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Support evidence statistics for operation reliability assessment using running state information and its application to rolling bearing

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ABSTRACT

Traditional reliability evaluation method generally requires a large amount of previous data and information on historical lifetime. For an individual mechanical device without historical lifetime data, it is difficult to carry out the reliability assessment by using the traditional method. To attempt exploring this difficult problem, support evidence statistics (SES) as an approach to operation reliability assessment is presented in this paper. Moreover, this presented method is also expected to indicate the physical state changes of the individual mechanical device. Since in scientific research, evidence usually goes towards supporting or rejecting a hypothesis. For a running device, evidences derived from the running state information should consistently demonstrate its current sole-running-state within a given short time interval. In practice, due to the interference of environmental noises, these evidences lose the consistency. Accordingly, they can be classified into two classes: the firm evidences and the flimsy evidences. Analogous to the support vector data description (SVDD), these firm evidences which show remarkable consistency can form a support evidence space (SESP) through one-class classification. Suppose that a SESP is obtained by using the evidences accumulated from the normal running state, the device operation reliability at any time of unknown running state can be evaluated through the statistical comparison between the normal SESP and the unknown SESP. This reliability evaluation process is named as SES. The most fundamental distinction between the proposed method and the traditional method lies in different statistical objects. The traditional methods are to analyze lifetime data while the proposed methods are to analyze running state data. Obviously, the evidence feature optimization plays a crucial role in the presented method. The maximum correlation and minimum redundancy (MCMR) method is improved by principal component analysis (PCA) to select evidence features based on vibration signals. Finally, the effectiveness of the presented method is validated through a new experiment of rolling bearing.

Abbreviations: SES, support evidence statistics; SESP, support evidence space; TES, test evidence space; NES, normal evidence space; SVDD, support vector data description; PCA, principle component analysis; MCMR, maximum correlation and minimum redundancy

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1. Introduction

Traditional reliability based on lifetime observation data plays an important role in almost all the aspects of mechanical manufacture industry, especially in design and production [1–5]. Since manufacturers care more about a large number of products, they mainly pay attention to the overall characteristics of products. Obviously, traditional reliability methods meet their requirements just quite well [6]. O'Connor [7] pointed out that reliability must be applied to the product's overall lifecycle from production to use. However, specific modern manufacturing processes often involve a specific machine, whose reliability cannot be individually investigated well by traditional methods [8]. In addition, for some critical equipment, especially which are small-lot and high-value equipment, reliability tests can be hardly be performed. Even if the reliability tests are eventually completed, they are maintained to be costly and time-consuming [9]. As a useful complement to the traditional reliability, Operation reliability has the potential capacity of characterizing the individual service performance of a product and expands the application domain of reliability.

Fong [10] pointed out that using condition-based monitoring information is an effective way to assess the characteristic performance of individual equipment in 2012. In early years, several studies have been done on operation reliability assessment in mechanical engineering [11–13]. For example, Chen [14] proposed a reliability estimation approach for cutting tools by performing the logistic regression on vibration signals. The operation condition information of the CNC machine is incorporated into reliability analysis to reflect time-varying characteristics of the product. Ma [15] developed a real time reliability evaluation method utilizing the field data, which integrates the advantages of reliability evaluation method based on performance degradation data and Bayesian method. Zhao [16] created a real-time reliability model of the product by using the on-site monitoring data through Bayesian method and the local updating ideas. Gebraeel [17] presented a Bayesian updating method in which the real-time condition monitoring information was used to update the stochastic parameters of exponential degradation models. Compared with the traditional methods, the advantage of the above reliability analysis methods is that they can make use of the information more comprehensively besides the lifetime data, hence the analysis accuracy is improved. However, with few exceptions, a certain amount of life test training samples are still indispensable in these methods. It is undeniable that their evaluation results of operation reliability are still affected more or less by the averaged behavior of prepared training samples. In addition, it is well known that the product reliability distribution shows certain dispersions in most cases, even though the products are of the same type and same batch. Therefore, It is worthy for the further research on how operation reliability reflects the individualized running characteristics of a specific device.

The bearing usually undergoes a degeneration process from a normal state to a failure state [18], which can be recorded through the bearing running state information. The bearing running state information is a kind of immediate response to the gradual degeneration process as well as a direct response to its service cumulative process, so the running information necessarily implies the valuable evidence concerning the bearing reliability. As such, revealing and utilizing these evidences is beneficial for bearing operation reliability assessment. If these evidences are collected within a short time interval, the majority of the collected evidences should show remarkable consistency, except for a small quantity of flimsy evidences derived from the seriously-contaminated signals. How to effectively distinguish the consistent evidences from the flimsy evidences? Analogous to the support vector data description (SVDD) [19–22], the problem can be formulated as a boundary method of one-class classification. By searching a hypersphere in the evidence space, a tight boundary is obtained. The obtained hypersphere contains almost all these consistent evidences, among which only a few evidences span the tight boundary. Therefore, these evidences spanning the tight boundary are called support evidences, and the space contained by the hypersphere is called a support evidence space (SESP). Actually, these support evidences are extreme vectors of these consistent evidences.

Apparently, two groups of evidences collected within two specific time intervals should show different distribution patterns in the bearing running process. Suppose that the first group of evidences is derived from the normal running state while the second group from unknown state, the first group is called normal evidences and the second group test evidences. Furthermore, the two SESPs formed by normal evidences and test evidences are called normal evidence space (NES) and test evidence space (TES) respectively. Considering a gradual degradation process in the entire lifecycle of bearing, topology relationships are investigated to illustrate the correlation between the NES and the TES. The solution procedure of topology relationships is actually a statistical comparison process, and hence the presented operation reliability assessment method is called support evidence statistics (SES). The most remarkable distinction between the presented method and the traditional method is that they have different statistical objects of their own. The presented method is to analyze the running state data while the traditional method is to analyze lifetime data.

There is no doubt that the evidence feature optimization is of vital importance for the presented method. In this paper, the total 146 time domain, frequency domain and time–frequency domain statistical features [23–26] are extracted from vibration signals as candidate features, and then the MCMR [27] are employed in the process of evidence feature optimization. However, the MCMR method frequently has a locally optimal solution because high values of similarity thresholds are usually adopted in practice. An improved MCMR enhanced by PCA are proposed to perform the evidence feature optimization in this paper.

Finally, a new experiment on rolling bearing is conducted by the group which the authors are belonging to. The experiment analyzing result shows that the presented method is a promising way to conduct accurate operation reliability assessment.