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Physics of failure-based degradation modeling and lifetime prediction of the momentum wheel in a dynamic covariate environment

Guang Jin [a,b,*], David Matthews [a], Youwen Fan [c], Qiang Liu [d]

[a] Department of Statistics and Actuarial Science, University of Waterloo, Waterloo, ON, Canada N2L 3G1
[b] College of Information System and Management, National University of Defense Technology, Changsha 410073, China
[c] Beijing Institution of Control Engineering, Beijing 100080, China
[d] The Secondary Artillery Equipment Academy, Beijing 100085, China

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ABSTRACT

We consider the problem of reliability modeling and evaluation of the Momentum Wheel (MW) in long-life satellites under small sample circumstances, proposing a physics-of-failure-based degradation model and life prediction method for such MWs in a dynamic covariate environment. From the results of a physics of failure experiment, we first derive models for the distribution and microcirculation of bearing lubricant. Next, we identify the qualitative and quantitative relationships between the key factors, e.g. rotation speed and bearing temperature, and the loss of lubricant. Then, taking the bearing temperature as a dynamic covariate, we build a degradation model for lubricant loss in the bearing assembly that corresponds to a Wiener process with drift that is positively associated with the covariate. To estimate the parameters of this degradation model, we use the method of maximum likelihood and the data from the physics of failure experiment. To predict the lifetime of an individual MW under orbital conditions, we suggest using Empirical Mode Decomposition (EMD) and regression analysis to model the trend in bearing temperature derived from telemetry data. Bootstrap simulation provides a satisfactory way of coping with the various sources of uncertainty in our prediction. Based on the predicted bearing temperature and the lubricant loss model, we estimate the amount of lubricant lost by an individual MW bearing, and hence obtain the lifetime of the lubrication system by comparing the predicted values for residual lubricant with the designed lubricant capacity. A case study involving data from a particular type of MW demonstrates the merits of this lifetime prediction method that we propose.

1. Introduction

The Momentum Wheel (MW) in a satellite attitude control system is a typical executive component that provides mission-critical orientation, stabilization, and energy storage for a long life satellite. The torque produced by changing the rotational speed of the MW is used to overcome the environmental disturbing momentum and stabilize the satellite [1–4]. Consequently, the performance of a long-life satellite in orbit depends largely on the operation of the MW; extreme reliability, long life and high precision of the MW are key requirements that ensure the success of satellite missions [5–7]. In the face of increased engineering requirements, such as extending the mission life duration of the MW from 3–5 years in the

* Corresponding author at: Department of Statistics and Actuarial Science, University of Waterloo, Waterloo, ON, Canada N2L 3G1.
E-mail address: guangjin.nudt90@gmail.com (G. Jin).

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mid-1960s to more than 20 years at present [8], ensuring the performance and reliability of components of the attitude control system such as the MW has become increasingly important.

But the high cost of ground life testing hinders the use of large-sample testing to explore the complex modes and mechanisms of MW failure. In addition, the current state of knowledge about liquid lubrication mechanisms in space is very limited. We can only test the reliability of the MW under 1:1 conditions [9,10], which means we can seldom obtain trustworthy failure data during any ground-based lifetime tests. As a result, to assess the degradation of the MW in orbit, and to predict its residual life, we lack a trustworthy model for MW failure. Using classical lifetime data inference and information fusion techniques, including Bayesian methods [9,11], previous researchers have tried to model the lifetime distribution; thus far, however, their efforts to assess MW performance in orbit and predict the remaining effective lifetime have not been fruitful. Despite the availability of orbital performance data accumulated by TELEDIX concerning 588 MWs operating without failure in 235 satellites during more than 2200 years of collective operation, the lack of progress in failure modeling has been singularly evident. And for most other companies, with newly-developed products, accumulating such a large amount of product failure data would be an overwhelming challenge.

