An accelerated life test model for harmonic drives under a segmental stress history and its parameter optimization

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Abstract Harmonic drives have various distinctive advantages and are widely used in space drive mechanisms. Accelerated life test (ALT) is commonly conducted to shorten test time and reduce associated costs. An appropriate ALT model is needed to predict the lifetime of harmonic drives with ALT data. However, harmonic drives which are used in space usually work under a segmental stress history, and traditional ALT models can hardly be used in this situation. This paper proposes a dedicated ALT model for harmonic drives applied in space systems. A comprehensive ALT model is established and genetic algorithm (GA) is adopted to obtain optimal parameters in the model using the Manson fatigue damage rule to describe the fatigue failure process and a cumulative damage method to calculate and accumulate the damage caused by each segment in the stress history. An ALT of harmonic drives was carried out and experimental results show that this model is acceptable and effective.

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1. Introduction
Harmonic drives are widely used in space drive mechanisms, such as solar panel deployment systems and antenna drive mechanisms, due to their advantages of high transmission ratio, low weight, and compact structure.1-3 Reliability of harmonic drives is of great importance to the functioning of spacecraft. Failures of harmonic drives might cause malfunctions of spacecraft and significant economic losses, and for this reason, predicting the lifetime of harmonic drives used in space mechanisms has become very important.

Life test is a practical way to assess lifetimes for mechanical components.4,5 The lifetime of harmonic drives which are used in space could be several thousands of hours and a life test would be lengthy and expensive.6 Accelerated life test (ALT) is an effective method to accelerate the failure processes of products and shorten test time. In an ALT, tested samples work under higher environmental or working stresses and failures can be induced in a relatively shorter time.7 After an ALT
An accelerated life test model for harmonic drives under a segmental stress history and its parameter optimization

Up to now, several types of ALT models have been proposed. As will be reviewed in the next section, most existing ALT models belong to statistics-based models and thus cannot reflect the in-depth failure mechanism of corresponding components. In addition, most of the existing ALT models can only be used in constant stress ALTs. However, harmonic drives which are used in space mechanisms typically work under stress with a segmental nature. Hence, in order to simulate the failure process more accurately, the stress history for ALTs of harmonic drives used in space mechanisms is typically treated as segmental. Majority of previously mentioned ALT models cannot be used to directly process ALT data of harmonic drives with this type of stress history. Furthermore, an effective ALT model for harmonic drives should also be able to predict the lifetime of a harmonic drive under a baseline condition, which also has a segmental stress history. This cannot be easily accomplished with most ALT models.

Considering the above problems, this paper proposes a dedicated ALT model for harmonic drives. Firstly, the failure mechanism of harmonic drives is investigated. For harmonic drives used in space mechanisms, the flex spline is the most important failure mode. The Manson fatigue rule, which divides the fatigue failure process mathematically into two phases, gives an in-depth reflection of the failure mechanism and can better describe the fatigue phenomenon than the commonly used linear damage rule. Therefore, it is used to describe the fatigue failure process of the flex spline in the ALT model development in this article. Secondly, as the acceleration stresses of harmonic drives are usually rotation speed and load, the generalized Eyring model is used to describe the stress-life relationship under constant stress situations. Next, a cumulative damage method is used to accumulate the fatigue in each segment of the stress history and the entire ALT model is built. Genetic algorithm (GA) is then used to obtain the optimal parameters in this model. This physics-statistics-based model reflects the primary failure mechanism of harmonic drives and can determine the cumulative damage under the segmental stress history.

The rest of this paper is organized as follows. In Section 2, the structure and failure mechanism of harmonic drives are briefly introduced. A model is established and a maximum likelihood function is deducted based on the Manson fatigue damage rule to describe the fatigue failure process, and a cumulative damage method is used to calculate damages caused by stress in each of the segments. In Section 3, the interval for each parameter in the proposed model is specified and a parameter optimization method based on GA is given. In Section 4, an ALT of harmonic drives is carried out and the proposed ALT model is validated by experimental data. Section 5 provides conclusions.

