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FAULT DETECTION AND ISOLATION OF ACTUATOR FAILURES FOR A LARGE TRANSPORT AIRCRAFT

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ABSTRACT
We consider the problem of designing residual generators with least dynamical orders to solve actuator fault detection and isolation problems for a Boeing 747-100/200 aircraft. The main result of our analysis is the proof of feasibility of the complete isolation of all primary actuator/surface faults in the nominal case by using a minimal number of additional surface angle sensors. The analysis of the nominal case provides residual filter specifications which can be employed in a more realistic design, where robustness aspects with respect to external noise (gusts, measurements) and parametric/flight condition uncertainties are also considered.

1. INTRODUCTION

In this paper we address the detection and isolation of actuator faults for a Boeing 747-100/200 from the perspective of *fault tolerant control* (FTC). The main goal of FTC is to allow, after a successful identification of occured faults, the application of appropriate control reconfiguration to ensure a safe operation of the aircraft in the presence of identified failures or, in extreme cases, to guarantee a safe landing to the nearest airport. The most relevant faults for our analysis are related to four categories of primary control surfaces: elevator, stabilizer, ruder, and ailerons.

In numerous studies, the occurrence of actuator faults for the Boeing 747-100/200 aircraft has been addressed in a simplistic way, by assuming that all faults related to a surface category occur simultaneously [11, 8]. For example, it is typically assumed that all four elevators are simultaneously affected by the same fault or, equivalently, each elevator fault is assimilated with a global fault on all elevator surfaces. As a consequence, the typical approach to compensate the elevator faults is to use the stabilizer for the aircraft altitude control and ignore the possibility to employ, for the same purpose, the remaining healthy elevator surfaces. For the purpose of FTC, such a simplifying assumption of simultaneous elevator faults prevents exploiting the existing freedom in using healthy surfaces which could compensate (fully or partially) the disturbance induced by the faulty surfaces.

This way to address the fault occurrence problematic is clearly not appropriate for the purpose of FTC, where the precise information on the available healthy actuators/surfaces and faulty ones could be vital for a proper control reconfiguration. The usually existing redundancy in control surfaces allows to cope easier with partial failures providing an increased overall safety. Thus, handling only complete surface failures is not a realistic option for a FTC approach.

In this paper we focus on the design of residual generators with least dynamical orders to solve actuator fault detection and isolation problems for the Boeing 747-100/200 aircraft. The main result of our analysis is the proof of feasibility of the complete isolation of all primary actuator/surface faults in the nominal case by using a minimal number of additional surface angle sensors. The analysis of the nominal case provides residual filter specifications which can be employed in a more realistic design, where robustness aspects with respect to external noise (gusts, measurements) and parametric/flight condition uncertainties are also considered.

The paper is organized as follows. First we shortly review the solution of the fault detection problem using scalar output detectors with least dynamical order. The corresponding design procedure is based on the nullspace method in combination with dynamic cover techniques. This method is the basis to design a bank of residual generators to solve the more involved fault detection and isolation problems, where a given fault-to-residual influence structure must be achieved. The design methods of residual generators for fault detection and isolation have been recently implemented as robust numerical software, which extends the Fault Detection Toolbox [18] of DLR. The new tools served to study the feasibility of a complete fault detection and isolation of actuator faults for a Boeing 747-100/200 aircraft. Fault detection both at component (actuator) level as well as at the whole system level are discussed. Residual synthesis results are presented for detecting and isolating both longitudinal and lateral axis failures for several influence structures of increasing complexity. The main result of this paper is the solution of the complete isolation problem by employing a minimum number of additional surface sensors.

2. DESIGN OF LEAST ORDER SCALAR OUTPUT DETECTORS

Consider the linear time-invariant system described by the input-output relations

$$\text{(1)} \quad \mathbf{y}(s) = G_u(s)\mathbf{u}(s) + G_d(s)\mathbf{d}(s) + G_f(s)\mathbf{f}(s),$$

where $\mathbf{y}(s)$, $\mathbf{u}(s)$, $\mathbf{f}(s)$, and $\mathbf{d}(s)$ are Laplace-transformed vectors of the p-dimensional system output vector $y(t)$, m_u-dimensional control input vector $u(t)$, m_f-dimensional fault signal vector $f(t)$, and m_d-dimensional disturbance vector $d(t)$, respectively, and where $G_u(s)$, $G_f(s)$ and $G_d(s)$ are the *transfer-function matrices* (TFMs) from the control inputs to outputs, fault signals to outputs, and disturbances to outputs, respectively.

To detect faults, residual generator filters (or fault detectors) having the general form

$$\mathbf{r}(s) = R(s) \begin{bmatrix} \mathbf{y}(s) \\ \mathbf{u}(s) \end{bmatrix} \tag{2}$$

are employed, where $r(t)$ is the residual signal generated from the available measurements $y(t)$ and control inputs $u(t)$. A residual generator must fulfill two basic requirements: (1) to generate zero residuals in the fault-free case, for arbitrary control and disturbance inputs; (2) to generate nonzero residuals when any fault occurs in the system. These requirements can be made precise as follows:

Fault Detection Problem (FDP): Determine a proper and stable linear residual generator having the general form (2) such that:

(i) $r(t) = 0$ when $f(t) = 0$ for all $u(t)$ and $d(t)$;
(ii) $r(t) \neq 0$ when $f_i(t) \neq 0$, for $i = 1, \ldots, m_f$.

