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Parameter auto-selection for hemispherical resonator gyroscope's long-term prediction model based on cooperative game theory

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ABSTRACT

As a new vibration gyro with features of high accuracy, long lifespan, no wear-out, and great reliability, the hemispherical resonator gyroscope's (HRG's) lifespan prediction without whole lifetime test is a tough task. Dai et al, based on data driven, proposed a residual modified autoregressive grey model ARGM to predict HRG's lifespan, in which the parameters however are selected by expert experience. In order to enhance the predictive lifetime, we propose a novel approach to auto-select parameters for the multi-parametric long-term prediction model ARGM based on cooperative game theory that we call CoG-ARGM. Our idea is to map parameter auto-selection of the prediction model to coalition formation in a combined cooperative game, which is proofed convex, where each parameter is respectively considered as a sub-coalition in its own pure cooperative game. In addition, we also bring failure mode originally derived from FMEA to evaluate the real-time prediction reliability. The experiments indicate that CoG-ARGM with real-time reliability evaluation yields high-quality prediction results. Furthermore, we also demonstrate the superiority of CoG-ARGM over state-of-the-art prediction methods through detailed experiments using evaluation criteria such as MAPE, Ln(Q) and time consumption on real HRG drift data.

1. Introduction

The hemispherical resonator gyroscope (HRG) [1], also called wine-glass gyroscope or mushroom gyro, is made using a thin solid-state hemispherical shell, anchored by a thick stem. With its outstanding reliability, high precision, no wear-out, and long lifespan, HRG is widely used in space applications [1], space launcher [2], and precision pointing applications [3]. Nevertheless, HRG is a high-tech device which requires sophisticated manufacturing tools. This high level of sophistication strongly limits the dissemination of this technology. Moreover, HRG is relatively expensive due to the cost of the precision ground and polished hollow quartz hemispheres. Therefore, the traditional methods such as whole lifetime test and accelerated life test [4,5] to analyze HRG are unsuitable. Prediction, a lifetime prejudging method, can not only evaluate life cycle of spacecraft, but also provide maintenance or replacement time for spacecraft, with no extra expenditure and no damage to units.

Prediction, a methodology which uses some techniques to find out the future trend based on existing data, can be divided into three categories such as short-term, medium-term and long-term forecast. In modern methods, grey theory-based (GM-based) [6–8], Neural Networks-based (NN-based) [9–11], Support Vector Machine-based (SVM-based) [12–14] are all famous prediction methods in many related studies. However, Dai et al [15] concluded that grey model is poor in analyzing nonlinear data while Back Propagation Neural Networks (BPNN) and SVM cannot response in a long-term period, as Fig. 1 shows. Therefore, Dai et al proposed an improved long-term prediction model for HRG, called grey auto-regression model ARGM, which outperforms GM, BPNN, and SVM, also seeing Fig. 1.

However, the parameters of the conventional ARGM [15] are selected by hand which degrades the reliability of the prediction. In this work, we propose a novel method based on cooperative game theory to auto-select these parameters, in order to enhance the predictive lifetime for HRG.

1.1. Motivation

Components with high reliability, like HRGs, can work for a long time because of advanced manufacturing techniques and materials, but it becomes more expensive and difficult to evaluate their lifetime with whole life testing or accelerated life test because of its sophisticated manufacturing as well as materials. Prediction in long term with existing data solves the problem, which saves the

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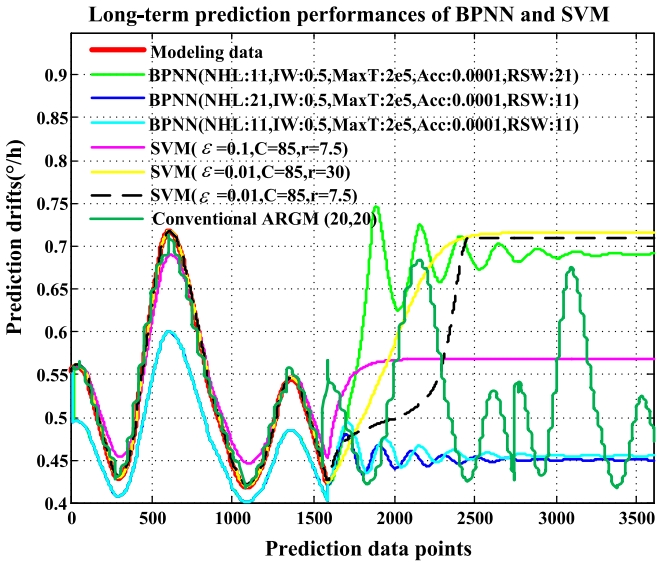

* NHL: Nodes in hidden layer of BPNN; IW: Inertia weight; MaxT: Max training times; Acc: Terminal accuracy; RSW: Regression step width of training; ε: Insensitive loss parameter of SVM regression; C: Penalty parameter; r: Kernel function parameter.