### 2. Brief review to existing ALT models

The earliest and most widely used ALT models are the accelerated failure time (AFT) models, which include the Arrhenius model, the Eyring model, the inverse power-law model, and so on. AFT models are based on two assumptions: (1) failure time distributions under different environmental or working stresses are of the same type, and (2) time to failure under higher stresses is shorter than that under lower stresses. Other types of commonly used ALT models include: (1) the proportional hazards (PH) model proposed by Cox which assumes that the failure rates are proportional to the applied stresses; (2) the extended hazard regression (EHR) model that encompasses both the PH and AFT models as special cases; (3) the extended linear hazard regression (ELHR) model that incorporates the time-varying coefficient effect into the EHR model and enhances its capability; (4) the proportional mean residual life (PMRL) model which is based on mean residual life proportionality and provides a viable alternative to the AFT models and the PH model; and (5) the proportional odds (PO) model which follows the phenomenon in a medical observation and assumes that the defined odds functions under different stress levels are proportional to each other.

There are also other types of ALT models, such as a dedicated ALT model for solid lubricated bearings based on dependence analysis, etc.

According to Elsayed’s review, all the existing ALT models can be classified into three categories: (1) statistics-based models, (2) physics-statistics-based models, and (3) physics-experimental-based models. The statistics-based models can be further classified into parametric models and non-parametric models. According to this classification, most of the previously mentioned models belong to the category of statistics-based models. Thus far, no dedicated ALT models for harmonic drives have been proposed. In general, compared with statistics-based models, physics-statistics-based models assume in-depth understanding of the failure mechanism of corresponding components or materials, and are preferred whenever possible. However, since the failure mechanism and the performance degradation process of mechanical components are usually complex due to varying working conditions, an accurate physics-statistics-based ALT model cannot be easily established.

### 3. ALT model development

A harmonic drive typically consists of three subcomponents: a wave generator (WG), a flex spline (FS), and a circular spline (CS), as shown in Fig. 1. The flex spline is a compliant element, and its deformation is essential for the operation of a harmonic drive. Generally, the flex spline of a harmonic drive exhibits a cup shape which is coaxially connected to the output shaft.

![Fig. 1 An exploded view of a harmonic drive used in a spacecraft manipulator.](image-url)
To clearly show the circular spline, the flex spline is simplified as a gear-ring-shaped object in Fig. 1.

A harmonic drive may work under different operating patterns via varying the transmission chains and the service environment. For instance, the circular spline can be driven by the wave generator and the fixed flex spline. Besides, torque can be transmitted out of the flex spline aided by the wave generator while locking the circular spline. No matter what operating pattern a harmonic drive is working in, the flex spline deforms periodically, and the influences of material and geometrical model on the performance of the harmonic drive in this periodical deforming process have been deeply studied.20,21 A harmonic drive might have several types of failure modes, and fatigue fracture of the flex spline is the most common failure mode.5 For harmonic drives used in space applications, failure is easier to occur due to light load, including wear and fatigue. As wear is unlikely to occur as long as the manufacturer’s guidelines for assembly and lubrication are fulfilled,22 fatigue damage can still be the primary failure mode.

3.1. Derivation of the cumulative distribution function under segmental stress history

According to the Manson and Halford9 for mechanical components with fatigue damage as the primary failure mode, the approximate probability distribution function of product life, i.e., the cumulative distribution function, can be denoted as

$$F(t) = \frac{1}{0.18} \left[ a_0 + (0.18 - a_0) \left( \frac{t}{\eta} \right)^{\frac{2}{6}} \right]$$

$$a_0 > 0, \ 0 \leq t \leq \eta, \ \eta > 0 \quad (1)$$

where $\eta$ is the characteristic life, $a_0$ is the parameter which needs to be estimated, and $t$ is the time. When $t = 0$, $F(t) = a_0/0.18$, which is different from zero, and hence strictly, Eq. (1) is not a cumulative distribution function. However, since $a_0$ is typically less than 0.02, i.e., $a_0/0.18$ is very close to zero,9 Eq. (1) can be considered as a cumulative distribution function for most cases.

Additionally, Wang et al. pointed out that dependence of the characteristic life of rotating machinery versus stress could be described by the generalized Eyring model.23 As the thermal and radiation isolations for mechanical components like harmonic drives mounted on a satellite are usually good, thermal cycle and radiation in space are not likely to cause their malfunctions. Therefore, acceleration stresses of harmonic drives are usually rotation speed and load, and hence the corresponding generalized Eyring model can be represented as

$$\eta = \eta_0 \left( \frac{V_0}{V} \right)^x \left( \frac{P_0}{P} \right)^{\beta} \quad (2)$$

where $\eta$ is the characteristic life under an accelerated condition, $V$ and $P$ are the rotational speed and load under the accelerated condition, $x$ and $\beta$ are parameters to be estimated, $\eta_0$ is the characteristic life under a baseline condition, and $V_0$ and $P_0$ are the values of the rotation speed and load under the baseline condition, respectively.