Besides the above two requirements, it is often required for practical use that the TFM of the detector $R(s)$ has the least possible McMillan degree. Note that as fault detector, we can always choose $R(s)$ as a rational row vector.

The fulfillment of requirement (ii) ensures that faults produce non-zero residual responses. When designing fault detectors this requirement for *fault detectability* is usually replaced by the stronger request that persistent (constant) faults produce asymptotically persistent (constant) residuals. This requirement is known as *strong fault detectability* and has a special importance for practical applications.

Let $G_{f_i}(\lambda)$ be the i-th column of $G_f(\lambda)$. A necessary and sufficient condition for the existence of a solution of the FDP is the following one [3, 9]:

Theorem 1 *For the system (1) the FDP is solvable iff*

$$\text{rank}\,[\, G_d(\lambda)\ G_{f_i}(\lambda)\,] > \text{rank}\, G_d(\lambda),\ \ i = 1, \ldots, m_f \tag{3}$$

The requirements (i) and (ii) of the FDP can be easily transcribed in equivalent algebraic conditions. The condition (i) is equivalent to

$$R(s)G(s) = 0 \tag{4}$$

where

$$G(s) = \begin{bmatrix} G_u(s) & G_d(s) \\ I_{m_u} & 0 \end{bmatrix}, \tag{5}$$

while the detectability condition (ii) is equivalent to

$$R_{f_i}(s) \neq 0,\ \ i = 1, \ldots, m_f \tag{6}$$

where $R_{f_i}(s)$ is the i-th column of

$$R_f(s) := R(s) \begin{bmatrix} G_f(s) \\ 0 \end{bmatrix} \tag{7}$$

Enforcing the strong detectability of constant faults is equivalent to ensure finite non-zero DC-gains for each column of $R_f(s)$, thus to ask

$$0 < \|R_{f_i}(0)\| < \infty,\ \ i = 1, \ldots, m_f \tag{8}$$

The conditions (4) and (6) (or (8)) lead to a straightforward design procedure:

FD Least Order Synthesis Procedure

1) Compute a minimal basis $N_l(s)$ for the *left nullspace* of $G(s)$.
2) Choose a rational vector $h(s)$ such that

$$R(s) = h(s)N_l(s)$$

has least McMillan degree and fulfills (6) (or (8)).
3) If necessary, replace $R(s)$ by $m(s)R(s)$, where $m(s)$ is chosen to achieve a desired dynamics for the resulting detector.

The scalar output detector $R(s)$ at Step 2) is determined as a linear combination of the basis vectors (rows of $N_l(s)$), such that conditions (6) or (8) are fulfilled. The above expression of $R(s)$ represents a parametrization of *all* possible detectors and is the basis for the class of *nullspace methods* introduced in [4]. While this work relies on using polynomial nullspace bases for $N_l(s)$, an alternative approach relying on proper rational bases has been proposed by the author in [14]. The main advantage of this latter method is to rely exclusively on reliable numerical techniques based on state-space computations (see Section 4).

3. SOLVING FAULT ISOLATION PROBLEMS

The more advanced functionality of fault isolation (i.e., exact location of faults) can be often achieved by designing a bank of fault detectors [5] or by direct design of fault isolation filters [16]. Designing detectors which are sensitive to some faults and insensitive to others can be reformulated as a *standard* FDP, by formally redefining the faults to be rejected in the residual as fictive disturbances.

Let $R(s)$ be a given detector and let $R_f(s)$ be the corresponding fault-to-residual TFM in (7). We denote $R^i_{f_j}(s)$ the (i, j) entry of $R_f(s)$. We define the fault influence matrix S, with the (i, j) entry S_{ij} given by

$$\begin{aligned} S_{ij} &= \ \ 1 \ \text{ if } R^i_{f_j}(0) \neq 0 \\ S_{ij} &= -1 \ \text{ if } R^i_{f_j}(0) = 0 \text{ and } R^i_{f_j}(s) \neq 0 \\ S_{ij} &= \ \ 0 \ \text{ if } R^i_{f_j}(s) = 0 \end{aligned}$$

If $S_{ij} = 1$ then we say that the fault j is *strongly* detected in residual i. If $S_{ij} = -1$ then the fault j is only *weekly* detected in residual i. The fault j is not detected in residual i if $S_{ij} = 0$.

