresholds;
- 3) The reliability model of the transmission performance of harmonic reducers is constructed considering the coupling of hysteresis and transmission errors.

D. ORGANIZATION

The organization of this paper is as follows. In section 2, the methodology of performance margin modeling and reliability analysis is presented. In section 3, the harmonic reducer is introduced, and hysteresis and transmission errors are selected as two key parameters to describe its transmission performance through a function/performance analysis. Additionally, the performance margin degradation models of the harmonic reducer considering the wear as the source of degradation are established. Then in section 4, the uncertainties of harmonic reducers including manufacturing errors, uncertainties in operational and environmental conditions, and uncertainties in performance thresholds are analyzed and quantified separately. Afterward, the reliability model of the transmission performance of harmonic reducers is conducted in section 5. Section 6 presents a numerical study of a harmonic reducer and conducts the reliability sensitivity analysis for the design of the harmonic reducer. Finally, section 6 concludes all the work.

II. METHODOLOGY OF PERFORMANCE MARGIN MODELING AND RELIABILITY ANALYSIS FOR HARMONIC REDUCERS

Reliability describes the capability of a component or system to perform a specified function for a given period of time under stated operating conditions. In order to describe the function of products, it is necessary to pay attention to the performance parameters that can characterize the functional states of products. It is considered that the product can perform its desired functions and is reliable when its performance parameters are within their corresponding threshold ranges. The distance between the performance parameter and its threshold is defined as the performance margin [23] and the performance margin determines how reliable the object is.

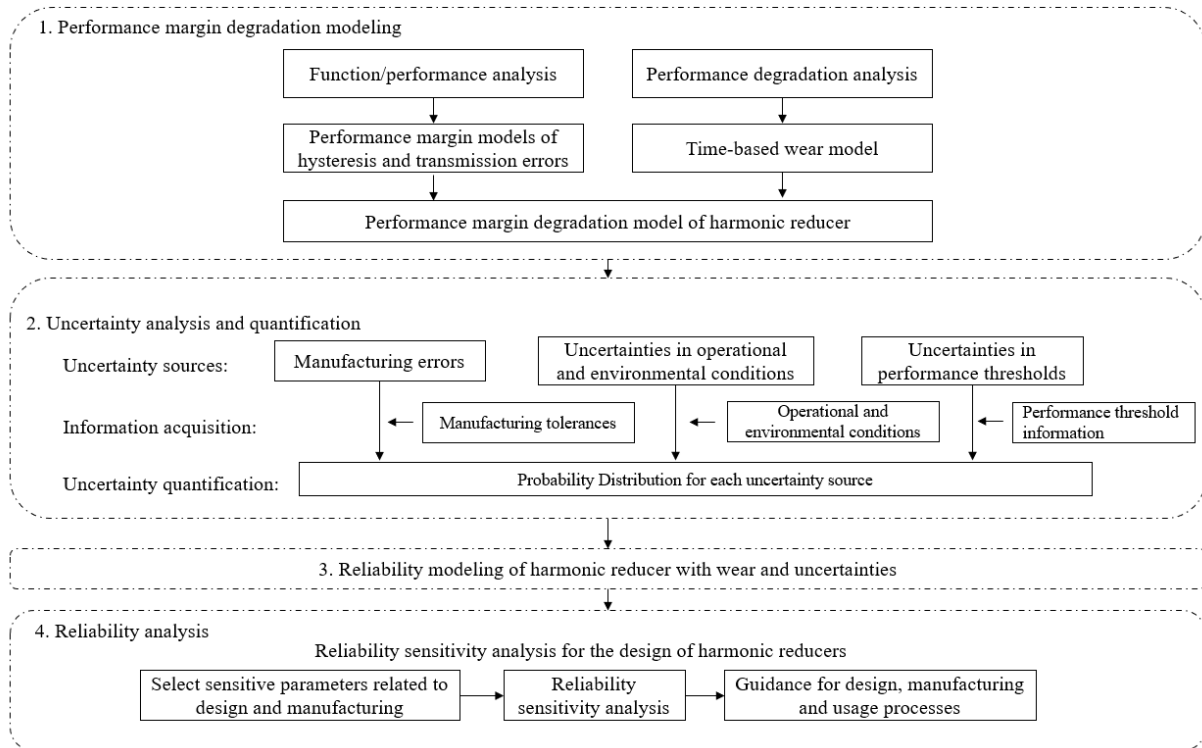


FIGURE 1. Framework of the performance margin modeling and reliability analysis with wear and uncertainties.

Therefore, a method of performance margin modeling and reliability analysis for harmonic reducers is proposed.

The framework of performance margin modeling and reliability analysis for harmonic reducers is shown in Figure 1. First of all, the function and performance of harmonic reducers are analyzed and the hysteresis and transmission errors are selected as the key performance parameters to describe the transmission performance of harmonic reducers. Based on the mechanical principles of harmonic reducers, the performance margin models of hysteresis and transmission errors are constructed, respectively. Then, the performance degradation analysis is conducted and a time-based wear model to describe the increase in the backlashes between tooth surfaces during the usage process is employed. Afterward, considering the influence mechanism of wear on the hysteresis and transmission errors, the margin degradation models of hysteresis and transmission errors are constructed, respectively. In addition, the margin degradation model of the transmission performance of harmonic reducers is constructed considering the coupling of hysteresis and transmission errors. Next, the uncertainties that affect the transmission performance margin of harmonic reducers during the manufacturing and usage processes are analyzed, including the manufacturing errors, the uncertainties in operational and environmental conditions, and the uncertainties in performance thresholds. These uncertainties are quantified using certain probability distributions. Then, combining the uncertainty quantification results and the performance margin degradation model of

the harmonic reducer, the reliability model is established and the reliability analysis is implemented. Finally, the reliability analysis is carried out. The sensitive parameters related to design and manufacturing should be selected, and the reliability sensitivity analysis is applied, then the guidance for design, manufacturing and usage processes is proposed.