As mentioned above, harmonic drives which are used in space mechanisms typically work under stress with a segmental nature. Without loss of generality, here we account for an arbitrary segmental stress history, as depicted in Fig. 2. Compared with the duration of each step, time of the increase or decrease of stress is very short; hence it is not shown in Fig. 2.

In Fig. 2, the test starts at $t = 0$. In Step 1, the test sample works under $S_1(V_1, P_1)$ until $t = t_1$, and then in Step 2, it works under $S_2(V_2, P_2)$ until $t = t_2$. The test continues in this way until it comes to an end. In an accelerated life test, $S_1(V_1, P_1), S_2(V_2, P_2), \ldots, S_i(V_i, P_i), \ldots$ and $t_1, t_2, \ldots, t_n, \ldots$ can be determined according to the real stress history. In Fig. 2, $V_i$ and $P_i$ denote the values of rotation speed and load in Step $i$, respectively.

Firstly, in Step 1, the test sample works under $\tilde{S}_1(V_1, P_1)$ from $t = 0$ to $t = t_1$, and the cumulative distribution function in $[0, t_1]$ can be represented by

$$F_1(t) = \frac{1}{0.18} \left[ a_0 + (0.18 - a_0) \left( \frac{t}{\eta_1} \right)^{\frac{2}{6}} \right] \quad 0 \leq t < t_1 \quad (3)$$

where $\eta_1 = \eta_0 \left( \frac{V_1}{V} \right)^x \left( \frac{P_1}{P} \right)^{\beta}$, is the characteristic life under $\tilde{S}_1(V_1, P_1)$. In the following context, $\eta_2, \eta_3, \ldots, \eta_i$ denote the characteristic life under $S_2(V_2, P_2), S_3(V_3, P_3), \ldots, S_i(V_i, P_i)$, respectively.

Then in Step 2, the test sample works under $\tilde{S}_2(V_2, P_2)$ from $t = t_1$ to $t = t_2$. Here we introduce $\tau_1$, which is determined by $F_2(t_1) = F_2(t_1)$, i.e., the fatigue damage under $S_1(V_1, P_1)$ from $t = 0$ to $t = t_1$ is equal to that under $\tilde{S}_2(V_2, P_2)$ from $t = 0$ to $t = \tau_1$. Hence, the test shown in Fig. 2 from $t = 0$ to $t = t_2$, i.e., in Steps 1 and 2, is equivalent to the test $t = 0$ to $t = t_2 - t_1$ under $S_2(V_2, P_2)$. Then the cumulative distribution function in $[t_1, t_2]$ can be represented by

$$F_2(t) = \frac{1}{0.18} \left[ a_0 + (0.18 - a_0) \left( \frac{t - t_1 + \tau_1}{\eta_2} \right)^{\frac{2}{6}} \right] \quad t_1 \leq t < t_2 \quad (4)$$

where $\eta_2 = \eta_0 \left( \frac{V_2}{V} \right)^x \left( \frac{P_2}{P} \right)^{\beta}$.

The test continues until Step $i$, and the cumulative distribution function in $[t_{i-1}, t_i]$ can be represented by

$$F_i(t) = \frac{1}{0.18} \left[ a_0 + (0.18 - a_0) \left( \frac{t - t_{i-1} + \tau_{i-1}}{\eta_i} \right)^{\frac{2}{6}} \right] \quad t_{i-1} \leq t < t_i \quad (5)$$

![Fig. 2](image-url) Arbitrary segmental stress history.
where \( \eta_j = \eta_0 \left( \frac{t_j}{t_j^*} \right)^\beta \) and \( \tau_{ij} = (t_{i-1} - t_{i-2} + t_{i-2}) \left( \frac{t_{i-1}}{t_{i-1}^*} \right)^\beta \). This is the cumulative distribution function for the segmental stress history.

3.2. The maximum likelihood function

Suppose that a total of \( n \) samples (harmonic drives) are under test. Each sample endures a segmental stress history, as shown in Fig. 2. As some of the tested samples are censored during the test, here we also take censored samples into consideration. For each sample, there are two characteristics which we should consider:

1. Censored or not (whether this sample is removed from the test prior to failure or not);
2. Complete stress history (censored/failure time, stress level in each stress segment, stress change time).