The following *fault detection and isolation problem* (FDIP) can be now formulated: Given a $q \times m_f$ fault influence matrix S determine a bank of q stable and proper scalar output residual generator filters

$$\mathbf{r}_i(s) = R^i(s) \begin{bmatrix} \mathbf{y}(s) \\ \mathbf{u}(s) \end{bmatrix},\ i = 1, \ldots, q \tag{9}$$

such that, for all $u(t)$ and $d(t)$ we have:

(i) $r_i(t) = 0$ when $f_j(t) = 0, \forall\, j$ with $S_{ij} \neq 0$;
(ii) $r_i(t) \neq 0$ when $f_j(t) \neq 0, \forall\, j$ with $S_{ij} \neq 0$.

In this formulation of the FDIP, each scalar output detector $R^i(s)$ achieves an influence structure representing the

i-th row of the desired fault influence structure matrix S. For example, to achieve the complete isolation of maximum k simultaneous faults the choice $S = I_k$ is necessary. In many practical applications such a specification can not be achieved due to the lack of sufficient number of measurements. If we can assume that the faults occur one at a time, a so-called *week isolation* of k faults could be possible by using a specification matrix whose i-th row contains all ones excepting the element in column i which is zero. For example, for 3 faults S is chosen as

$$S = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

If this fault influence specification can be achieved, then the occurrence of fault i can be detected if all residuals (excepting the i-th residual) are non-zero. More insight on how to specify fault influence matrices can be found in [6].

Let S be a given $q \times m_f$ fault influence matrix and denote by $\overline{G}_f^i(s)$ the matrix formed from the columns of $G_f(s)$ whose column indices j correspond to zero elements in row i of S. The solvability conditions of the FDIP build up from the solvability of q individual FDPs.

Theorem 2 *For the system (1) the FDIP with the given fault influence matrix S is solvable if and only if for each $i = 1, \ldots, q$, we have*

$$\text{(10)} \quad \textit{rank}\,[\, G_d(s)\ \overline{G}_f^i(s)\ G_{f_j}(s)\,] > \textit{rank}\,[\, G_d(s)\ \overline{G}_f^i(s)\,]$$

for all j such that $S_{ij} \neq 0$.

The *standard* approach to determine $R(s)$ is to design for each row i of the fault influence structure matrix S, a detector $R^i(s)$ which generates the i-th residual signal $r_i(t)$, and thus represents the i-th row of $R(s)$. For this purpose, the nullspace method can be applied with $G(s)$ in (5) replaced by

$$G(s) = \begin{bmatrix} G_u(s) & G_d(s) & \overline{G}_f^i(s) \\ I_{m_u} & 0 & 0 \end{bmatrix}$$

and with a redefined fault to output TFM $\widetilde{G}_f^i(s)$, formed from the columns of $G_f(s)$ whose indices j correspond to $S_{ij} \neq 0$.

The resulting global detector can be assembled as

$$\text{(11)} \qquad R(s) = \begin{bmatrix} R^1(s) \\ \vdots \\ R^q(s) \end{bmatrix}$$

and has a total McMillan degree which is bounded by the sum of the McMillan degrees of the component detectors. Note that this upper bound can be effectively achieved, for example, by choosing mutually different poles for the individual detectors.

Using the least order design techniques described in this paper, for each row of S we can design a scalar output detector of least McMillan degree. However, even if each detector has the least possible order, there is generally no guarantee that the resulting order of $R(s)$ is also the least possible one. To the best of our knowledge, the determination of a detector of least global McMillan degree for a given specification S is still an open problem. A solution to this problem has been recently suggested in [20] and is summarized in the following synthesis procedure:

FDI Synthesis Procedure

1) For $i = 1, ..., q$
   - 1.1) Redefine disturbance vector d to include all faults f_j for which $S_{ij} = 0$.
   - 1.2) Redefine fault vector f by deleting all faults f_j for which $S_{ij} = 0$.
   - 1.3) Compute $R^i(s)$ of order ν_i using the **FD Least Order Synthesis Procedure**.
2) Ensure that for $\nu_i \leq \nu_j$, the poles of $R^i(s)$ are among the poles of $R^j(s)$.
3) Form the global detector $R(s)$ according to (11).

It was conjectured in [20] that the McMillan degree of $R(s)$ resulting with this procedure is the least possible one.

We describe now an improved two steps approach to design a bank of detectors, which for larger values of q, is potentially more efficient than the above standard approach. In a first step, we can reduce the complexity of the original problem by decoupling the influences of disturbances and control inputs on the residuals. In a second stage, a residual generation filter is determined for a system without control and disturbance inputs which achieves the desired fault influence structure.

Let $N_l(s)$ be a minimal left nullspace basis for $G(s)$ defined in (5) and define a new system without control and disturbance inputs as

$$\text{(12)} \qquad \widetilde{\mathbf{y}}(s) := N_f(s)\mathbf{f}(s),$$

where

$$\text{(13)} \qquad N_f(s) := N_l(s) \begin{bmatrix} G_f(s) \\ 0 \end{bmatrix}.$$

The system (12) has generally a reduced McMillan degree [19] and also a reduced number of outputs $p - r_d$, where r_d is the normal rank of $G_d(s)$.

