Storage Life Modeling and Analysis for Contacting Slip Ring Based on Physics of Failure

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***Abstract*— The storage life of the contacting slip ring in the inertial navigating platform cannot be easily estimated because of the difficulty of obtaining field data. This paper proposes a new approach about the storage life modeling and analysis for the contacting slip ring based on the combination of failure mechanism and statistical data. The analysis of failure mechanism shows that the increase of contact resistance caused by the stress relaxation of brushes and organic thin-film growth leads to the storage failure of the contacting slip ring in most cases. Based on the microscopic contact and thin-film electrical conduction mechanism, the relaxation resistance and thin-film resistance growth models are developed, which can transform the failure data of contact resistance into the storage life data. Some measures are presented to extend the storage life of the contacting slip ring through the life prediction and analysis of critical factors.**

***Index Terms*— Contact resistance, contacting slip ring, reliability, storage life, stress relaxation, thin-film growth.**

Nomenclature

Abbreviations

AIC	Akaike information criterion.
BIC	Bayesian information criterion.
LRM	Linear regression model.
MLE	Maximum likelihood estimation.
POF	Physics of failure.

Notation

A_i	Actual contact area of a single asperity, $i = 1, 2, \ldots, N$.
a_i	Actual contact radius of a single asperity, $i = 1, 2, \ldots, N$.
P_i	Actual loading of a single asperity, $i = 1, 2, \ldots, N$.
N	The number of asperities.
R	The average curvature radius of all asperities.
E_M	Elasticity modulus.
V	Poisson's coefficient.
$v(s)$	Stress relaxation rate.
A_E	Activation energy.
k	Boltzmann's constant.
α_1	Time dilution factor of relaxation rate.
T	Environmental temperature.
R_r	Relaxation resistance, Ω.
R_f	Thin-film resistance, Ω.
R_t	Total contact resistance, $R_t = R_r + R_f$, Ω.
ρ_i	Resistivity of two contact materials, $i = 1, 2$.
$\rho(l)$	Tunnel resistivity, $\Omega \cdot \mathrm{m}^2$.
l	Thin-film thickness, 10nm(10^{-8}m).
A_{app}	Total apparent area, m^2.
α_2	Temperature correction index.
τ	Temperature constant.
G_1	Fixed parameter, no relation with temperature.
G_2	Fixed parameter, no relation with the concentration of organic matter.
β_1	Another influence pattern of the concentration of organic matter on the thin-film growth rate.
β_2	Concentration correction index.
C	Reduced concentration.

Manuscript received June 4, 2017; revised July 19, 2017 and August 16, 2017; accepted September 6, 2017. Date of publication October 6, 2017; date of current version December 21, 2017. This work was supported by the National Natural Science Foundation of China under Grant 61473014 and Grant 61471385. Recommended for publication by Associate Editor T. J. Schoepf upon evaluation of reviewers' comments. *(Corresponding author: Xiaobing Ma.)*

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Digital Object Identifier 10.1109/TCPMT.2017.2751583

I. Introduction

THE contacting slip ring consists of slip rings, electrical brushes, seal chamber shells, insulating materials, precision bearings, binding materials, combination supports, and lubricant. As shown in Fig. 1, the most important parts of the contacting slip ring are slip rings, electrical brushes, and insulating materials. Specifically, the making material of slip rings and brushes is brass whose surface is plated with layers of a noble metal (hard silver) that can improve the contact quality. The type of plating is the barrel plating, where a very small amount of antimonic salt is added to increase the hardness of silver. The hardening effects mainly include four aspects: smoother and homogeneous, more attrition resistant, more corrosion resistant, but the slight increase of the contact resistance. The major ingredient of the insulating material is the epoxy resin, which is relatively easily oxidized under the condition of light, water, and heat. Moreover, the epoxy resin can dissolve in acetone. Slip rings contact with brushes relying on elastic pressure to realize the connection of the rotators and transmission of power and signals in the multifunctional,

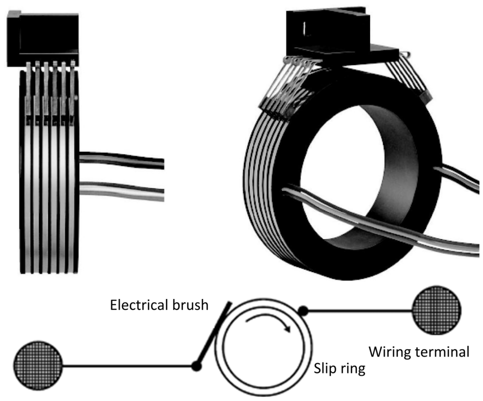

Fig. 1. Structure diagram and schematic of contacting slip ring.