Suppose that the number of uncensored samples is \( n_1 \) and the number of censored samples is \( n_2 \). Here \( n = n_1 + n_2 \). Suppose that the \( j \)th sample, the number of steps of the stress history is \( t_j \), where \( j = 1, 2, \ldots, n \), and the segmental stress history is \( S_j(V_{ij}, P_{ij}) \), \( S_2(V_{ij}, P_{ij}) \), \( \ldots \), \( S_{ij}(V_{ij}, P_{ij}) \). Each \( S_j(V_{ij}, P_{ij}) \) corresponds to a stress level, including two types of accelerated testing stresses, i.e., rotation speed and load, and the corresponding stress change with respect to time is \( 0 \rightarrow t_{j1} \rightarrow t_{j2} \rightarrow \ldots \rightarrow t_{jg} \), as shown in Fig. 3. The test of the \( j \)th sample stops at \( t_{jg} \), and this is the failure or censored time for this sample.

Let \( \eta_j \) denote the characteristic life under \( S_j(V_{ij}, P_{ij}) \), and \( Y_j \) denote the failure or censored time for the \( j \)th sample, i.e., \( Y_j = t_{jg} \), in which \( Y_1, Y_2, \ldots, Y_n \) denote the failure time, and \( Y_{n+1}, Y_{n+2}, \ldots, Y_n \) denote the censored time.

The probability density function for the \( j \)th failure sample can be represented by

\[
 f_j(Y) = 0.18 - a_0 \cdot \eta_j^{-0.6} \cdot \left( \frac{Y_j - t_{jg-1} + t_{jg-1}}{\eta_j} \right)^{0.6} \]

(6)

where \( j = 1, 2, \ldots, n \), and \( \eta_j = \eta_0 \left( \frac{t_j}{t_j^*} \right)^\beta \) represents the characteristic life under \( S_j(V_{ij}, P_{ij}) \), while \( V_{ij} \) and \( P_{ij} \) denote the values of rotation speed and load from \( t_{jg-1} \) to \( t_{jg} \) for the \( j \)th test sample, respectively.

The reliability function for the \( j \)th censored sample can be represented as

\[
 R_j(Y) = 1 - \frac{1}{0.18} \left[ a_0 + (0.18 - a_0) \left( \frac{Y_j - t_{jg-1} + t_{jg-1}}{\eta_j} \right)^{0.6} \right] \]

(7)

where \( j = n_1 + 1, n_1 + 2, \ldots, n \), and \( \eta_{ij} = \eta_0 \left( \frac{t_j}{t_j^*} \right)^\beta \) represents the characteristic life under \( S_j(V_{ij}, P_{ij}) \), while \( V_{ij} \) and \( P_{ij} \) denote the values of rotation speed and load from \( t_{jg-1} \) to \( t_{jg} \) for the \( j \)th test sample, respectively.

Taking into consideration all the probability and reliability functions specified above, the maximum likelihood function can be represented as

\[
 L = \prod_{j=1}^{n} f_j(Y) \prod_{j=n_1+1}^{n} R_j(Y) \]

(8)

The log maximum likelihood function is

\[
 \ln L = \sum_{j=1}^{n_1} \ln f_j(Y) + \sum_{j=n_1+1}^{n} \ln R_j(Y) \]

(9)

After substituting \( l_1 = \sum_{j=1}^{n_1} \ln f_j(Y) \) and \( l_2 = \sum_{j=n_1+1}^{n} \ln R_j(Y) \), the log maximum likelihood function can be represented as

\[
 l = l_1 + l_2 \]

(10)

where \( l_1 \) can be calculated as

\[
 l_1 = \sum_{j=1}^{n_1} \ln \left[ 0.18 - a_0 \cdot \eta_j^{-0.6} \cdot \left( \frac{Y_j - t_{jg-1} + t_{jg-1}}{\eta_j} \right)^{0.6} \right] \]

\[
 = n_1 \ln(0.18 - a_0) - n_1 \ln 0.27 - 0.6 \sum_{j=1}^{n_1} \ln \eta_j + \frac{2}{3} \sum_{j=1}^{n_1} \eta_j^{0.4} \ln \eta_j \]

(11)

where \( \eta_j \) is the characteristic life for the \( j \)th unit under corresponding stresses, which can be calculated by Eq. (2).

In this ALT model, there are four parameters which need to be estimated, i.e., \( \eta_0, a_0, \alpha, \) and \( \beta \). With ALT data and an appropriate parameter optimization method, this model can be used to extrapolate lifetime under an arbitrary segmental stress history. Intervals for these parameters can be prespecified based on physical constraints, which would help reduce calculation time and increase accuracy.