For the reduced system (12) with TFM $N_f(s)$ we can determine, using the **FDI Synthesis Procedure**, a bank of q scalar output least order detectors of the form

$$\text{(14)} \qquad \mathbf{r}_i(s) = \widetilde{R}^i(s)\widetilde{\mathbf{y}}(s),\ i = 1, \ldots, q$$

such that the same conditions are fulfilled as for the original FDIP. The TFM of the final detector can be assembled as

$$\text{(15)} \qquad R(s) = \begin{bmatrix} \widetilde{R}^1(s) \\ \vdots \\ \widetilde{R}^q(s) \end{bmatrix} N_l(s)$$

Comparing (15) and (11) we have

$$\text{(16)} \qquad R^i(s) = \widetilde{R}^i(s)N_l(s),$$

which can be also interpreted as an updating formula of a preliminary (incomplete) design. The resulting order of the i-th detector is the same as before, but this two steps approach has the advantage that the nullspace computation and the associated least order design involve systems of reduced orders (in the sizes of state, input and output vectors).

The above procedure has been used for the example studied in [21, Table 2], where a 18×9 fault influence matrix S served as specification. Each line of S can be realized by a detector of order 1 or 2 with eigenvalues $\{-1\}$ or $\{-1, -2\}$. The sum of orders of the resulting individual detectors is 32, but the resulting global detector $R(s)$ has McMillan degree 6. Recall that the "least order" detector computed in [21] has apparently order 14.

4. COMPUTATIONAL ASPECTS

For numerical computations state space representation based algorithms have been developed to serve as basis for robust software implementations. For this purpose, a state space realization of (1) is employed

$$\begin{aligned} \dot{x}(t) &= Ax(t) + B_u u(t) + B_d d(t) + B_f f(t) \\ y(t) &= Cx(t) + D_u u(t) + D_d d(t) + D_f f(t) \end{aligned} \tag{17}$$

with the n-dimensional state vector $x(t)$. The corresponding TFMs of the model in (1) are

$$\begin{aligned} G_u(s) &= C(sI - A)^{-1}B_u + D_u \\ G_d(s) &= C(sI - A)^{-1}B_d + D_d \\ G_f(s) &= C(sI - A)^{-1}B_f + D_f \end{aligned}$$

A numerically sound computational approach to design scalar output residual generators with least dynamical orders has been proposed recently in [20]. This approach represents an enhancement of the minimal dynamic covers techniques introduced in [14], by employing Type I dynamic covers (instead Type II covers) to achieve the maximal order reduction of the resulting detector. A basic computational ingredient to perform Step 1) is a reliable numerical algorithm to compute least order rational nullspaces of rational matrices using state-space methods [14]. The main computation in this algorithm is the orthogonal reduction of the system pencil matrix of the realization of $G(s)$ in (5) to a Kronecker-like form, which allows to obtain, practically without any additional computation, a least order rational nullspace basis. The existence conditions of the solution (6) can be easily checked using the outcome of the nullspace computation algorithm [20]. The least order fault detector at Step 2) can be obtained by selecting an appropriate linear combination of the basis vectors by eliminating nonessential dynamics using Type I dynamic covers based order reduction [20, 15]. To perform Step 3), stable coprime factorization techniques can be used for which reliable numerical algorithms based on pole assignment techniques are available [12].

The efficient implementation of the enhanced **FDI Synthesis Procedure** requires an explicit updating of a preliminary design (16). State space realization based computations of $N_f(s)$ in (13) as well as of the resulting least order detectors $R^i(s)$ in (16) are described in [19]. Remarkably, the matrices of the underlying state space realizations of $N_f(s)$ can be obtained using exclusively orthogonal transformations on the system matrices of the original state space realization (17). By using these updating techniques, any need to determine minimal realizations has been practically eliminated.

For all underlying numerical computations robust numerical software is available in the DESCRIPTOR SYSTEMS Toolbox [13]. This software served to implement a first version of a FAULT DETECTION Toolbox [18], where several tools are available to solve the main classes of fault detection problems. The recently developed enhancements have been implemented in a new function `fdsyn` which is fully documented in [19].

5. MONITORING ACTUATOR FAILURES FOR A BOEING 747

The monitoring of primary actuator failures of an aircraft is of paramount importance for the aircraft safe operation and for a continuous situation awareness of pilots. In this section we address the fault detection and isolation of all FTC relevant actuator failures by combining component level and system level fault monitoring techniques. The main goal of our analysis is to prove the feasibility of a complete fault diagnosis system capable to localize individual or simultaneous actuator/surface faults.

For our study we consider the Boeing 747-100/200 aircraft for which a high fidelity nonlinear simulation model with a full set of control surfaces is available. This model with 11 primary control surface actuators (4 elevators, 1 stabilizer, 4 ailerons, 2 rudders) has been set up within the GARTER AG16 as a benchmark for FTC studies. The original model [7] with only pilot inputs has been used in several fault detection studies [8], with focus on various particular aspects mentioned in Section 1.

