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A case study of remaining storage life prediction using stochastic filtering with the influence of condition monitoring

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ABSTRACT

Some systems may spend most of their time in storage, but once needed, must be fully functional. Slow degradation occurs when the system is in storage, so to ensure the functionality of these systems, condition monitoring is usually conducted periodically to check the condition of the system. However, taking the condition monitoring data may require putting the system under real testing situation which may accelerate the degradation, and therefore, shorten the storage life of the system. This paper presents a case study of condition-based remaining storage life prediction for gyros in the inertial navigation system on the basis of the condition monitoring data and the influence of the condition monitoring data taking process. A stochastic-filtering-based degradation model is developed to incorporate both into the prediction of the remaining storage life distribution. This makes the predicted remaining storage life depend on not only the condition monitoring data but also the testing process of taking the condition monitoring data, which the existing prognostic techniques and algorithms did not consider. The presented model is fitted to the real condition monitoring data of gyros testing using the maximum likelihood estimation method for parameter estimation. Comparisons are made with the model without considering the process of taking the condition monitoring data, and the results clearly demonstrate the superiority of the newly proposed model.

1. Introduction

The remaining life prediction of engineering systems has gained some momentum over the last decade owing to the increasing demand for higher efficiency, lower cost, and longer service time [1–4]. On one hand, accurate remaining life prediction is the key for better operations planning and maintenance scheduling of the industrial and military systems. On the other hand, remaining life prediction has become a major scientific challenge and bottleneck issue for the implementation of prognostics and health management (PHM) activities. With the advances in condition monitoring (CM) techniques and signal processing, the health state of systems can be monitored better than before, and therefore, the remaining life of the system can be inferred from the measured CM data more accurately. The remaining life of a system may include remaining useful life (RUL) (also called as remaining service life) and remaining storage life (RSL). For continuous working systems or systems working most of the time, such RSL is usually ignored and therefore the remaining life is equal to RUL. However, for those systems which are not working all the time, and particularly for some military systems which may spend most of their time in storage, the RSL will be of concern and cannot be ignored. The definitions of RUL and RSL depend heavily on the specific context and operational characteristics [5]. In general, the term RUL represents the period during which a system is expected to be usable for the purpose it was acquired, and RSL can be defined as the length of time that the system can be stored without losing its expected functionality. Thus, the studies for RUL and RSL are both important for those systems which may not work all the time.

The prediction of RUL has been widely studied for several decades [6–8] with a common assumption that the system's state remains constant while in storage if any. However, to our best knowledge, comparing with the immense studies on RUL estimation, very limited researches involving RSL prediction can be found in literature. Generally, the studies of the RSL prediction mainly focus on weapon systems, microelectronic components, batteries, synthetics, food, pharmaceuticals, etc. For example, Ning [9] presented a physics-based method for the RSL prediction of the missile inertial platform based on the analysis of the failure principle of the inertial platform. However, it depended highly on the physics knowledge of the inertial platform, which was usually hard to get due to the complexity of the practical systems and the variation of external environment. Wise et al. [10]

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Nomenclature

Acronyms

ALT	accelerated life testing
CM	condition monitoring
FR	failure replacement
INS	inertial navigation system
MLE	maximum likelihood estimation
MAPE	mean absolute percentage error
PDF	probability density function
PHM	prognostics and health management
PdR	predictive replacement
RSL	remaining storage life
RUL	remaining useful life
TMSER	total mean squared error for RSL predictions

Notations

t_i	the start time of the ith CM
t_n	the start time of the last CM (i.e. the nth CM)
t_f	failure time
X_i^-	RSL before the ith CM, with its realization x_i^-
X_i^+	RSL after the ith CM, with its realization x_i^+
Y_i	CM variable of the ith CM, with its realized value of y_i
r_i	CM duration of the ith CM
b	parameter that reflects the influence of the CM data taking process upon the RSL
c_f	FR cost
c_p	PdR cost
c_m	CM cost for each CM
$\mathfrak{I}_i$	CM history of y_i with $\mathfrak{I}_i = \{y_1, y_2, ..., y_i\}$
$\mathfrak{R}_i$	CM history of r_i with $\mathfrak{R}_i = \{r_1, r_2, ..., r_i\}$
$p(y_i \mid x_i^+, r_i)$	PDF of y_i conditional on x_i^+ and r_i
$p_i(x_i^+ \mid \mathfrak{I}_i, \mathfrak{R}_i)$	PDF of x_i^+ conditional on $\mathfrak{I}_i$ and $\mathfrak{R}_i$

