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An application of $\mathscr{H}_\infty$ fault detection and isolation to a transport aircraft ☆

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Abstract

This paper presents an application of $\mathscr{H}_\infty$ fault detection and isolation (FDI) to the longitudinal motion of a Boeing 747-100/200 aircraft. FDI filters are synthesized for open-loop linear, time invariant (LTI) models of the aircraft to detect and isolate faults in the elevator actuator and pitch rate sensor while attenuating the effect of disturbances and noise on the fault signals. Simulations with a nonlinear B-747 aircraft model augmented with a flight controller in the presence of gust and noise validate the fault detection and isolation, the disturbance rejection, and the robust properties of the $\mathscr{H}_\infty$ LTI FDI filters.

Keywords: Fault detection; Diagnosis and isolation; $\mathscr{H}_\infty$-optimization; Aircraft applications

1. Introduction

The fields of fault detection and isolation (FDI) and fault tolerant control (FTC) have attracted much attention from control engineers, especially in the flight control community during the last 30 years. The increased dependency of our modern society on technologically complex systems has given rise to new levels of safety and reliability for these systems not previously considered. The most common approach to provide a system with FDI/FTC functionality is to use hardware redundancy (i.e. duplicate, triplicate, etc. the critical software and hardware and use a voting scheme to make a decision as to which component is faulty). The main drawbacks with the hardware redundancy approach is the added complexity and costs resulting from the additional weight and volume of the redundant elements. Another drawback is its un-reliability for components whose outputs are not easily measurable, e.g. actuators. Model-based FDI approaches address those drawbacks by using a mathematical model of the monitored system to make a fault/no-fault decision. Since no mathematical model is exact, robustness to modeling uncertainty becomes a critical issue. Observer-based FDI approaches are the most widespread among the model-based algorithms, and particularly $\mathscr{H}_\infty$-optimization-based methods are increasingly of interest due to the issue of robustness of the fault detection and isolation filter.

The basic concepts underlying observer-based FDI schemes are the generation of residuals and the use of an optimal or adaptive threshold function to differentiate faults from disturbances, see (Frank & Ding, 1997; Patton & Chen, 1997). Generally, the residuals, also known as diagnostic signals, are generated by the FDI filter from the available input and output measurements of the monitored system. The threshold function is used to robustify the detection of the fault by minimizing the effects from false faults, disturbances and commands on the residuals. For fault isolation, the generated residual has to include enough information to differentiate said fault from another, usually this is accomplished through structured residuals or directional vectors. Robustness of the FDI algorithm is determined by its capability to de-sensitize the filters from disturbances, errors, and model discrepancies.

In $\mathscr{H}_\infty$-optimization methods, the filtering problem is formulated so that different performance indexes are optimized. The FDI filter has two main design goals: to minimize the influence of nonfault signals (noise,

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disturbances, uncertainties, commands) on the residuals and to maximize the effects of the faults. These goals are often contradictory since usually a trade-off is required between the residual sensitiveness to faults and its robustness to non-faults. Solutions to the FDI problem using different $\mathscr{H}_\infty$-based techniques have already been proposed: for example, the factorization approach was studied in Ding and Frank (1990), Frank and Ding (1994), Ricatti-based approach solutions were given to the robust $\mathscr{H}_\infty$ filter problem in Edelmayer, Bokor, and Keviczky (1994), Mangoubi, Appleby, Verghese, and Vander Velde (1995), Edelmayer, Bokor, and Keviczky (1996); and the use of an integrated control/filter approach and a standard formulation of the problem were given in Stoustrup, Grimble, and Niemann (1997).