For the Boeing 747-100/200 aircraft several fault scenarios can be of particular interest. For example, the ability to detect of single primary actuator faults is of critical importance, since it can be seen as part of the aircraft specification according to the requirements of FAA/FAR and EASA/CS. Thus a minimum request from the FTC perspective is the requirement for the modern aircraft design that no single failure must lead to a catastrophic consequence.

Simultaneous faults can also occur, especially when surface damages occur. The detection and isolation of simultaneous faults requires a more involved residual generation system and also the availability of a sufficiently large number of measurements. Although surface angle sensors can be installed on each control surface, an interesting aspect is to determine the minimum number of sensors necessary to completely solve the fault isolation problem. We give an answer to this problem by combining component level and system level fault monitoring.

The main goal of our study of detectability and isolability of actuator/surface faults was to demonstrate the feasibility of FDI for a complete set of faults. The full isolation requires placing a minimum number of additional surface angle sensors. An interesting result of our study is also to reveal the best achievable isolation capabilities in the absence of additional sensors.

Only the nominal case is studied corresponding to a normal cruise flight. The obtained results, consisting of several designed residual generators and the corresponding fault-to-residual filter specifications, can serve as meaningful specifications for a more realistic design where input/output noise and uncertainties in the model parameters and flight conditions are also addressed. Finding the minimal number of additional sensors allowing the isolation of all surface faults is one of the main achievements of this study.

In what follows, we show first the capabilities of component level monitoring, which is traditionally used on present day aircraft. The intrinsic limitations of this approach, for example, to detect surface failures leading to loss of effectiveness, require addressing the FDIP using a system level monitoring. However, the system level approach has its own limitations due to the restricted number of available measurements, therefore a full FDI is not possible unless additional surface sensors are used. As can be easily guessed, the final solution of the FDIP is a combination of both approaches by employing a minimal number of sensors.

5.1. Component level monitoring

Typically actuators are modelled as first order linear systems which together with the corresponding control surfaces have transfer functions of the form

$$g_u(s) = \frac{K}{s+K} \tag{18}$$

Here the value of K is determined taking into account the physical rate limits of the respective surface, and represents an average value applicable to all flight conditions. Typical choices for the Boeing actuators are: $37/(s+37)$ for elevators, $0.5/(s+0.5)$ for stabilizer, $50/(s+50)$ for ruders and ailerons. The task of the fault detection at the actuator level is to detect typical actuator faults like "stuck actuator" (also called *lock-in place failure*), "actuator runaway" (also called *hard-over failure*), "free-play" (called also *float-type failure*), or loss of actuator effectiveness. In what follows we discuss some aspects of fault detection and isolation for a generic actuator.

Consider the actuator model (18) for which we would like to design a fault detector able to detect several fault types mentioned previously. For this purpose, a simple detector which estimates the deviation of surface position on the basis of measured control surface position and commanded control surface position is given by the simple observer-like structure

$$R(s) = \begin{bmatrix} 1 & -g_u(s) \end{bmatrix}$$

Note that the dynamics of filter can be arbitrarily assigned by replacing $R(s)$ with $m(s)R(s)$, where $m(s)$ is an arbitrary stable transfer function.

With such a detector, an actuator fault can be easily detected by checking the condition $r(t) \neq 0$. The stationary value of the residual signal $r(\infty)$ can be used also to estimate the actual DC-gain of the actuator, say g_0, and thus the actuator effectiveness. Since $g_0 = 1 - r(\infty)$, in the fault-free case we have $g_0 = 1$. DC-gain values in the range $[\,0,\,1\,]$ indicate a loss of actuator effectiveness with a zero gain indicating "free-play". Values outside this domain indicates either a "stuck actuator" in a certain position or even an "actuator runaway" (i.e., stuck in an extreme position).

The main weakness of this simple fault detection scheme is that it is not working properly in the case of surface position sensor failures. This lack of reliability against combined actuator and sensor failure could be a source of false alarms. Another potential problem is when the actuator is fault free but the corresponding control surface is damaged. The associated loss of effectiveness of the actuation/control surface system can not be detected in this way.

A typical approach to overcome the first weakness is to add hardware redundancy by increasing the number of sensors to a level which ensures a satisfactory reliability of measurements. A standard approach is to use a number of 3 sensors in a voting logic for validity checking. This is the minimum hardware redundancy to guarantee the reliability of monitoring. Interestingly, using model based fault detection techniques, it is possible to obtain practically the same level of confidence by using only 2 sensors. Thus, the model based approach provides a third "virtual" sensor.

The actuator system with two identical sensors is described by the transfer-function matrix

$$G_u(s) = \begin{bmatrix} 1 \\ 1 \end{bmatrix} g_u(s)$$

The fault TFM corresponding to the actuator fault f_1 and two sensors fault f_2 and f_3 is

$$G_f(s) = [\,G_u(s)\ I_2\,]$$

A possible least order detector for this setup can be chosen as

$$R(s) = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -g_u(s) \\ 1 & 0 & -g_u(s) \end{bmatrix}$$

and can be still realized as a first order system. The resulting fault detection system achieves the following fault-to-residual influence structure

$$S = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

Assuming that the actuator fault and sensor faults occur one at a time, this structure provides a complete isolation of a single fault by using the following isolation logic:

– actuator fault occurred if $r_1 = 0$, $r_2 \neq 0$, and $r_3 \neq 0$;

– first sensor failed if $r_1 \neq 0$, $r_2 = 0$, and $r_3 \neq 0$;

– second sensor failed if $r_1 \neq 0$, $r_2 \neq 0$, and $r_3 = 0$.