Previous engineering practice and test results [12–14] have shown that the life and reliability of the MW depend largely on these same properties of its bearings. Thus, we could, perhaps, make better progress on the lifetime prediction problem for the well-designed, carefully manufactured, MW by relying on research results concerning its bearing components. Because of the overwhelming importance of bearings in nearly all modern industries [15], there is a deep pool of research focused on bearing life and reliability that first began in the 19th century. Most of this work concerns fatigue life. Since the first bearing life prediction equation of Lundberg–Palmgren, many investigators have proposed modifications and improvements, e.g. the Ioannides–Harris equation, the Zaretsky equation, and various modified models based on fatigue limit and debris contamination mechanisms [15]. Such formulae have been widely used in ground-based settings, as well as in some space applications [9].

However, using a fatigue life formula such as the Lundberg–Palmgren equation, or one of its modifications, to predict the lifetime of liquid-lubricated space bearings always yields unrealistic results because of the ultra-high precision involved in their production, and the comparatively low operational stress relative to rated stress that these components experience. For example, a 145-year 99% reliability life has been obtained for a particular type of MW. It is well known that fatigue and wear are no longer the primary failure mechanisms for liquid-lubricated space bearings under normal lubrication conditions [14,16–20]. Instead, the primary failure mechanism is lubricant insufficiency and the resulting lubrication failure. Armed with this insight, some researchers have initiated approaches that focus on the lubricant life of space bearings. Using Spiral Orbit Tribometer (SOT) test results as a starting point [21], proposed an exponential model to characterize the relationship between lubrication life and contact stress for Solar Array Drive Mechanism (SADM) bearings. Michael [22] adopted an Arrhenius model to describe the influence of temperature on the oxidation of the lubricant, and then predicted lubricant life based on the theory of accumulated damage. William and Mark [16] introduced a ball-pass (or stress cycle) model to predict the life of liquid-lubricated bearings. His approach is based on lubricant degradation at the sites in the inner race where Hertz contact stress in the boundary lubricating regime occurs; the applicable range of Hertz stress is 0.4–0.6 GPa. Other studies, such as those of [23,24], involve a qualitative lubrication loss mechanism under boundary lubrication conditions. Generally speaking, assessing the quantitative reliability of MWs based solely on the physics of failure is still a difficult problem.

Degradation-based reliability techniques provide another way of approaching the MW life prediction problem. In fact, researchers have attached increasing importance to reliability estimation based on performance degradation over time [25,26] because, in comparison with classical lifetime data inferential techniques, this approach facilitates more effective joint modeling of experimental data and the failure mechanism. For example, the Russian Academy of Sciences used this degradation-based method and the corresponding test technology to estimate the lifetime of the dynamically tuned gyroscope КИНЛ05-78. During 3000 h of testing under 1:1 stress conditions, various performance measures related to the gyro's life were monitored periodically. Based on the estimation method they used, the research team extrapolated the gyro's life to be 30,000 h. In another study [27], defined an MW life prediction model that used telemetry current data as a marker of the lubricant degradation process. Nevertheless, the literature concerning life prediction methods for liquid-lubricated space bearings is still rather limited.

As our introductory remarks have amply illustrated, the key issue is closely related to a lack of adequate sample data and the absence of an explicit failure mechanism model. Without adequate data and a corresponding model to fit, reaching a valid conclusion about the life and reliability of an MW represents a serious scientific challenge. In what follows, we propose a degradation-based model for MW reliability. We assume that a suitable covariate is provided, and proceed to develop a combined description of orbital performance and lifetime prediction that enables us to assess cumulative degradation and thereby predict the lifetime of an individual MW. The primary contributions of this paper are the following:

(1) Based on experimental results from the physics of failure and the current understanding in the literature, we propose a model for the microcirculation of lubricant in a space bearing, and derive a quantitative effect analysis of the corresponding mechanism for lubricant loss in space.
(2) Using this physics of failure analysis as our starting point, we next investigate a stochastic degradation model involving a dynamic covariate to characterize the lubrication life of a particular type of MW. We then present a detailed method of estimating the parameters in that model.