Finally, the ALT model development process is illustrated in Fig. 4.

4. Parameter optimization

4.1. Interval pre-specification

The four parameters to be estimated in the proposed ALT model can be classified into three types, as shown in Table 1. The characteristic life of a harmonic drive under a baseline condition, \( \eta_0 \), is considered to be Type I. The design life of harmonic drives used in space mechanisms is typically several thousand hours.\(^{24}\) Here we set the interval for \( \eta_0 \) as \((0, 10^5]\).
The parameter in the cumulative distribution function, $a_0$, is considered to be Type II. This parameter has no explicit physical meaning. \(^9\) We set the interval for $a_0$ as $[0, 0.02]$. According to literature \(^9\), if $a_0$ is out of this interval, $F(t)$ in Eq. (1) could not be used as a cumulative distribution function.

The power exponents in the generalized Eyring model, $\alpha$ and $\beta$, are considered to be Type III. According to the summary in Ref. \(^{25}\), we set the intervals for $\alpha$ and $\beta$ as $(0, 10^3]$.

### 4.2. Parameter optimization with genetic algorithm

After an ALT of harmonic drives is carried out and lifetime data and a complete stress history are obtained, a maximum likelihood function can be obtained. The optimal parameters in the ALT model are the ones that make the maximum likelihood function have the maximum value. Therefore, the maximum likelihood function, Eq. (9), is adopted as the objective function, and with the pre-specified interval for each parameter, the optimization issue in this article can be written as:

$$
\max l = \max \left( \sum_{j=1}^{n_1} \ln f_j(Y_j) + \sum_{j=n_1+1}^{n} \ln R_j(Y_j) \right)
$$

being subject to the interval criteria

$$
\begin{cases}
0 < \eta_0 < 10^5 \\
0 \leq a_0 \leq 0.02 \\
0 < \alpha \leq 10^3 \\
0 < \beta \leq 10^3
\end{cases}
$$

### 5. Verification with experimental data

#### 5.1. Introduction to the experiment

An accelerated life test of a harmonic drive was carried out to validate the proposed ALT model. This type of harmonic drive, which was designed and manufactured by Beijing Harmonic Drive Technology Institute in 2013, was used in

GA is used in this work to achieve the optimal parameters for the proposed ALT model. It is apparent that this is a problem with multiple parameters and a single objective, and the corresponding relationship between input and output is complex. It is well known that GA can find the global optimum in a computationally efficient manner. Meanwhile, GA is sensitive to the value of the initial population. Without a relatively small pre-specified interval for the initial population, divergence might occur or the convergence speed could be very slow. As in the proposed model, $\eta_0$ means the characteristic life of a harmonic drive and its interval can be pre-specified based on engineering experience, while the intervals for the other three parameters could be pre-specified according to their mathematical meanings. In this case, GA is likely to find the optimal parameters very quickly, which makes it very suitable in parameter optimization for the proposed model.\(^{26}\)

The flow chart of GA used in this instance is shown in Fig. 5. Firstly, the total generation and population scale, as well as the crossover probability and mutation probability, are specified in the initialization step. Secondly, the initial random population is created based on the pre-specified parameter intervals. Thirdly, the fitness of each individual is evaluated. If the termination criteria is not satisfied, crossover and mutation are performed, and the fitness of each individual in the new population is evaluated until the termination criteria is met and the optimal results are obtained. Then in the optimal results, $\eta_0$ would be the lifetime of the tested harmonic drive under the baseline condition predicted by the proposed ALT model.

### Table 1 Parameters to be estimated in the proposed ALT model.

<table>
<thead>
<tr>
<th>Type</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$\eta_0$</td>
</tr>
<tr>
<td>II</td>
<td>$a_0$</td>
</tr>
<tr>
<td>III</td>
<td>$\alpha$, $\beta$</td>
</tr>
</tbody>
</table>
the antenna drive system of a satellite. The trade symbol was XB3-40. The test setup is shown in Fig. 6. Each set of test component consisted of an encoding disk, a stepper motor, a harmonic drive, a fly wheel, and a base. The fly wheel was used as load. The test was carried out in vacuum, and the vacuum degree was less than $1.3 \times 10^{-3}$ Pa. The number of test samples was 2. According to the user’s manual provided by the manufacturer, the flex spline of the tested harmonic drive is made of 30CrMnSiA, and the circular spline is made of 40Cr. The teeth numbers of the flex spline and the circular spline are 400 and 404, respectively, which give a transmission ratio of 100:1. Additional parameters of the tested harmonic drive are shown in Table 2.