In this way, the occurrence of each fault can be reliably detected. For fault identification, the information provided by either residual signal r_1 or r_2 can be employed.

To address the second aspect of loss of control surface effectiveness a system level analysis could be appropriate (see next section).

For component level diagnosis more detailed actuator models can be used, by explicitly modelling the dynamics of all actuator components. Such an approach based on physical parametric models is also suited to serve for health monitoring purposes.

Another application of potential interests is to detect the so-called "oscillatory failure" (e.g., of a rudder) as a result of limit cycle oscillations. This type of failure can trigger an aeroelastic resonance behavior of the aircraft with unacceptably high loads. To detect this type of faults, the above detection scheme can be supplemented with an additional signal analysis based oscillation detection system (e.g., sub-band filtering followed by Fourier analysis).

5.2. System level monitoring

The monitoring of actuator faults at the system level is primarily intended to increase overall aircraft safety by detecting fault categories which can not be handled by the usual component level monitoring. Such faults are, for example, the loss of efficiency of control surfaces due to possible structural damages or as a result of icing.

The study of the nominal cases has as main purpose getting a clear understanding of the intrinsic limitations in solving the FDIP in an idealized situation. Furthermore, the achieved fault-to-residual specifications can serve as reference models for a model-matching formulation of the FDIP [17], where system variabilities (parametric, flight conditions) are fully considered.

Actuator fault diagnosis for the whole aircraft can be done in several ways. An approach advocated by several authors is to use so-called multi-models describing the aircraft in normal flight conditions as well as in faulty situations. A bank of *model detection* filters can be designed to ensure a desired model-to-residual signature allowing the application of a simple decision logic to identify the current model (normal or faulty). The main advantage of this approach is its simplicity, both because of a simple design of the detectors as well as because of the simple residual evaluation scheme. As main disadvantage we can mention the need for a large number of models (and thus detectors) to cover many faults and combinations of faults. Moreover, different levels of actuator efficiency loss are usually represented as separate models, thus making the number of necessary detectors increasing exponentially.

The approach we follow in our study is to model actuator faults as additive disturbances. The linearized fault model of the aircraft corresponding to a given set of parameter values and a specific flight condition (e.g., straight-and-level flight) has the standard input-output form (1) and the detector is designed in the filter form (2). The employed linearized models have been determined using the nominal values of the parameters.

The longitudinal and full order linearized state space models of the aircraft are given in [19] (see also Appendix A). These models correspond to the following parameter values: mass = 317,000 kg, center of gravity coordinates: $X_{cg} = 25\%$, $Y_{cg} = 0$, $Z_{cg} = 0$. The chosen flight condition is a straight-and-level flight at altitude 600 m, with speed of 92.6 m/s, with a flap setting at 20^o and with landing gear up. For more details on the employed model and for additional references see [19].

5.3. Pitch axis fault monitoring

To detect elevator and/or stabilizer faults, we use the longitudinal aircraft model in state-space form (17), where the state, input and output variables are defined as follows:

$$x = \begin{bmatrix} \delta q \\ \delta V_{TAS} \\ \delta\alpha \\ \delta\theta \\ \delta h_e \end{bmatrix} \left(\begin{array}{rl} pitch\ rate & [rad/s] \\ true\ airspeed & [m/s] \\ angle\ of\ attack & [rad] \\ pitch\ angle & [rad] \\ altitude & [m] \end{array} \right),$$

$$u = \begin{bmatrix} \delta_{eir} \\ \delta_{eil} \\ \delta_{eor} \\ \delta_{eol} \\ \delta_{ih} \\ \delta EPR_1 \\ \delta EPR_2 \\ \delta EPR_3 \\ \delta EPR_4 \end{bmatrix} \left(\begin{array}{r} right\ inner\ elevator [rad] \\ left\ inner\ elevator [rad] \\ right\ outer\ elevator [rad] \\ left\ outer\ elevator [rad] \\ stabilizer\ trim\ angle [rad] \\ thrust\ engine\ \#1 [rad] \\ thrust\ engine\ \#2 [rad] \\ thrust\ engine\ \#3 [rad] \\ thrust\ engine\ \#4 [rad] \end{array} \right),$$

$$y = \begin{bmatrix} \delta\alpha \\ \delta\dot{V}_{TAS} \\ \delta\theta \\ \delta q \\ \delta V_z \\ \delta h_e \end{bmatrix} \left(\begin{array}{rl} angle\ of\ attack & [rad] \\ acceleration & [m/s^2] \\ pitch\ angle & [rad] \\ pitch\ rate & [rad/s] \\ vertical\ velocity & [m/s] \\ altitude & [m] \end{array} \right)$$

There are no disturbance inputs. The matrices A, B_u, C, and D_u for this model are given in Appendix A. The elevator and stabilizer fault inputs are defined as

$$f = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \end{bmatrix} \left(\begin{array}{r} right\ inner\ elevator\ fault [rad] \\ left\ inner\ elevator\ fault [rad] \\ right\ outer\ elevator\ fault [rad] \\ left\ outer\ elevator\ fault [rad] \\ stabilizer\ fault [rad] \end{array} \right)$$

and thus $B_f = B_u(:, 1:5)$ and $D_f = D_u(:, 1:5)$.

