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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.

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

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is carried out and lifetime data under an accelerated condition are obtained, an ALT model is applied to infer the lifetime or other reliability indices under a baseline condition.

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 solar panel deployment systems and antenna drive mechanisms in spacecraft, fatigue fracture of the flex spline is the most important failure mode.[8] 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.[9] 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.[10] 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;[11] (2) the extended hazard regression (EHR) model that encompasses both the PH and AFT models as special cases;[12] (3) the extended linear hazard regression (ELHR) model that incorporates the time-varying coefficient effect into the EHR model and enhances its capability;[13] (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;[14] 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.[10,15] There are also other types of ALT models, such as a dedicated ALT model for solid lubricated bearings based on dependence analysis,[16] etc.

According to Elsayed's review,[10] 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 semi-parametric or 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.[17] 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.[18] Generally, the flex spline of a harmonic drive exhibits a cup shape which is coaxially connected to the output shaft.[19]

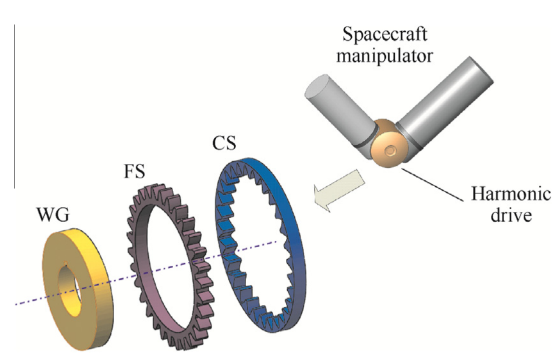

Fig. 1 An exploded view of a harmonic drive used in a spacecraft manipulator.