proposed a lifetime prediction model based on the physical principles for microcircuits in storage and non-operating conditions. Bagherpour et al. [11] investigated the effects of storage aging and the concentrated hydrochloric acid on the mechanical properties of fiber glass polyester composite to determine the usability of glass-fiber-reinforced polymers sheet specimens that were stocked over 15 years and used in Iran steel company. Perfetti et al. [12] evaluated the influence of the storage conditions on the effective resistance to attrition using scanning electron microscope and repeated the impact test in aged coated particles, and the aging process was found to affect the breakage mechanism. Feng et al. [13] used a multi-phase Wiener degradation model to predict the storage life of high-voltage-pulse capacitor with a premise that the inspection to acquire the CM data (i.e. capacitance) is nondestructive. Moreover, the accelerated life testing (ALT) schemes have been widely carried out for RSL prediction problems. Ragnarsson and Labuza [14] reviewed the accelerated shelf-life testing methods for fatty food with an emphasis on the testing of antioxidant effectiveness. More recently, Mizrahi [15] provided a summary of the state of the art of the fundamentals of accelerated storage testing in food industry. For the ALT-based RSL predicting researches, readers are suggested to refer to above two review articles and the other papers therein. We will not review them again here since the study in this paper does not focus on the ALT-related methodologies. Specifically, the RSL prediction method and the case study discussed in this paper are different from the ones mentioned in the above papers in that both the CM data and the testing process of taking the CM data are considered together for RSL prediction. For some systems, taking the CM data may require that the system is under an actual using condition and therefore may accelerate the degradation and shorten the remaining storage time. This factor must be taken into account when predicting the RSL for those systems.

The case studied in this paper is based on the gyros equipped in inertial navigation systems (INS), which is a key component for some kinds of one-shot industrial and military systems (weapon systems in this case). In practice, gyros are tested at a condition similar to the actual condition to ensure the optimal performance. The CM data collected during the test is called the gyroscopic drift rate, which can reflect the long-term stability, and therefore, the evolution of the gyros' RSL. There are two types of degradation mechanisms for the gyros, the slow degradation caused by creep deformation in storage and rapid degradation during the drift rates taking process since the gyros are subjected to harsh operating environments similar to real operation use. The RSL is influenced mainly by these two types of degradations which can be partially reflected by the drift rates observed, but the number of and duration of taking the drift rates may directly impact on the RSL. It should be noted that there could be failure of the gyro due to its mechanical component problems either at storage or during testing. However, experience from the field told us that there have been no reported failures at all and all the replacements of gyros were due to the drift rate exceeding the threshold. Therefore, we assume that the gyros studied in this case study degrade gradually and the only failure is when the degradation represented by the drift rate exceeding the threshold.

As such, in this paper both the gyro's drift rate data and the influence of taking such drift rates are modeled with respect to the RSL prediction. It is noted that although we have investigated in literature for the life prediction methods (such as Weiner process, gamma process, proportional hazards model, etc.) [5], few models can be found to treat the case considered in this paper except the so-called stochastic filtering model proposed by Wang and Christer in [16]. Such model uses a stochastic filtering method on the basis of the conditional remaining time concept which defines the remaining life at the time of CM as the state of a monitored system. It differs from well-known Kalman filtering since any distribution can be used as the life time distribution, and also differs from particle filtering since analytical solution is available rather than using simulations [17]. Till now, it is proved to be an effective model for remaining life prediction after years of applications [18–22]. However, all the reported works of the stochastic filtering based prognostic model of this type mainly focus on the RUL prediction of the systems. In this paper we extend Wang and Christer's model in [16] to RSL prediction in this specific case study.

The rest of this paper is organized as follows. In Section 2, the gyro's working mechanism is described and the drift rate data of six liquid floated gyros are presented as the data for this case study. Section 3 focuses on the influence of the drift rates taking duration on RSL prediction and how it can be modeled within a general stochastic filtering structure. Section 4 presents the parameter estimation procedure in detail. In Section 5, the results and discussions for the case study are presented along with the comparative works with the model without taking the drift rates acquiring duration into account. Section 6 concludes the paper and highlights some further research directions.