The achievable fault influence structure is

$$S = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 \\ -1 & -1 & 0 & 0 & 0 \\ 0 & 0 & -1 & -1 & 0 \\ 0 & 0 & 0 & 0 & -1 \end{bmatrix}$$

From the last three lines of S it can be observed that the isolation of faults grouped in three groups (f_1, f_2), (f_3, f_4) and f_5 is achievable, although all groups are only weekly detectable.

System level monitoring can be used as a complementary tool to the device level monitoring in the case when sensor fault monitoring is not additionally provided. The simplest fault detection task is to determine if any actuator fault in the pitch axis occurred. This comes down to design a fault detector achieving the trivial influence structure corresponding to the first row of S

$$S_0 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

by using the lowest order dynamics. To design such a detector, the function `fdsyn` has been used. Using the least order design option, a first order residual generator can be determined. The resulting fault-to-residual dynamics is

$$R_f(s) = \begin{bmatrix} \frac{10}{s+10} & \frac{10}{s+10} & \frac{10.43}{s+10} & \frac{10.43}{s+10} & \frac{-5.188s+58.45}{s+10} \end{bmatrix}$$

If we would like to isolate elevator and stabilizer faults, only the following choice of the influence matrix is achievable

$$S_1 = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & -1 \end{bmatrix}$$

with the second row having only a weak detectability structure. If we assume that elevator and stabilizer faults can not simultaneously occur, we can achieve elevator and stabilizer fault isolation by using the specification matrix

$$S_2 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

To isolate (f_1, f_2, f_3, f_4) and f_5 the following decision logic can be used:

- elevator fault occurred if $r_2 \neq 0$;
- stabilizer fault occurred if $r_1 \neq 0$ and $r_2 = 0$.

A residual generator achieving the above specification can be obtained as a bank of two detectors using the function `fdsyn`. Using the least order design option, two first order detectors can be determined, leading to a residual generator of total order 2.

Provided we can assume that the groups of faults (f_1, f_2), (f_3, f_4) and f_5 do not simultaneously occur, the achievable specification

$$S_3 = \begin{bmatrix} 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 \end{bmatrix}$$

can be used for week isolation using the following decision logic:

- inner elevator fault occurred if $r_1 = 0$, $r_2 \neq 0$, and $r_3 \neq 0$;
- outer elevator fault occurred if $r_1 \neq 0$, $r_2 = 0$, and $r_3 \neq 0$;
- stabilizer fault occurred if $r_1 \neq 0$, $r_2 \neq 0$, and $r_3 = 0$.

Using the least order design option, three first order detectors can be obtained using the function `fdsyn` leading to a detector of total order 3. Note that without the least order design option, a detector of total order 10 results, while

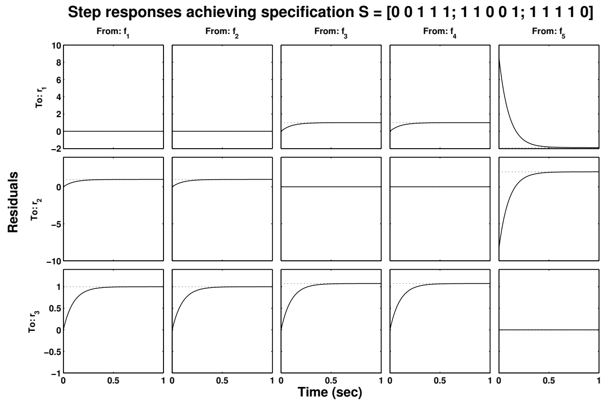

FIG. 1: Step responses from the faults: $f_1 = 1$, ..., $f_4 = 1$, $f_5 = 0.01$.

using the standard observer based approach (see for example [10]), a detector of total order 15 is to be expected. The resulting fault-to-residual dynamics is

$$R_f(s) = \begin{bmatrix} 0 & 0 & \frac{10}{s+10} & \frac{10}{s+10} & \frac{862.7s-1889}{s+10} \\ \frac{10}{s+10} & \frac{10}{s+10} & 0 & 0 & \frac{-835.1s+2028}{s+10} \\ \frac{10}{s+10} & \frac{10}{s+10} & \frac{10.74}{s+10} & \frac{10.74}{s+10} & 0 \end{bmatrix}$$

The step responses from the faults are presented in FIG. 1.