Fig. 1. Long-term prediction performance comparison.

extra expense and time. But in long-term prediction, we should face the problems of how to achieve the trend in data sequence and how to use it to predict the future. Dai et al [15] proposed a long-term prediction model, ARGM, for HRG and experiments indicate the model has good efficacy on long-term prediction, but parameters in that article are set according to expert knowledge, which obviously affects the reliability and completeness of prediction results. We bring in cooperative game theory to automatically select parameters for multi-parametric prediction model in this study. The relationship among parameters actually can be regarded as the competitors or collaborators to achieve the best results for the whole multi-parametric system, which is similar to the cooperative game. So we map the parameter auto-selection to the coalition formation in a cooperative game in our study. Meanwhile, prediction reliability enhances the reliability of model's prediction results, but it is seldom considered in existing prediction models in studies and in practice. Therefore, we also take the prediction reliability into account in our work to evaluate the prediction model in real time based on the failure mode derived from the FEMA system.

1.2. Related work

In the research [15], Dai et al proposed a long-term prediction model for HRG and the experiments indicate the model has good efficacy on long-term prediction, but the parameters in this model are set by hand, which obviously influences the reliability and completeness of prediction results. Namely, the impact to the prediction results is parameter selection. In order to improve the quality of prediction results for HRG, the optimal parameter selection is valuably explored. In practice, to search the optimal parameters, many works are done actually. Recently, the most famous methods for parameter optimization are hill climbing, evolutionary algorithms, and cross entropy.

Hill climbing [16] is a mathematical optimization technique which belongs to the family of local search. It is an iterative algorithm that starts with an arbitrary solution to a problem, then attempts to find a better solution by incrementally changing a single element of the solution. Moreover, hill climbing is good for finding a local optimum but it is not necessarily guaranteed to find the best possible solution out of all possible solutions.

Evolutionary algorithms often perform well approximating solutions to problems, but its computational complexity is a prohibiting factor in most real applications. As one popular evolutionary algorithm PSO (particle swarm optimization) is widely used in multi-parameter systems [17–19]. Whereas, PSO-based methods may result in premature convergence and it may get locally optimal solution because of the loss of species diversity in the search space.

Cross entropy method [20] is a general Monte Carlo approach to combinatorial optimization. The method aims to construct a random sequence so that it can converge to an optimal or sub-optimal solution within a probability, whose result relies on the probability distribution.

Although these methods can solve some problems of parameter selection, most of them select optimal parameters by searching all the potential parameters. In addition, it is necessary to propose more advanced or new techniques to solve parameter auto-selection for multi-parametric systems.

In this work, we auto-select optimal parameters for ARGM based on cooperative game theory. Optimal parameter auto-selection in the study is regarded as a coalition formation in which every single parameter is considered to cooperate and compete with each other. This process is similar to the cooperative game intuitively. Based on the cooperative game theory, the optimal parameter selection is auto-selected out without searching and comparing all the potential parameters. In another word, the idea based on cooperative game theory reduces the searching time consumption.

1.3. Contributions and outline

In this paper, we make following innovations and contributions:

(1) We propose a novel approach to improve the long-term prediction model ARGM for HRG's lifespan proposed by Dai et al [15] through auto-selecting the optimal parameters based on the cooperative game theory, that we call CoG-ARGM. To the best of our knowledge, it is the first try to use cooperative game theory to seek the optimal parameters instead of based on expert's experience.
(2) We formulate parameter auto-selection as a transferable utility (TU) cooperative game and proof the game is convex. It means that CoG-ARGM select optimal parameters without searching all the potential parameters, which saves much time compared with the state-of-the-art methods.
(3) Since the prediction reliability is seldom considered in the traditional prediction models, we put forward a reliability evaluation based on Failure Mode and Effect Analysis (FMEA) to measure model's real-time prediction reliability, to enhance the reliability of prediction results.
(4) We demonstrate the efficacy of our approach through detailed experimentation. CoG-ARGM is evaluated through predicting different lengths of data with different amounts of real drift data. The results of our experiments clearly show that the CoG-ARGM yields superior prediction results over the state-of-the-art methods with respect to the MAPE, Ln(Q), and the time consumption.

The rest of this paper is organized as follows: In Section 2, a succinct background encompassing important concepts from cooperative game and FMEA are provided and the long-term prediction model is also discussed in this section. Our parameter auto-selection method for long-term prediction model based on cooperative game theory is presented in Section 3. A detailed analysis

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