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Fault Detection and Diagnosis in Propulsion Systems: A Fault Parameter Estimation Approach

Ahmet Duyar*
Florida Atlantic University, Boca Raton, Florida 33431
Vasfi Eldem†
Marmara Scientific and Industrial Research Institute, Gebze, Turkey
and
Walter Merrill‡ and Ten-Huei Guo§
NASA Lewis Research Center, Cleveland, Ohio 44135

The paper presents the development of a fault detection and diagnosis (FDD) system with applications to the Space Shuttle main engine. The FDD utilizes a model-based method with real-time identification and hypothesis testing for actuation, sensor, and performance degradation faults.

Introduction

THERE is a growing demand to improve the control systems of liquid propulsion rocket engines for enhanced performance with increased reliability, durability, and maintainability. This demand can be met by improving the individual reliabilities of system components and also by an intelligent control system[1] with fault detection, diagnostics, and accommodation capabilities. This paper focuses on the development of a model-based fault detection and diagnosis (FDD) system that can be used as an integral part of such an intelligent control system.

During the last two decades of the development of fault detection methods, the so-called model-based fault detection approach has received considerable attention. These schemes basically rely on the idea of analytical redundancy. As opposed to physical redundancy, which uses measurements from redundant sensors for fault detection purposes, analytical redundancy is based on the signals generated by the mathematical model of the system being considered. These signals are then compared with the actual measurements obtained from the system. The comparison is done by using the residual quantities that give the difference between the signals being measured and the signals being generated by the mathematical model. Hence, the model-based fault detection and diagnosis can be defined as the determination of faults of a system from the comparison of the measurements of the system with a priori information represented by the model of the system through generation of residual quantities and their analysis.

In the absence of noise and modeling errors, the residual vector is equal to the zero vector under fault-free conditions. Hence, a nonzero value of the residual vector indicates the existence of the faults. When noise and modeling errors are present, their effect has to be separated from the effect of faults. In the simplest case, this is done by comparing the residual magnitudes with threshold values. Using the distribution of the residuals under fault-free conditions, one can determine threshold values to minimize false alarms and missed detections by selecting the level of confidence.

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*Professor, Mechanical Engineering Department.

†Research Scientist, Division of Applied Mathematics.

‡Branch Chief, Advanced Control Technology Branch, Mail Stop 77-1, 21000 Brookpark Road. Senior Member AIAA.

§Research Engineer, Mail Stop 77-1, 21000 Brookpark Road.

The basis for the isolation of a fault is the fault signature, i.e., a signal obtained from a diagnostic model defining the effects associated with a fault. A diagnostic model is obtained by defining the residual vector in such a manner that its direction is associated with known fault signatures. Furthermore, each signature has to be unique to one fault to accomplish fault isolation.

Since the generation of residual quantities is a central issue in model-based FDD schemes, it will be briefly reviewed in this section. Survey papers by Frank,[2] Gertler,[3] Willsky,[4] and Isermann[5] discuss the rich variety of approaches that have been proposed for the generation of residuals. These approaches can be classified as observer- or filter-based approaches, a parity relations approach, and parameter estimation approaches. The first two classes are closely related because it has been shown by Massoumnia[6] that a parity relations approach is equivalent to using deadbeat observers.

The basic idea within the observer- or filter-based approaches is to estimate the outputs of the system from the measurements or a subset of measurements by using either Luenberger observer(s) in a deterministic setting or filter(s) in a stochastic setting. Then the output estimation error or innovations in the stochastic case are used as a residual. The flexibility in selecting observer gains has been fully exploited in the literature, yielding a rich variety of fault detection schemes.

The parity relations approach is based on checking the consistency of the mathematical relations between the outputs (or a subset of outputs) and inputs. These relations may lead to direct redundancy, which gives the static algebraic relations between the sensor outputs, or temporal redundancy, which gives the dynamic relations between inputs and outputs.

All of the fault detection schemes either explicitly or implicitly are based on the assumption that faults cause changes in parameters of the system. In the parameter estimation approach system parameters are estimated on-line to monitor these changes for fault detection and diagnostics purposes. Therefore, it is a simpler and more direct approach than the others. In this approach fault decision logic can also employ the estimates of some physical parameters[5] such as efficiency, fuel consumption, etc., which can effectively be used in fault diagnosis logic.

It is believed that the success of an FDD scheme depends on the accurate and appropriate modeling of the faulty process. The model of the faulty process defines the effects associated with faults. If the faulty process is modeled to distinguish the faults, then the residuals carry meaningful information that can be used for diagnostics purposes. Therefore, the main attention of this work is devoted to the modeling of the faulty