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An accelerated life test model for solid lubricated bearings based on dependence analysis and proportional hazard effect

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ABSTRACT

Solid lubricated bearings are important mechanical components in space, and accelerated life tests (ALT) of them are widely conducted. ALT model is needed to give the lifetime of solid lubricated bearings with ALT data, and former accelerated life test models of solid lubricated models are mainly statistical models, while physical models can imply an understanding of the failure mechanism and are preferred whenever possible. This paper proposes a physical model, which is called copula dependent proportional hazards model. A solid lubricated bearing is considered as a system consisting of several dependent items and Clayton copula function is used to describe the dependence. Proportional hazard effect is also considered to build the model. An ALT of solid lubricated bearing is carried out and the results show that this model is effective.

1. Introduction

Solid lubricated bearings are widely used in space drive mechanisms, like antenna drive mechanism and solar panel deployment mechanism. Like many other mechnical components in space drive mechanisms, their reliability is critical to the longevity of satellites and spacecrafts and has drawn more and more attention [1,2]. Failure of solid lubricated bearings might cause numerous economic loss, and therefore, providing the accurate lifetime of solid lubricated bearings is becoming more and more important. In engineering, life test is an effective way to get the lifetime of a product. However, lifetime of solid lubricated bearings used in space is usually very long. ALT is a feasible way to accelerate failure process and can shorten the test time. As a result, ALT has drawn more and more attention in life assessment of solid lubricated bearings. In ALT, testing specimen are working under more serious stress than in normal working condition, and failures can be induced in relatively short time. After getting data of failure time, ALT model is needed to infer the reliability of solid lubricated bearings at normal condition.

There are several types of commonly used ALT models. Accelerated failure time models (AFT) are the earliest and the most widely used ALT model. In an AFT model, it is assumed that under different stresses, failure time distributions are of the same type, and time to faiure at higher stress is shorter than that at lower stress. One of the most famous AFT models is the Arrhenius model [3]. Another type of ALT model is the proportional hazards model (PH), which was firstly introduced by D.R. Cox [4]. In a PH model, the failure rates are proportional to the applied stresses, and a PH model can take time dependent covariates into consideration. Other types of commonly used ALT models include (1) extended linear hazard regression model (ELHR), which considers time-changing, proportional hazard and time-varying coefficient effects, and the above AFT and PH model can be treated as special cases of ELHR model [5]; (2) proportional mean residual life model (PMRL), which is based on mean residual life

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proportionality [6]; and (3) proportional odds model (PO), which follows the idea in an medical observation and in this model, the defined odds functions under different stress levels are proportional to each other [7].

Elsayed classifies the existing ALT models into three categories: statistics-based models, physics–statistics-based models, and physics-experimental-based models [3]. According to this classification, all the models above belong to statistics-based models. For solid lubricated bearings, there has been an AFT model, which uses rotation velocity as acceleration stress [8]. Compared with statistics-based model, physics–statistics-based model implies an understanding of the underlying failure, so they are more preferred whenever possible [9]. However, in many cases, an accurate physics–statistics-based model is not easy to establish because failure mechanism of testing objects is usually very complicated.

In this work a physics–statistics-based model of solid lubricated bearings is built, and firstly, correlation between the structure of a solid lubricated bearing and its failure process is analyzed. A solid lubricated bearing usually has four parts, i.e., inner race, outer race, rolling elements and retainer. When a solid lubricated bearing is working, these four parts act against one another. And therefore, a solid lubricated bearing can be considered as a system with dependent items.

Copula function has been used to describe dependence, and M. Finkelstein applied the Clayton copula function on a new class of bivariate distributions [10]. Later he generalized the AFT model and PH model to the case of possibly dependent items, and derived a new ALT model for a series system consisting of two dependent items [11]. Here Clayton copula function is used to calculate the reliability function of the system with the reliability function of the two items, and proportional hazard effect is also taken into consideration. In this paper we introduce these ideas into the modeling for ALT of solid lubricated bearings. Based on the analysis of the failure mechanism of solid lubricated bearings, a physics–statistics-based ALT model for solid lubricated bearing is built. A solid lubricated bearing here is considered as a system consisting dependent items, and as a generalization to the work of M. Finkelstein, the number of dependent items is four. Meanwhile, the proportional hazard coefficients in the proposed model is calculated by the stress level. Parameters in this model is estimated with a numerical method, and then the model is applied to the data of an actual accelerated life test of solid lubricated bearings.

This paper is organized as follows. In Section 2, wear progress and fault mechanism of solid lubricated bearings are analyzed, and the copula dependent proportional

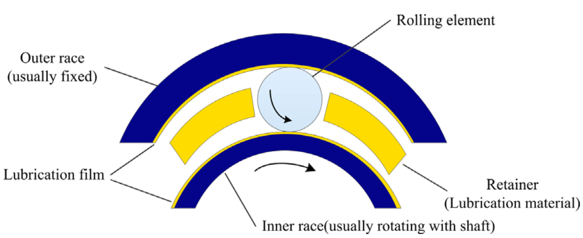

Fig. 1. Structure of a solid lubricated bearing.

model is built. In Section 3, parameter estimation of this model is illustrated, including the derivation of the likelihood function. In Section 4, an accelerated life test of solid lubricated is carried out, and the proposed model is verified by the experimental data. Section 5 concludes the paper.

2. ALT model development

2.1. Wear progress and fault mechanism of solid lubricated bearings

Structure of a solid lubricated bearing is shown in Fig. 1. Like bearings lubricated with oil or grease, a solid lubricated bearing usually has four parts, inner race, outer race, rolling elements and retainer. The difference is that usually in a solid lubricated bearing, inner and outer races are plated with solid lubrication film, the retainer is made of lubrication material and the rolling element is made of steel or other non-lubrication material.

When a solid lubricated bearing is working, no outer lubricant supplier is needed. Firstly, lubrication film on inner and outer races act as lubricant. As these part of lubricant gradually consumes, lubrication material on retainer is transferred onto inner and outer races by the rotation of rolling element and acts as lubricant. When both parts of lubricant are exhausted, a solid lubricated bearing turns into failure due to wear which is caused by lack of lubrication.

However, the wear process of a solid lubricated bearing is very complicated to clearly identify. Here are two main reasons. On the one hand, wear process of solid lubricated bearings is significantly affected by the transfer rate of retainer lubricant film. If this rate is too small, the bearing will gradually turn into failure after the lubricant on inner and outer races are consumed. If this transfer rate is too big, transferred film would accumulate on inner and outer races, which might lead to blocking and then cause heavy vibration and noise, and in this case, a solid lubricated bearing might turn into failure very quickly [12]. On the other hand, when lubrication material on retainer is transferred onto inner and outer races, the size of cagepockets becomes larger and the collision of balls on cagepockets will increase. This could aggravate the instability of retainers and accelerate the wear process.

It can be seen that as a compact component, solid lubricated bearing has complicated failure mechanism. When a solid lubricated bearing is working, the inner and outer races, the rolling elements and the retainer act against one another. Therefore, a solid lubricated bearing can be considered as a system with four dependent items. In the following section, based on this assumption and the ALT model of a system with two dependent items proposed by M. Finkelstein [11], we generate the ALT model of solid lubricated bearings.

2.2. Model development

M. Finkelstein derived an ALT model based on hazard proportionality [11]. With $\lambda_s(t) = k\lambda_b(t)$ to describe the