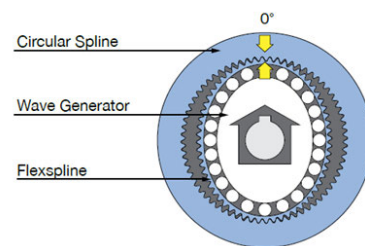


FIGURE 2. Structure of the harmonic reducer [25].

III. PERFORMANCE MARGIN DEGRADATION MODELING FOR THE HARMONIC REDUCER

A. INTRODUCTION TO THE HARMONIC REDUCER

The harmonic reducer serves as one of the gear drive systems, which has the advantages of high transmission accuracy, high ratio reduction, and low weight, etc., and has been widely used in precision transmission fields such as robotics and aerospace [24]. The harmonic reducer consists of a wave generator, a circular spline, and a flexspline, shown in Figure 2.

The movement of harmonic reducers is based on the elastic dynamics and utilizes the flexibility of metal [16], which is described as follows. The wave generator is made up of two separate parts: an elliptical disk called a wave generator plug and a flexible bearing. The elliptical plug is inserted into the bearing, forcing the bearing to conform to the elliptical shape but still allowing rotation of the plug within the outer bearing. Before assembly, the flexspline is circular, whose circular pitch is equal to that of the circular spline, but the tooth number of the flexspline is slightly less than that of the circular spline. Generally, the difference between the tooth numbers in the flexspline and the circular spline is two. After assembly, since the maximum diameter of the wave generator is slightly larger than the diameter of the inner circle of the flexspline, the flexspline deforms to the shape of the wave generator. It causes the teeth of the flexspline in two regions on opposite sides of the major axis of the wave generator to exactly mesh with the teeth of the circular spline and the teeth of the flexspline at the minor axis are completely disengaged from the teeth of the circular spline. For those teeth located between the major and minor axes of the wave generator, they are in a transition state in which some are meshed and some are disengaged. With the continuous rotation of the wave generator, the flexspline produces continuous elastic deformation, so that the teeth between the flexspline and the circular spline continuously repeat the process of "mesh-disengage" to transmit meshing movement. The illustration of the movement of harmonic reducers is shown in Figure 3. During the operation of the harmonic reducer, one of the components is fixed, and the other two are active, where one of the active parts is the drive part and the other is the follower part. Any one of these three components can be used as the drive, follower, or fixed part, and their mutual relationship can be changed as needed. For the harmonic reducer in the space drive mechanism to be studied, the circular spline is fixed, the wave generator is the drive part, and the flexspline is the follower part.

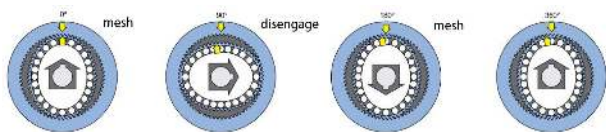


FIGURE 3. Operation principle of the harmonic reducer [25].

B. PERFORMANCE MARGIN MODELING

The hysteresis and transmission errors are two key performance indexes to describe the transmission characteristics of the harmonic reducer. Large hysteresis and transmission errors can cause the unbalanced rotation, shocks and short-term output interrupt in the operating harmonic reducer, and further affects the function of the space drive mechanism [2]. Thus, in practical applications, the requirements for hysteresis errors and transmission errors are usually strict, and once these parameters cannot meet the requirement, the

harmonic reducer is considered to fail and unable to transmit precisely. Therefore, in this paper, we use the hysteresis and transmission errors as the key performance indexes to establish the performance margin model of the harmonic reducer.

1) MARGIN MODELING FOR THE HYSTERESIS ERROR

The hysteresis error of the harmonic reducer is the lag in the rotation angle of the output shaft when the rotation direction of the input shaft is changed [26]. According to [27], the hysteresis error of harmonic reducer can be calculated by,

$$B = \frac{6.876 \times \tan \alpha \times (E_M + 2e_3 + e_5 - 2\Delta F_t)}{mZ_G} \quad (1)$$

Assuming that the allowable limit error for B is $P_{th,B}$, i.e. the threshold of B , the margin for the hysteresis error of the harmonic reducer is defined as the relative distance between B and $P_{th,B}$,

$$M_B = \frac{P_{th,B} - B}{P_{th,B}} \quad (2)$$

The harmonic reducer is reliable whenever $M_B > 0$.

