Abstract

It is well known that, for many engineering systems, such as aircrafts and vehicles, there is a high demand for maintaining a system's safety during its operation. A fault in a system may lead to a complete break-down of the system operation. The detection and the handling of faults therefore play an important role in the design and operation of an engineering system.

In this project, a fault detection and diagnosis system using the concept of the Beard-Jones (BJ) filter is designed and demonstrated for a Multi-Input Multi-Output (MIMO) mechanical plate structure. The structure includes a top plate, a base plate, a disturance transducer, and three pairs of co-located sensors and actuators that bond the top and base plates together. Structural vibrations introduced by the disturbance transducer at the base plate are controlled by the three sensor-actuator pairs, such that the top plate can remain stationary despite the constant vibration excitation induced from the base plate. The main goal of the fault detection and diagnosis system is to detect and identify each actuator fault that may occur during the operation of the MIMO control system.

A transfer function representation of the plate structure is constructed through dedicated theoretical analysis and physical experiment. The theoretical analysis aims to derive the general mathematical expression of the transfer function model while the physical experiment, using the ModalVIEW software, aims to produce the parameters (such as mode shapes, damping ratios, and natural frequencies) of the transfer function model. For the purpose of fault detection, a state-space representation of the system with a defined dimension representing a pre-selected frequency range of concern is developed based on the identified transfer function representation of the system.

A fault detection process is constructed using the BJ filter detection theory that offers a set of straightforward design and implementation properties with a wide range of applicability. Essentially, a BJ filter acts as a state observer and produces the estimated output of a system under no-fault operation conditions. When a fault vector $\boldsymbol{f_i}$ is introduced into the system, the output difference between the fault system and the BJ filter will produce a specific directional residual associated with the fault such that the value of the output residual is stable and proportional to $\mathbf{C}\boldsymbol{f_i}$ (where $\mathbf{C}$ is the output matrix of the system). The key in designing the BJ filter is therefore to construct the detection gain matrix $\mathbf{L}$ based on a set of design criteria and restrictions. In particular, for a multiple-fault detection, two restrictions, namely the mutual detectability and the output separability, will need to be checked in priority.

In order to validate the BJ filter design principle and procedure, a random system with pre-defined fault vectors is first tested via simulation in MATLAB SIMULINK. A conceptual BJ filter structure for the underlying plate control system is then designed (assuming the satisfaction of the design restrictions) and tested in MATLAB SIMULINK via different configurations (namely, SISO configuration – considering one pair of the inputs and outputs of the real system only, 2I2O configuration – considering two pairs of the inputs and outputs of the real system only, and MIMO configuration – considering all three pairs of the inputs and outputs of the real system, respectively). Simulation results confirm that the designed conceptual BJ filters are able to detect the pre-defined faults in the both the random and the real plate systems successfully.

Upon the validation of the conceptual BJ filter design principle and procedure, an operable BJ filter is designed specifically for actuator fault detection of the given plate control system in real-time operations. Considering that the initial state-space model of the given plant does not meet the output separability requirement of the BJ filter design, an extended model of the system is proposed where the derivative of each output is included in the system output vector, thus extending the existing system from 3I3O to 3I6O. Such an arrangement guarantees that the extended system, while keeping the features of the original plate control system, provides a revised form of the system output matrix that satisfies the output separability requirement. The corresponding extended version of the BJ filter, capable of performing real-time actuator fault detection and diagnosis of the given plate control system, is then designed and validated via simulation in MATLAB SIMULINK.

The designed real-time BJ filter is finally tested via experiment. For effective actuator fault detection and diagnosis, a dual BJ filter configuration is implemented where one BJ filter acts as an online observer of the given plate system by producing the extended system output from the truncated model of the true plant, and another BJ filter acts as a fault detector and identifier by producing the required residual proportional to $\mathbf{C}\boldsymbol{f_i}$ (where $\mathbf{C}$ is the output matrix of the extended system). This arrangement takes into account the inevitable modelling errors between the real plant and the modelled plant used for the BJ filter design purpose, and increases the accuracy of the fault detection and identification in practice. A set of experimental data is obtained that verifies the design and implementation of the proposed BJ fault detection and diagnosis system for real-time operation of the given MIMO plate control structure.