The importance of this paper is on the application (simulation) of the $\mathscr{H}_\infty$ Ricatti-based LTI FDI technique to a nonlinear system, the Boeing 747-100/200 aircraft, where issues of model uncertainty, realistic disturbances and robustness have to be accounted for in the design stage. Five $\mathscr{H}_\infty$ FDI filters are developed based on the open-loop aircraft model (i.e. independent from the controller design process) with the main design goal of detecting, isolating, and identifying faults in the longitudinal motion of the Boeing 747 aircraft during closed-loop flight: elevator actuator and pitch rate sensor faults. These five filters are designed at five different equilibrium points using the same interconnection and weights (the latter specifically designed for one of the trim points) in order to study possible strategies to cover the entire flight envelope (e.g. scheduling of filters, linear parameter varying approaches,...).

2. Literature survey

A chronological literature survey of $\mathscr{H}_\infty$ FDI applications is provided to further motivate the contribution of this paper. Most of these applications deal mostly with LTI systems where issues of model uncertainty and large deviations from equilibrium are not considered.

In Appleby (1990) an LTI application to the estimation of the lateral dynamics of a landing pad with uncertain sea motion using a robust estimator design, which parallels the μ-synthesis control design, was presented. Extending the previous results to include sensitivity analysis to model uncertainty (Mangoubi, Appleby, & Farrel, 1992) applied the same algorithm to the simplified longitudinal dynamics of an A4-D aircraft. Noise and wind gust disturbances were represented by the addition of wide-band noise filters for analysis but otherwise the analysis focused on linearized plants that changed with forward velocity. The fault detection factorization approach given in Frank and Ding (1994) was applied to an industrial electromechanical facility for sensor and actuator faults in Alcorta García, Köppen-Seliger, and Frank (1995).

A robust failure detection and isolation algorithm based on robust $\mathscr{H}_\infty$ estimation filters was presented in Mangoubi et al. (1995) and applied to the open-loop pitch dynamics of an underwater vehicle to detect a single actuator fault. Their analyses were based on open-loop LTI responses where the filters were designed for a nominal condition and tested for a second off-nominal LTI plant for robustness analysis. An empirical evaluation of an estimation algorithm based on $\mathscr{H}_\infty$ filtering techniques was applied in Kawabata and Fujita (1998) to a 2-D visual servoing tracking of a moving target with good results for fast parameters variations.

Focusing on the appropriate selection of the fault reference model (i.e. model matching-based approach) for the robust diagnostic residual generation, (Frisk & Nielsen, 1999) gave an example based on a second order DC-servo model with parameter uncertainties. An application of μ-synthesis and D–K iteration, using the integrated approach, to an inverted pendulum was given in Cardoso and Dourado (1999). The Youla parameterization and the two-degree-of-freedom controller formulation was used in Suzuki and Tomizuka (1999) for an integrated application of a fault detector and controller on a three mass system (LTI simulation, no noise). Douglas and Speyer (1999) proposed an approach using the geometric concepts behind the classical fault detectors of Beard (1971), Jones (1973), and Massoumnia (1986), but providing $\mathscr{H}_\infty$-norm bounding gains and fault enhancement through appropriate selection of a performance index. It also provided an application to a linearized model of the longitudinal dynamics of an F16XL aircraft with fault detection capabilities (accelerometer sensor and elevator faults) and with gust (first-order Dryden filter) and sensor noise in the simulation environment.

A robust failure detection filter for a reentry vehicle attitude control system was given in Agustin, Mangoubi, Hain, and Adams (1999). Their approach was based on dedicated failure detection filters for steady-state, build upon previous work in Mangoubi et al. (1995), and in $\mathscr{H}_\infty/\mu$ robust filters for transient fault detection. Nominal LTI filters were synthesized for faults on the aerosurfaces and on the jet thrusts for the lateral dynamics of the Space Shuttle Orbiter and their robustness tested by implementation with an off-nominal LTI plant.

The problem of fault detection was addressed through $\mathscr{H}_\infty$ robust estimator using Popov–Tsypkin multipliers in Collins and Song (2000). An application of the approach to a simplified longitudinal flight control system (i.e. short-period dynamics and LTI) with noise and disturbances resulting from Butterworth filters and considering system parameter fluctuations was given.