2) MARGIN MODELING FOR THE TRANSMISSION ERROR

The transmission error refers to the deviation between the actual output angle of the gear and the theoretical output angle when the harmonic reducer is driven in one direction [28]. According to [29], the maximum transmission error of the harmonic reduce can be expressed as:

$$\varphi = \pm \frac{K_B}{\sqrt{z_\Sigma}} \left\{ 0.25 \left[\sum \Delta T_{\Sigma K} + \frac{\pi d_R}{4u\omega_0 i} \left(\sum \Delta \rho_n \right) \right] + 0.4 \sqrt{\sum (\Delta T_{\Sigma K})^2 + \left(\frac{\pi d_R}{4u\omega_0 i} \right)^2 \sum (\Delta \rho_n)^2} \right\} \frac{6.88}{d_R} \quad (3)$$

where

$$\Delta T_\Sigma = \sqrt{e_1^2 + e_2^2} + \Delta F_r + \Delta f_{pb} \quad (4)$$

$$\Delta \rho_n = e_3 + \sqrt{e_4^2 + e_5^2} \quad (5)$$

Assuming that the allowable limit error for φ is $P_{th,\varphi}$, i.e. the threshold of φ . In equation (3), the transmission error contains the plus and the minus signs due to the direction of transmission error. In practice, as far as the magnitude of the transmission error exceeds the allowable limit error $P_{th,\varphi}$, the harmonic reducer can be regarded to fail. Therefore, the magnitude other than the direction of the transmission error is of more interest, and we use the absolute value of transmission error $|\varphi|$ for the further calculation of performance margin. The margin of the transmission error is defined as the relative distance between the absolute value of φ and $P_{th,\varphi}$, i.e.,

$$M_\varphi = \frac{P_{th,\varphi} - |\varphi|}{P_{th,\varphi}} \quad (6)$$

The harmonic reducer is reliable whenever $M_\varphi > 0$.

3) WEAR MODELING

As the harmonic reducer operates, the backlash between the tooth surfaces will increase due to the wear caused by the mutual mesh between gear surfaces, which results in the degradation of the hysteresis and transmission errors. Generally, the typical wear process can be divided into three phases, the running phase, the stable phase, and the accelerated wear phase [30], shown in Figure 4.

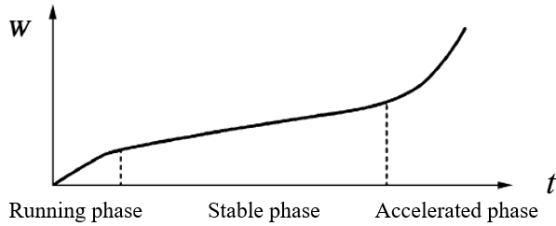


FIGURE 4. Typical wear process.

The harmonic reducer has gone through the running process before use. So, it can be considered that the wear process of the harmonic reducer is in the stable phase with a constant wear rate, so the circumferential wear amount accumulates linearly with time,

$$W(t) = at + \xi \tag{7}$$

C. PERFORMANCE MARGIN DEGRADATION MODELING

Considering the influence of the accumulated wear amount on the meshing process, the accumulated circumferential wear amount should be coupled into the hysteresis error model. Then equation (1) can be updated to:

$$B(t) = \frac{6.876 \times [W(t) + \tan \alpha \times (E_M + 2e_3 + e_5 - 2\Delta F_t)]}{mZ_G} \tag{8}$$

Similarly, the updated model of the transmission error considering wear can be expressed as:

$$\begin{aligned} \varphi(t) &= \pm \frac{K_B}{\sqrt{z_\Sigma}} \left\{ 0.25 \left[\sum \Delta T_{\Sigma K} + \frac{\pi d_R}{4u\omega_0 i} \left(\sum \Delta \rho_n + W(t) \right) \right] \right. \\ &\quad \left. + 0.4 \sqrt{\sum (\Delta T_{\Sigma K})^2 + \left(\frac{\pi d_R}{4u\omega_0 i} \right)^2 \sum (\Delta \rho_n + W(t))^2} \right\} \\ &\quad \times \frac{6.88}{d_R} \end{aligned} \tag{9}$$

Then the margin models (2) and (6) for hysteresis and transmission errors can be rewritten as,

$$M_B(t) = \frac{P_{th,B} - B(t)}{P_{th,B}} \tag{10}$$

$$M_\varphi(t) = \frac{P_{th,\varphi} - |\varphi(t)|}{P_{th,\varphi}} \tag{11}$$

From engineering practices and experiences, once one of the above performance margins, i.e. equations (10) and (11)

is smaller than 0, it is known that the harmonic reducer will be unable to transmit precisely and be considered to fail consequently. So, it can be considered that the harmonic reducer has the competition failure mode, and the performance margin degradation model for the harmonic reducer can be expressed as the minimum of $M_B(t)$ and $M_\varphi(t)$,

$$M(t) = \min(M_B(t), M_\varphi(t)) \tag{12}$$

The above performance margin degradation model shows the degradation law of the performance margin with time, and the harmonic reducer is reliable whenever $M(t) > 0$.

IV. UNCERTAINTY ANALYSIS AND QUANTIFICATION

In the manufacturing and usage processes, uncertainties are inevitable and can affect the hysteresis and transmission errors of the harmonic reducer. Therefore, it is important to figure out the uncertainty sources of the harmonic reducer and quantify them one by one precisely. The uncertainties of harmonic reducer in the manufacturing and usage processes are primarily from the manufacturing errors, the uncertainties in operational and environmental conditions, and the uncertainties in the performance thresholds. In this section, these uncertainties are analyzed and quantified separately.

