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Fault diagnosis of sensor networked structures with multiple faults using a virtual beam based approach

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ABSTRACT

This paper presents a virtual beam based approach suitable for conducting diagnosis of multiple faults in complex structures with limited prior knowledge of the faults involved. The "virtual beam", a recently-proposed concept for fault detection in complex structures, is applied, which consists of a chain of sensors representing a vibration energy transmission path embedded in the complex structure. Statistical tests and adaptive threshold are particularly adopted for fault detection due to limited prior knowledge of normal operational conditions and fault conditions. To isolate the multiple faults within a specific structure or substructure of a more complex one, a 'biased running' strategy is developed and embedded within the bacterial-based optimization method to construct effective virtual beams and thus to improve the accuracy of localization. The proposed method is easy and efficient to implement for multiple fault localization with limited prior knowledge of normal conditions and faults. With extensive experimental results, it is validated that the proposed method can localize both single fault and multiple faults more effectively than the classical trust index subtract on negative add on positive (TI-SNAP) method.

1. Introduction

Fault detection and fault localization techniques are among the prominent technical processes ensuring reliability. This is particularly true regarding safety related processes in contexts such as trains, power plants, and aircrafts characterized by limited datasets compiled through real measurements. In large space structures (LSS), it is practical to apply the sensor network to fault diagnosis, but it was not effective to use all of them in terms of computational complexity and efficiency [1]. Thus, the methods for sensor placement have been developed to obtain the fewer sensors for fault diagnosis. The effective independence (EfI) sensor placement method was proposed in [2] for selecting the fewer sensors for model identification of LSS according to their contributions to the linear independent target mode partitions. Afterward, the EfI has been widely applied to obtain the optimal sensor set for fault diagnosis [1,3,4]. To decrease the error between the real and estimated target mode, Genetic Algorithm (GA) was proposed for sensor selection from the candidates [5], which has proven to be superior to EfI by providing higher accuracy target mode for estimation at the cost of higher computational complexity.

With the continuous advances in sensor technology and senor placement methods, the sensor networks can be

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implemented for fault diagnosis of LSS with low-cost and high-efficiency. Though many fault diagnosis techniques have been proposed, most are not applicable because of certain serious disadvantages [6], e.g., unavailable of prior knowledge of faults, limited data collected from the normal operation conditions, the unfamiliarity of operational environment (for the measurement noise), etc. For example, since satellites are unreachable in remote space, their fault diagnosis has become a hot and challenging task [7]. Before the launch of a new satellite, the health condition of the system needs to be examined thoroughly. However, measurements need to be limited since each measurement of a satellite system is costly in terms of capital costs, fuel consumption, and material usage. More importantly, the system could get damaged if measurements are unduly frequent. In a typical experiment, it is usually practical to detect the system with limited priori assumptions. Such disadvantages factors have greatly increased the challenges associated with fault diagnosis. The presence of multiple faults implies the simultaneous presence of a set of single faults. The number of faults and faulty sites are usually unknown and some faults get masked by others [8,9]. These considerations render multi-fault localization a difficult task.

Most classical methods in use for solving the problem in question involve model-based fault diagnosis via estimation of the physical features of the structures using a set of mathematical equations. Generally, this group of methods produce accurate results, provided the physical information on the structure has been well defined [10,11]. However, if the parameters defined for the initial estimation of the state are not correct, then the fault detection and isolation are likely to be inaccurate. It means that the model-based methods would be less effective for fault diagnosis when there is a challenge for modeling the studied system. In assessing the state of health of a satellite system, there is a need for a more flexible and easy-to-implement technique that considers the unavailable prior knowledge and dynamic environment one encounters in space. In comparison to model-based fault diagnosis, model-free techniques are more flexible for fault diagnosis without dependence on specific structures. Model-free fault diagnosis can be data-driven or signal-based [12]. To address the harsh conditions with less or limited prior knowledge, among the data-driven methods, unsupervised methods are preferred where the data basis for fault detection is developed and trained using the knowledge obtained in normal operation conditions [13–15]. While it is more often for signal-based methods to detect the health condition of the system by matching the fault or unknown features to the basis functions (or known signal pattern) [8,16] when the prior knowledge of faults are unavailable. Even so, there is a challenge for above methods to obtain an appropriate threshold value for fault detection. Statistical methods and statistic-based indicators like Kolmogorov-Smirnov test (K-S test) [17–19], analysis of variance (ANOVA) [20,21], rank-sum testing [22,23], Bayesian hypothesis testing [24,25], and likelihood-ratio test [26–28] have been widely used for fault or damage diagnosis since they are standardized and easy to implement though the available data might be limited. The thresholds associated with a statistical test are obtained according to the *p*-values listed in statistical tables. This measures the underlying probability distribution differences between two group data, which has been successfully applied for fault detection of gears.

Among the model-free localization methods without a requirement of prior knowledge of faults, a series of binary estimators are proposed for fault localization because of simple, low-cost and fault-tolerant. In [29], a method named as subtract on negative add on positive (SNAP) was proposed for fault localization using the sensor networks. A likelihood matrix was created to record the (negative or positive) contribution of each sensor node based on their observations. The potential fault is isolated at the event with the maximum value in that matrix. To address the multiple fault localization, the method named as decentralized subtract on negative add on positive (DSNAP) [30] was developed, in which all the alarm sensor nodes were the fusion center and tracking the response of their neighbors. In [31], the frequently used binary estimators like fault tolerant maximum likelihood (FTML), Centroid Estimator (CE), Maximum Likelihood (ML), and SNAP were compared, indicating that the SNAP was superior to other three methods for fault localization in terms of accuracy and computational complexity. To decrease the negative influence of faulty sensors for localization accuracy, the strategy of trust index was adopted in SNAP, abbreviated as TISNAP [32], to assign the weights to the nodes from the sensor network based on their historic records in failing alarm. Generally, the localization based on sensor networks is effective and easy to implement for monitoring the large space structures.

1.1. The objective and contribution of this study

Based on the discussion above, this study is to develop a robust model-free method for the multiple fault diagnosis of complex structures, with possibly minor severity, without using prior knowledge of faults, and using only limited initial data from the normal conditions involved. Statistical approaches towards fault detection, together with adaptive threshold techniques, are utilized in the method. A virtual beam based approach is thus developed for multiple fault localization by taking into consideration of the damage information which could be captured by sensor networks regarding the changes of energy transmission. The "virtual beam", a recently-proposed new concept for fault localization in complex structures [6], consists of a chain of sensors representing a vibration energy transmission path embedded in a complex structure. The virtual beam can be constructed automatically using an optimization algorithm. To avoid the faults masking in a component, a new strategy named as "biased running" is developed and embedded in the evolutionary optimization algorithm for constructing the optimal virtual beams with biased sensors. In addition, a separation of sensor networks, which is based on components and a search space, is employed to reduce the computational complexity and improve the fault localization accuracy of the problem considered.

The existing method that is based on the principle of virtual beam [6] has demonstrated its effectiveness in single-fault localization without using prior knowledge of faults. However, it cannot be directly applied to the multiple-fault diagnosis