The entire test setup is shown in Fig. 7. Two sets of tested components, as shown in Fig. 6, were placed in a vacuum container. Each set of tested components has an encoding disk to monitor angular displacement, and it also has several temperature sensors to monitor the temperatures at different positions. These signals were collected and conditioned by a data collection system. The data collection system consisted of an industrial control computer with an ADVANTECH PCI-1716 card. Data collection software was programmed with National Instruments LabVIEW®.

The sampling frequency for angular position was 10 Hz, and temperature information was collected every 10 s. Failure of tested samples was determined based on operation precision and backlash, as well as temperatures at certain positions. Thresholds of operation precision and backlash were set as 0.05 and 0.03, respectively by the test operators based on their experience and dismantling results of previous life tests of the same type of harmonic drive. Both operation precision and backlash can be determined from the angular displacement signal.

### 5.2. Data analysis and model verification

Typical operating conditions for this type of harmonic drive are a rotation speed of 0.16 ($^\circ$/s) and a load of 0.1 kg·m². The stress histories of Sample 1 and Sample 2 are shown in Tables 3 and 4, respectively. It can be seen that the failure times of Sample 1 and Sample 2 are 2221 h and 2510 h, respectively.

Since the number of samples is only two, the life test data of two harmonic drives of the same type are used. Both of them are censored samples, and their stress histories are the same, as shown in Table 5.

With the proposed ALT model and the parameter optimization method, the optimal parameters can be obtained. The total generation and population scale are set as $i_g = 600$ and $i_s = 100$, respectively. The crossover probability and mutation probability are set as $p_c = 0.6$ and $p_m = 0.001$, respectively. The search history of the optimal parameters is shown in Fig. 8.

It could be concluded from Fig. 8 that the objective indicator gradually converges to an optimal solution after 550 generations. The optimal result computed by GA in generations 500–600 is shown in Table 6. The optimal result is reached when GA evolves to the 590th generation, and after that, the parameters stay constant in the last 10 generations.

The final parameter optimization result is $\eta_0 = 3911$ h, $a_0 = 0.00231$, $x = 3.9727$, $\beta = 2.8194$, which indicates that the estimated life of the harmonic drive under a normal condition is 3911 h.

Life from the manufacturer is 4000 h, and the estimated life determined by the proposed model is close to that given by the manufacturer. There is only a 2.23% difference, which
The proposed model is acceptable. Moreover, this model can be used to calculate the lifetime under an arbitrary segmental stress history and hence could be very practical in estimating the lifetime of harmonic drives used in space mechanisms.

6. Conclusions

This article proposes a dedicated physics-statistics-based ALT model for harmonic drives, which is an astronomic precision instrument. This model uses the Manson fatigue damage rule to describe the fatigue failure process and a cumulative damage method to calculate and accumulate the damage caused by each segment in a stress history. After a maximum likelihood function is derived, GA is used to obtain optimal parameters in the model. The proposed model can be used to predict the life of a harmonic drive under any segmental stress history, including a baseline condition for harmonic drives used in a satellite endure a segmental stress history. With other mathematical or physical expressions to describe their corresponding failure processes, this model can be generalized to other types of mechanical transmission components in aerospace applications.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cja.2015.07.003.

References


Table 5 Stress histories of two censored units.

<table>
<thead>
<tr>
<th>No.</th>
<th>Start time (h)</th>
<th>Terminate time (h)</th>
<th>Rotation speed (°)/s</th>
<th>Load (kg · m²)</th>
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<tr>
<td>1</td>
<td>0</td>
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<td>0.08</td>
<td>0.1</td>
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<td>2</td>
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<td>2750</td>
<td>0.16</td>
<td>0.1</td>
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Table 6 Optimal parameters in generations 500–600.

<table>
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<tr>
<th>Generation</th>
<th>(\eta_0) (h)</th>
<th>(\alpha_0)</th>
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<th>(b)</th>
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<td>0.00241</td>
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<td>2.8209</td>
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<td>0.00232</td>
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Fig. 8 Search history of the optimal parameters for the proposed ALT model.

However, since verification is based on a limited number of samples, it is recommended that more samples be tested to further validate the accuracy of the proposed model. In addition, majority of mechanical transmission components mounted on a satellite endure a segmental stress history. With other mathematical or physical expressions to describe their corresponding failure processes, this model can be generalized to other types of mechanical transmission components in aerospace applications.


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