A. MANUFACTURING ERRORS

Since manufacturing equipment cannot manufacture dimensions to the theoretical ones precisely, manufacturing errors exist in each component of the harmonic reducer. Generally, the manufacturing errors of components are regarded as random variables following normal distributions [31]. For the harmonic reducer to be studied, the manufacturing errors can be divided into the following categories:

- 1) The manufacturing errors of the circular spline: the measurement error of the gauge pin distance E_M , the coaxial error of the circular spline ΔF_t , the radial runout of the circular spline ΔF_r , and the basic pitch deviation of circular spline Δf_{pb} ;
- 2) The manufacturing errors of the flexible bearing: the radial circle run-out e_4 and the radial backlash e_5 of the flexible bearing;
- 3) The manufacturing errors of the wave generator: the radial error in the major axis of the wave generator e_3 ;
- 4) The manufacturing errors of the shaft and hole: radial circle run-out e_1 and e_2 of the shaft and hole respectively.

In the manufacturing process of products, in order to control manufacturing errors, a standardized tolerance system is used, and the manufacturing tolerances of the product are marked on the product as part of the manufacturing information. The manufacturing information of the harmonic reducer contains the manufacturing tolerance grades, the accuracy grades of flexible bearing and the circular spline, etc., which can be referred to in this paper to quantify the uncertainties in its manufacturing process.

The measurement error of the gauge pin distance E_M is the measuring difference between the nominal value and actual

value of gauge pin distance within one circle of the circular spline. According to the GB2363-90 [32], for a certain tolerance grade of the circular spline, the upper and lower deviations of E_M are E_{Ms} and E_{Mi} , respectively. Without loss of generality, it is assumed that the tolerance zone of E_M is symmetrical, then the mean of E_M can be calculated as,

$$\mu = \frac{E_{Ms} + E_{Mi}}{2} \quad (13)$$

According to the 6-sigma limit in the mechanical design [33], the standard variance of E_M can be calculated as,

$$\sigma = \frac{1}{6} (E_{Ms} - E_{Mi}) \quad (14)$$

According to the mentioned above, E_M follows the normal distribution with the mean as μ and variance as σ^2 , denoted as $E_M \sim N(\mu, \sigma^2)$. Similarly, according to the GB2363-90 [32], ISO 5753.1: 2009 [34], ISO 492: 2014 [35], ISO 7967-3-2010[36], GB/T 1803-2003 [37], the upper and lower deviations of the other manufacturing errors can be obtained; then the corresponding mean values and standard variances are calculated and the probability distributions of manufacturing errors are obtained. The uncertainty quantification results of the manufacturing errors of the harmonic reducer are shown in Table 1.

TABLE 1. Uncertainty quantification results of manufacturing errors.

PARAMS.	Distributions
E_M	$N\left(\frac{1}{2}(E_{Ms} + E_{Mi}), \left[\frac{1}{6}(E_{Ms} - E_{Mi})\right]^2\right)$
ΔF_t	$N\left(\frac{\varphi}{2}, \left(\frac{\varphi}{6}\right)^2\right)$
ΔF_r	$N\left(\frac{1}{2}(F_{rU} + F_{rL}), \left[\frac{1}{6}(F_{rU} - F_{rL})\right]^2\right)$
Δf_{pb}	$N\left(\frac{1}{2}(f_{pb} - f_{pb}), \left[\frac{1}{6}(f_{pb} - (-f_{pb}))\right]^2\right)$
e_1	$N\left(\frac{1}{2}(ES + EI), \left[\frac{1}{6}(ES - EI)\right]^2\right)$
e_2	$N\left(\frac{1}{2}(es + ei), \left[\frac{1}{6}(es - ei)\right]^2\right)$
e_3	$N\left(\frac{1}{2}(E_{RU} + E_{RL}), \left[\frac{1}{6}(E_{RU} - E_{RL})\right]^2\right)$
e_4	$N\left(\frac{K_{en}}{2}, \left(\frac{1}{6}K_{en}\right)^2\right)$
e_5	$N\left(\frac{1}{2}(G_{rmin} + G_{rmax}), \left[\frac{1}{6}(G_{rmax} - G_{rmin})\right]^2\right)$

B. UNCERTAINTIES IN OPERATIONAL AND ENVIRONMENTAL CONDITIONS

In practice, operational and environmental conditions impossibly remain constants. During the operation of the harmonic

reducer, the input torque, the rotation speed and the load of the harmonic reducer are usually not constants, which causes the fluctuation in the wear process and is reflected by the uncertainties in the wear rate. Therefore, we assume the wear rate to be a random variable following a normal distribution, shown in Table 2.

TABLE 2. Uncertainty quantification result of the wear rate.

Parameter	Distribution
a	$N(\mu_a, \sigma_a^2)$

C. UNCERTAINTIES IN PERFORMANCE THRESHOLDS

The performance thresholds characterize the boundaries conditions for the system to perform specified functions. In this paper, hysteresis and transmission errors are the two transmission performance parameters of concern. Large hysteresis errors and transmission errors can cause the unbalanced rotation, shocks and short-term output interrupt in the operating harmonic reducer, and further affect the function of the space drive mechanism. Therefore, in practical applications, the hysteresis and transmission errors are strictly required to reduce the impact of these two errors on the performance of the harmonic reducer. GB/T 30819-2014 [38] gives the error level requirements for the hysteresis and transmission errors of the harmonic reducer and specifies the upper and lower limits of the allowable error at each error level. Thus, we consider the thresholds of hysteresis error $P_{th,B}$ and transmission error $P_{th,\varphi}$ are random variables following uniform distributions, shown in Table 3.