and high-precision electronic equipment. Specifically, every set of electrical brush is corresponding to a set of slip ring, where the electricity can be carried by the sliding contact between electrical brushes and slip rings. However, the reliability of the sliding contact is relatively low due to the small contact surface, which causes the occurrence of most failures during the storage. Therefore, the emphasis of studying the storage life of the contacting slip ring lies in the contact problem between electrical brushes and slip rings.

Research is few on the storage life of the contacting slip ring. The existing literature mainly focuses on the statistical analysis of storage failure data. The disadvantages are the high cost of data collection and often missing data during sampling. Furthermore, even if the data can be fully collected, the single statistical analysis can only give the estimation results of storage life, but cannot reflect the failure mechanism and factors affecting the storage process, which makes it difficult to put forward specific life-extending measures. Consequently, it is necessary to model the storage life based on POF since the performance of device may be degraded during the storage phase, and the degradation data can be used for the evaluation of storage life. To be specific, the degradation (increase) of contact resistance (the resistance between electrical brushes and slip rings) leads to most failures, and many factors can affect the increase of contact resistance, such as material characteristics, contact stress, interface conditions, and temperature, and so on. Therefore, the degradation modeling considering main influencing factors for the contact resistance is crucial to the reliability and storage life analysis of the contacting slip ring.

The reliability analysis based on performance degradation has been widely applied in the engineering recently since the reliability of products becomes higher and higher, and a few failures occur in the life cycle. There are mainly three approaches for the degradation modeling based on the mechanism.

1) The degradation path model is suitable for the situation where the degradation path is relatively distinct and simple. Nelson [1] modeled the degradation path using LRM, which described the relationship between degradation measure and time. To deal with the case of rare or no failure data, Lu and Meeker [2] presented the Monte Carlo method for the nonlinear mixed effect regression model, which modeled the degradation path well. The degradation law of carbon film resistance was modeled using the linear degradation path [3].
2) The stochastic process model is suitable for the situation where the degradation studies for the product are sufficient, i.e., the stochastic process assumption should be justified with convincing proofs. Yang and Xue [4] used the continuous random process to describe the degradation measure of practical products. Furthermore, a model parameter estimation method was addressed in [5] when the degradation measure follows the Weibull distribution. Wei and Dietrich [6] proposed the half a likelihood reliability evaluation method based on the normal distribution.
3) The POF model can be divided into three categories, namely, the response theory model, the accumulative damage model, and the stress–strength model, which can be established and developed based on the actual product characteristics but requires professional analysis of failure physics. Lu and Pantula [7] established the failure model based on the response theory to solve the hot carrier problem of semiconductor transistor. According to the chemical and physical rule of failure caused by the increasing conductive fiber of insulating materials, Meeker and Luvalle [8] proposed the degradation path model. Furthermore, Meeker and Escobar [9] explored the crack growth process of sheet metal using the Paris model, which is used in the degradation analysis of fatigue failure frequently. Besides, the stress–strength model depends on the mutual relationship between the stress and strength, which was studied by Church and Harris [10].

However, there are few studies on the degradation modeling methods of storage life for the contacting slip ring, but studies on the electrical contact are extremely rich [11]–[13]. Therefore, based on the studies of electrical contact, this paper aims at investigating the modeling approach of storage life by analyzing the failure mechanism, which can tell us the life estimation and corresponding factors for the failure to adopt proper life-extending measures. Specifically, the performance degradation model of the contacting slip ring is modeled using POF method to formulate the storage life model. Moreover, the physical rule and scatter property of storage life are discussed, and the influence of several key factors, i.e., maintenance, electrical test on the storage life is studied.

The rest of this paper is organized as follows. Section III analyzes the storage failure of the contacting slip ring. Section IV gives the degradation model of contact resistance based on the stress relaxation of brushes. Section V gives the degradation model of contact resistance based on the thin-film growth. Section VI gives the estimation of storage life and life-extending measures. Section VII presents conclusions.

II. Storage Failure Analysis

A. Storage Environment Analysis

Generally, products such as the contacting slip ring are statically stored in a special warehouse or basement, where the