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Data-driven fault detection, isolation and estimation of aircraft gas turbine engine actuator and sensors ☆

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ABSTRACT

In this work, a data-driven fault detection, isolation, and estimation (FDI&E) methodology is proposed and developed specifically for monitoring the aircraft gas turbine engine actuator and sensors. The proposed FDI&E filters are directly constructed by using only the available system I/O data at each operating point of the engine. The healthy gas turbine engine is stimulated by a sinusoidal input containing a limited number of frequencies. First, the associated system Markov parameters are estimated by using the FFT of the input and output signals to obtain the frequency response of the gas turbine engine. These data are then used for *direct* design and realization of the fault detection, isolation and estimation filters. Our proposed scheme therefore does not require any *a priori* knowledge of the system linear model or its number of poles and zeros at each operating point. We have investigated the effects of the size of the frequency response data on the performance of our proposed schemes. We have shown through comprehensive case studies simulations that desirable fault detection, isolation and estimation performance metrics defined in terms of the confusion matrix criterion can be achieved by having access to only the frequency response of the system at only a limited number of frequencies.

1. Introduction

Research on aircraft gas turbine engine fault detection and isolation (FDI) has been at the core of an extensive body of literature [1]. Several excellent surveys and reviews have addressed this vast literature from various perspectives [1–4]. Model-based approaches constitute a major part of the aircraft gas turbine engine FDI literature [5–9]. The major drawback of model-based approaches can be associated with the need for a reasonably accurate mathematical model of the system, which is unfortunately rarely available. This fact has motivated researches to consider data-driven approaches as an alternative and a more practical solution [10–13]. Consequently, numerous data-driven solutions that are based on neural networks and machine learning [14–17], statistical and feature extraction methods [18], and fuzzy logic [19], among others have appeared in the literature. Yet, two challenges still remain outstanding. First, data-driven methods that are developed in the literature require a large amount of actual data that are difficult to process and can be as challenging to obtain as high fidelity mathematical models. Secondly, these methods have complicated structures that contain numerous tuning parameters that have to be determined or estimated through computationally involved procedures.

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In this paper, we propose a new data-driven fault diagnosis methodology to accomplish design and implementation of the fault detection, isolation and estimation (FDI&E) of aircraft gas turbine engine actuator and sensors. The design procedure is as follows. The healthy aircraft gas turbine engine is stimulated by a harmonic input containing a limited number of frequencies at a given operating point. The frequency response of the system is then obtained by computing the FFT of the input and measurement signals. Conventionally, one may invoke the *correlation analysis* to estimate the system impulse response coefficients (Markov parameters) from the frequency response data, however, our simulations have shown that this procedure is not robust when one is dealing with a low number of frequencies. Consequently, we utilize a method that is devised in [20], and which is robust for estimation of the Markov parameters. Once the Markov parameters of the system are estimated, we will be able to directly construct our proposed FDI&E filters as described in our work in [21,22].

Our proposed approach does not require any *a priori* knowledge of the system mathematical model. This is an important advantage over model-based techniques. Yet, it enjoys advantages of model-based techniques in terms of its simplicity and the guaranteed stability. It also has several advantages over the currently available data-driven solutions in the literature. First, our approach *does not* require availability of a large amount of data. The frequency response of the system at only a limited number of frequencies will suffice. Second, the FDI&E filters are *directly* and conveniently designed and constructed from the estimated Markov parameters. Consequently, one will *avoid* complicated trade-off studies, tuning techniques and iterative optimization procedures that are typically required in other data-driven methods such as statistical or neural network-based approaches that are developed in the literature.

It should also be noted that there are certain studies available that aim at identifying the system dynamics or tuning the thermodynamic model of the gas turbine engine by fitting a transfer function to the frequency response data [23]. One may suggest to utilize these models to first identify a model and then use model-based techniques to construct the FDI&E filters. This is not a reliable solution due to several reasons. First, for these methods *a priori* knowledge of the system number of poles and zeros is required. Different selection of the number of poles and zeros may lead to solutions that may not correspond to an accurate representation of the system actual dynamics. There is no formal and rigorous methodology for *a priori* optimally selecting the number of poles and zeros of the system model. Moreover, the system identification errors will stack up and compound with other errors that could result in an unreliable FDI&E scheme.

Our approach, on the other hand, allows a *direct design and construction* of the FDI&E filters from only the available system I/O data that can indeed significantly reduce the overall resulting representation errors. Finally, no *a priori* knowledge about the linearized model of the system as well as its number of poles and zeros are required.

To summarize, the *main contributions* of this work can be stated as follows:

- Development of a data-driven methodology for direct design of fault detection, fault isolation, as well as fault estimation filters by using only the gas turbine engine frequency response data that are collected at limited number of frequencies,
- Direct construction and realization of the FDI&E filters in the state space representation form, and
- Design and implementation of the FDI&E filters that do not require any *a priori* knowledge about the system order and its number of zeros.

This paper is organized as follows. The preliminaries are presented in Section 2. The Markov parameters estimation methodology accomplished by using the frequency response data is explained in Section 3. Section 4 is devoted to a detailed description of our proposed data-driven FDI&E schemes. Finally, comprehensive case studies simulations are presented in Section 5. The paper is concluded in Section 6.

2. Preliminaries

In this work, we have used the nonlinear model of a single spool gas turbine engine that was proposed and verified in [7] for generating the I/O data. We have provided a brief review of the mathematical model of the aircraft gas turbine engine [7] in Appendix A for convenience of the reader. This model has fuel flow rate as an input signal and five measurements that are denoted by T_C, P_C, N, P_T and T_T (representing the gas temperature after the compressor, the gas pressure after the compressor, the shaft rotational speed, the gas pressure after the turbine, and the temperature after the turbine, respectively).

All the measurements are noise corrupted, where the noise levels are taken from [7]. For our analysis, we have considered *one* actuator fault and *five* sensor faults. All the faults are additive in nature which represent the loss of effectiveness in the actuator and biases in the sensors. Our proposed scheme is based on our previous work [21,22] which requires that the following assumptions to hold, specifically (i) the aircraft gas turbine engine is stable and observable (at any given operating point), (ii) the gas turbine engine linearized model matrices and the order of the system at an operating point are *unknown*, (iii) the Markov parameters are to be estimated by using only the I/O data that are associated with the healthy (i.e., fault free) system, (iv) the gas turbine engine system has a well-defined relative-degree, and (v) the faults are detectable and isolable. Moreover, it is assumed that the feed-through matrix of the linearized model is zero.

For a given Power Lever Angle (PLA), the aircraft gas turbine engine reaches a steady state condition which defines a specific operating point. Therefore, we characterize an operating point by the level of the PLA, i.e. a PLA = 75% indicates and corresponds to an operating point when the PLA is set to 75% of its maximum PLA level. We have verified that the above