TABLE 3. Uncertainty quantification results of performance thresholds.

Parameters	Distributions
$P_{th,B}$	$U(U_{P_{th,B}}, L_{P_{th,B}})$
$P_{th,\varphi}$	$U(U_{P_{th,\varphi}}, L_{P_{th,\varphi}})$

V. RELIABILITY MODELING FOR THE HARMONIC REDUCER

According to the uncertainty analysis and quantification in section 3, there are many random variables in the performance margin degradation model (10) of the harmonic reducer; thus, the performance margin is also a random variable and represented by $\tilde{M}(t)$.

The reliability of the harmonic reducer can be expressed as:

$$\begin{aligned} R(t) &= P(\tilde{M}(t) > 0) \\ &= P(\min(\tilde{M}_B(t), \tilde{M}_\varphi(t)) > 0) \\ &= R_B(t) \cdot R_\varphi(t) \end{aligned} \quad (15)$$

$R(t)$ is the reliability after a using time t , which considers the performance margin with wear and the uncertainties in practical usage.

Since the explicit formula of the reliability (15) is impossibly given, the Monte Carlo method is applied to compute the reliability for the harmonic reducer, and its pseudocode is shown in Table 4.

TABLE 4. Pseudocode of monte carlo method to compute reliability.

Algorithm Monte Carlo method for computing reliability	
Initialization: operation time t , p and $q = 0$.	
1.	For $n = 1$ to N do
2.	Generate a random number for each random variable according to its corresponding distribution and obtain $x_p = (E_M, \Delta F_t, \Delta f_{pb}, \Delta F_r, e_1, e_2, e_3, e_4, e_5)$;
3.	Calculate $M_B(t)$ and $M_\varphi(t)$ by equations (10) and (11) using x_p .
4.	If $M_B(t) > 0$ then
5.	$p = p + 1$.
6.	Else
7.	$p = p$.
8.	If $M_\varphi(t) > 0$ then
9.	$q = q + 1$.
10.	Else
11.	$q = q$.
12.	End for
13.	Calculate $R_B(t) = p/N$ and $R_\varphi(t) = q/N$
14.	Calculate $R(t) = R_B(t) \cdot R_\varphi(t)$

VI. NUMERICAL STUDY

A. PARAMETER DETERMINATION

For this case of the harmonic reducer, we adopt an XBD-60-160 type harmonic reducer from some company, which is a key component in the space drive mechanism. The physical parameters of the harmonic reducer are shown in Table 5.

TABLE 5. physical parameters for the harmonic reducer XBD-60-160

PARAMs.	Values
m	0.2(mm)
u	2
i_H	160
d_R	64(mm)
z_G	322
b	12.8(mm)
α_H	28.6°
z_Σ	56
ω_0	0.2(mm)

The flexible bearing model is HDB 45/60/9, the manufacturing tolerance grades for circular spline and flexible bearing

are IT7, and the radial backlash of flexible bearing is the 3rd group.

The harmonic reducer works with the maximum output torque 32 Nm and maximum rotation speed 2⁷/s, under the temperature condition of 0 - 150 °C. According to section 3.2, the wear rate is regarded as a random variable following a normal distribution, $a \sim N(0.0114, 0.001012^2)$ (mm/h) [30], and the wear amount during the running phase ξ is set as 0.05mm.

The required error level of the harmonic reducer is B3, which means the required error level of transmission error is B and the required error level of hysteresis error is 3. Considering the uncertainties in performance thresholds, $P_{th,B}$ and $P_{th,\varphi}$ are regarded as random variables independently following uniform distributions $P_{th,B} \sim U(3', 6')$ and $P_{th,\varphi} \sim U(0.5', 1')$, respectively.

B. RELIABILITY ANALYSIS

According to the procedure in section 2 - 4, the hysteresis and transmission errors, their margins, and the performance margin of the harmonic reducer can be calculated, shown in Figure 5.

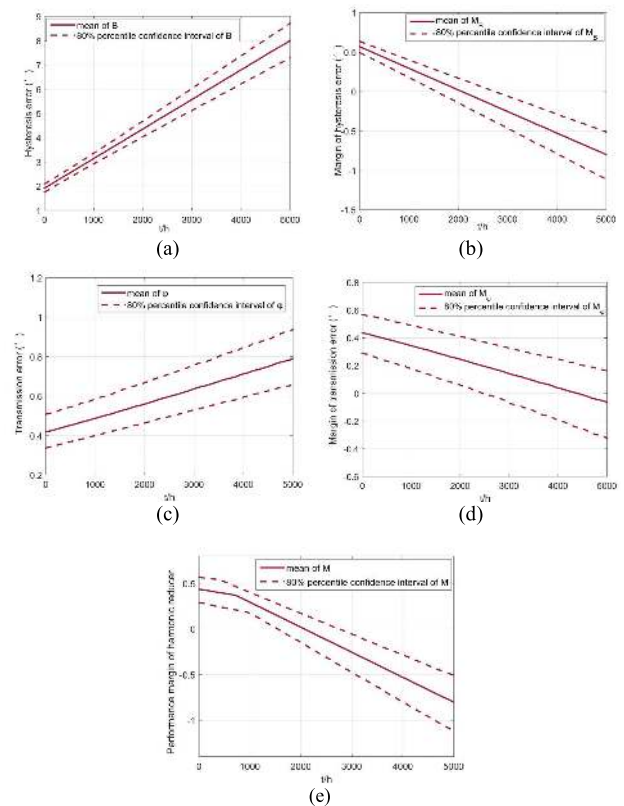


FIGURE 5. Transmission error; (b) Transmission error margin; (c) hysteresis error; (d) Transmission error margin; (e) performance margin of the harmonic reducer.

From Figure 5, some results can be obtained:

- 1) From Figure 5 (a) and (c) the hysteresis error and the transmission error increase with time, which means

these two performance parameters degrade with time. Corresponding to Figure 5 (b) and (d), their margins decrease with time;

- 2) The hysteresis and transmission errors are not 0 at the initial moment, which shows the existence of uncertainties of the harmonic reducer at the initial moment due to manufacturing errors;
- 3) From Figure 5 (a) ~ (d), the widths of 80% confidence interval of the hysteresis and transmission errors, and their margins increase with time, which reveals the uncertainties of the hysteresis and transmission errors, and their margins increase with time.
- 4) Comparing Figure 5 (b), (d), and (e), the performance margin of the harmonic reducer almost coincides with the transmission error margin before 700 hours and coincides with the hysteresis error margin after 700 hours, respectively. This shows that the performance margin of the harmonic reducer is mainly affected by the transmission error before 700 hours and mainly by the hysteresis error after 700 hours. Additionally, the performance margin of the harmonic reducer is always larger than 0 before 700 hours. Consequently, it is appropriate to pay more attention to the hysteresis error to ensure the reliability of the harmonic reducer.

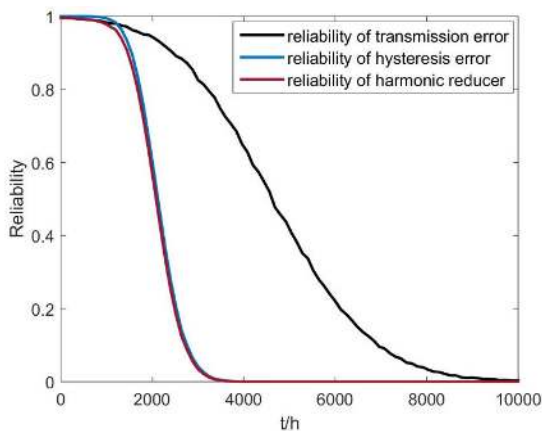


FIGURE 6. Reliability of the harmonic reducer.

Then the reliability of harmonic reducer is calculated, shown in Figure 6. From Figure 6, the reliability curve of harmonic reducer (blue line) almost coincides with the reliability curve of hysteresis error (red line), and the degradation of the reliability of transmission error is much slower than the hysteresis error (black line). The results reveal that the reliability of harmonic reducer mainly depends on the reliability of hysteresis error, which is corresponding to the results in Figure 6.

C. RELIABILITY SENSITIVITY ANALYSIS FOR THE DESIGN OF THE HARMONIC REDUCER

Reliability designs are supposed to be conducted in the design process which ensures that the product can perform

specified functions with high reliability. In this section, reliability sensitivity analysis for the design of the harmonic reducer is carried out.

1) RELIABILITY SENSITIVITY ANALYSIS FOR MANUFACTURING ERRORS

The manufacturing errors for the harmonic reducer include the manufacturing errors of the circular spline, the flexible bearing, the wave generator, and the fit between the shaft and hole. Among these four types of manufacturing errors, the values and uncertainties of the latter two manufacturing errors are rather smaller than the former two; correspondingly, it is reasonable that the latter two manufacturing errors have little influence on the reliability of the harmonic reducer. Therefore, we only carry out the reliability sensitivity analysis on the manufacturing errors of the circular spline and flexible bearing.

a: CIRCULAR SPLINE TOLERANCE

For the circular spline of the harmonic reducer, we select its manufacturing tolerance as IT4, IT5, IT6, and IT7 (original tolerance) while keeping the other parameters unchanged. The performance margins and the reliability of the harmonic reducer are shown in Figure 7.

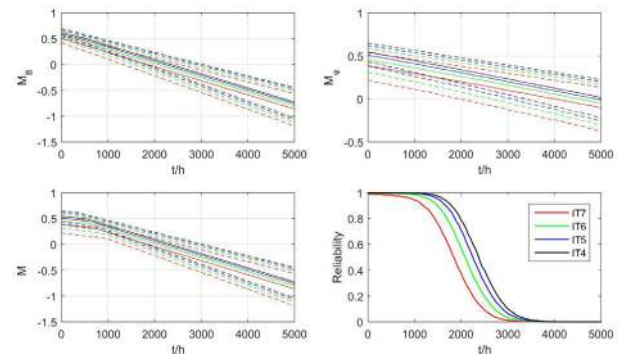


FIGURE 7. Performance margins and reliability of harmonic reducer with different tolerances of the circular spline.

From Figure 7, we can obtain that

- 1) From Figure 7 M_B , M_φ and M , the larger the tolerance is, the smaller the performance margins of the hysteresis and transmission errors are. It can be seen that the curve of the performance margin shifts up and down with the change of circular spline tolerance, which shows that the change of circular spline tolerance does not impact on the degradation process of the performance margin.
- 2) Corresponding to the result above, from Figure 7 Reliability, the larger the tolerance is, the lower the reliability will be. The reliability curve shifts left and right as the circular spline tolerance changes.
- 3) From Figure 7 Reliability curve, according to the distance between the reliability curves of two adjacent tolerances, the influence of the changed tolerance on

the reliability can be obtained. It can be found that the larger the tolerance value, the more early the reliability decreases.

b: FLEXIBLE BEARING TOLERANCE

For the flexible bearing of the harmonic reducer, IT4, IT5, IT6, and IT7 (original tolerance) are selected while keeping the other parameters unchanged. The performance margins and the reliability of harmonic reducer are shown in Figure 8.

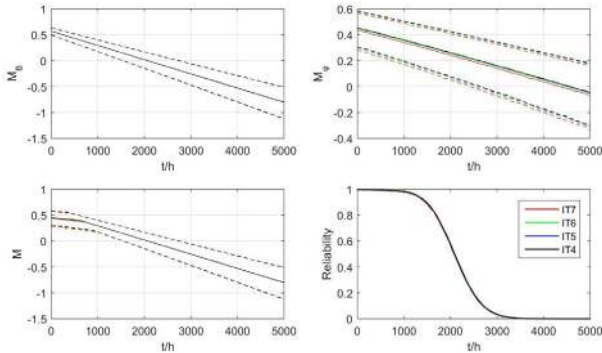


FIGURE 8. Performance margins and reliability of harmonic reducer with different tolerances of the flexible bearing.

From Figure 8, M_B , M_ϕ , and M change little under different flexible bearing tolerances. And in Figure 8 reliability curves under different flexible bearing tolerances nearly coincide. So, the results suggest that the reliability of the harmonic reducer is not sensitive to the manufacturing tolerances of the flexible bearing.

From Figure 7 and Figure 8, we can obtain that the performance margin and the reliability of harmonic reducer are not sensitive to the flexible bearing tolerance, on the contrary, the circular spline tolerance has a significant effect on the performance margin and reliability of harmonic reducer. In order to improve the reliability of the harmonic reducer, it is appropriate to pay more attention to the circular spline tolerance during the design phase.

2) RELIABILITY SENSITIVITY ANALYSIS FOR OPERATIONAL ENVIRONMENTAL AND CONDITIONS

The uncertainties for operational and environmental conditions considered in this article are mainly reflected in wear. In order to explore the effects of uncertainties in wear rates on the harmonic reducer, we vary the mean and standard value of wearing rate from its original value to its 0.8 and 1.2 times respectively while keeping the other parameters unchanged. The performance margin and corresponding reliability results are shown in Figure 9 and Figure 10.

From Figure 9, the following results can be obtained:

- a) From Figure 9 M_B , M_ϕ and M , the larger the mean of wear rate is, the faster the performance margins degrade; corresponding to the result in Figure 9 the reliability of the harmonic reducer degrades faster;

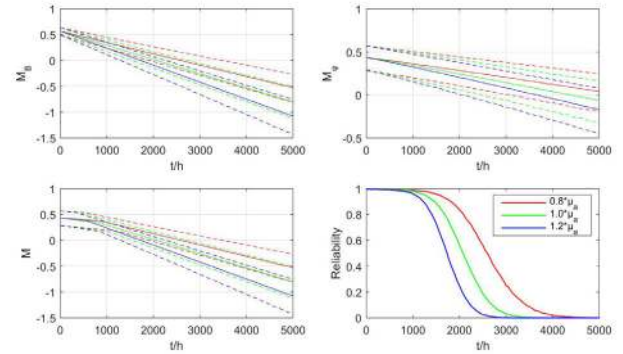


FIGURE 9. Performance margins and reliability of harmonic reducer in different means of wear rate.

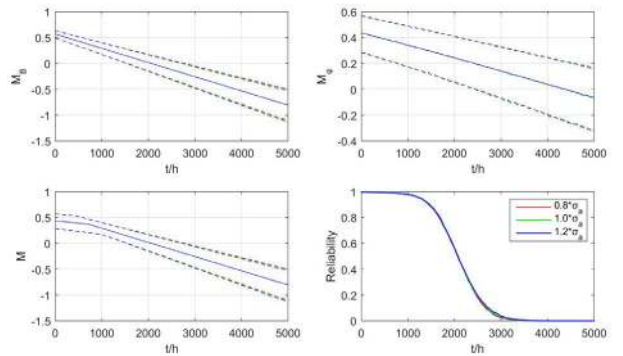


FIGURE 10. Performance margins and reliability of harmonic reducer in different standard variances of wear rate.

- c) Compared with Figure 9 M_B and M_ϕ , the mean of the wear rate has a larger influence on the performance margin degradation of the hysteresis error than the transmission error.

From Figure 10, the performance margins of hysteresis error, transmission error, and harmonic reducer hardly change under different standard variances of wear rate, and the reliability curves of different standard variances of wear rate nearly coincide. The result shows that the performance margin degradation and the reliability are not sensitive to the standard variance of wear rate.

In summary, the mean of the wear rate exerts a larger influence on the reliability of the harmonic reducer than the standard variance. Thus, in order to increase the reliability of the harmonic reducer, decreasing the mean of the wear rate is an efficient method, such as improving the lubrication condition.

3) RELIABILITY SENSITIVITY ANALYSIS FOR PERFORMANCE THRESHOLDS

Different performance thresholds give different functional boundaries of the system. In order to explore the impact of different performance thresholds on the performance margins and reliability of harmonic reducers, we selected 1, 2, 3, and A, B, and C allowable error levels for hysteresis and

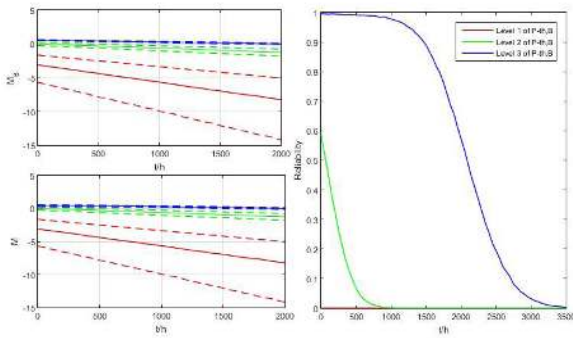


FIGURE 11. Performance margin and reliability of harmonic reducer under different levels of hysteresis error thresholds.

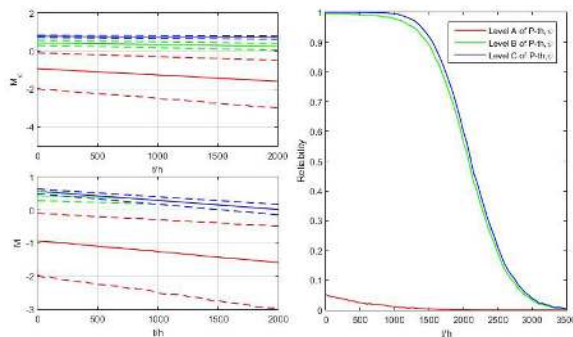


FIGURE 12. Performance margin and reliability of harmonic reducer under different levels of transmission error thresholds.

transmission errors [38], respectively, while keeping the other parameters unchanged. The performance margin and reliability results are shown in Figure 11 and Figure 12.

From Figure 11 and Figure 12, we can observe that:

- 1) The reliability changes a lot under different levels of hysteresis and transmission error thresholds;
- 2) From Figure 11, the performance margin M of the harmonic reducer is the same as the hysteresis error margin M_B when $P_{th,B}$ is level 1 and M is the same as the transmission error margin M_φ when $P_{th,B}$ is level 3; Similarly, from Figure 12, M is the same as M_φ when $P_{th,\varphi}$ is level A and M is the same as M_B when $P_{th,\varphi}$ is level C.

It can be seen that the performance thresholds exert a great impact on the reliability of the harmonic reducer and under the different selection of thresholds, the performance parameters which should gain more attention for engineers change correspondingly. Therefore, a clear understanding of the performance thresholds to describe the functional boundaries of the harmonic reducer is of vital importance.

VII. CONCLUSION

The harmonic reducer is one of the critical components in the space drive mechanism. In practical applications, the hysteresis and transmission errors are two key parameters of great interest to describe the transmission performance of the harmonic reducer. Aiming at the hysteresis and transmission

errors of the harmonic reducer, this paper presents a performance margin modeling and reliability analysis method considering the wear and multi-source uncertainties during the manufacturing and usage processes and carry out a numerical case from some company. Here draw some conclusions as follows:

- 1) Considering the functional principle of harmonic reducers and the influence of wear on hysteresis and transmission errors, the mechanism models considering degradation for hysteresis and transmission errors are constructed, and the corresponding margin degradation models are constructed by introducing their thresholds, respectively;
- 2) Multi-source uncertainties in the manufacturing and usage processes are considered and quantified separately including manufacturing errors, uncertainties in operational and environmental conditions, and uncertainties in performance thresholds;
- 3) Focused on the hysteresis and transmission errors of harmonic reducers, the gap between theoretical mechanism modeling and reliability modeling has been filled up, and the reliability model of the transmission performance of harmonic reducers is constructed considering the coupling of hysteresis and transmission errors;
- 4) A numerical study of a harmonic reducer is carried out and the reliability sensitivity is implemented, which shows the practicability of the method. The results reveal that the proposed method can provide quantitative advice on increasing the reliability of harmonic reducer for the design of the harmonic reducer, such as improving the manufacturing tolerance grades of gear, improving the lubrication condition, and recognizing thresholds more accurately.

Beyond the work in this paper, there are still some issues that deserve further research. In practice, the manufacturing process of the flexspline is rather complicated, which brings difficulties in the uncertainty quantification of the flexspline. Hence, the quantification of uncertainties in the flexspline should gain more attention in future studies. Besides, during the practical usage process, the wear process between the tooth surfaces is conditioned by multi factors such as lubrication, loading, and temperature conditions, etc. So, the explicit wear model between the tooth surfaces of harmonic reducers deserves further research.

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(Yun Li and Bang-An Tong are co-first authors.)

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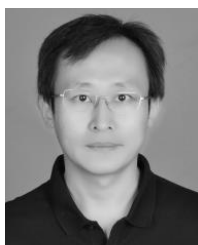
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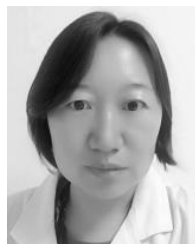
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