A more realistic setting is to add actuator dynamics to each input actuator-surface channel [8]. As already mentioned, the elevator dynamics can be approximated by transfer functions of the form $37/(s+37)$, while for the stabilizer dynamics we take $0.5/(s+0.5)$ as suggested in [8]. The resulting model has now order 10 and we can achieve the same influence structure with a bank of three detectors of total order 6. The step responses from the faults are presented in FIG. 2.

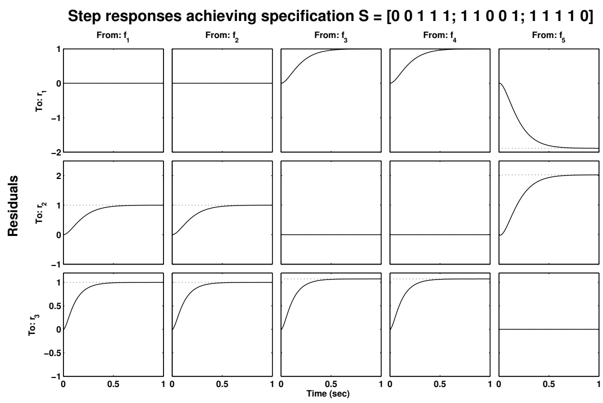

FIG. 2: Step responses from the faults with actuator dynamics included: $f_1 = 1$, ..., $f_4 = 1$, $f_5 = 0.01$.

Further enhancement of fault isolation is possible by employing direct measurements of surface positions. For example, with a single additional measurement of the stabilizer surface angle it is possible to achieve the specification

$$S_4 = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

and thus to isolate inner elevator, outer elevator and stabilizer faults. The above specification can be achieved using a bank of three detectors of total order 5. The step responses from the faults are presented in FIG. 3.

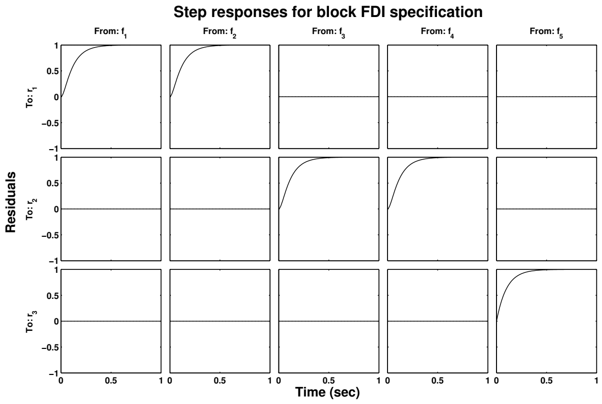

FIG. 3: Step responses from the faults with stabilizer angle measurement.

Finally, for a complete fault isolation it is to be expected that measurements from all surfaces are necessary. Solving the fault detection and isolation problem corresponds to achieve the specification $S_5 = I_5$ using the function `fdsyn` or employing directly the specially devised function `fdi`, available in the FAULT DETECTION toolbox [18]. This latter function is based on the method proposed in [16]. Using this function, we obtain a detector of order 5 which solves the complete fault detection and isolation problem. Interestingly, this detector is the same as that one obtained by using single surface monitoring schemes. This remarkable result also illustrates the real strengths of the recently developed minimal degree design techniques [16]. In contrast, the methods traditionally used (e.g., using a bank of 5 observer based detectors [10]) could lead to detector of total order up to 70 in the case when actuator dynamics are included.

Interestingly, the complete isolation can be also achieved by choosing a minimal number of three surface measurements: two from the left elevators and one from the stabilizer. The resulting bank of five detectors has a total order of 7 and achieves the fault-to-residual specification

$$R_f(s) = \text{diag}\left(\frac{10}{s+10}, \frac{370}{s^2+47s+370}, \frac{10}{s+10}, \frac{370}{s^2+47s+370}, \frac{10}{s+10}\right)$$

The step responses from the faults are presented in FIG. 4.

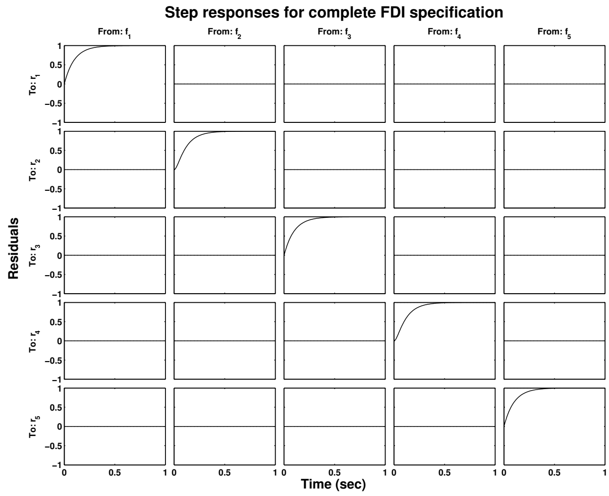

FIG. 4: Step responses from the faults with left elevators and stabilizer angles measurements.

5.4. Gear and roll axes fault monitoring

To detect rudder and/or aileron faults, we consider the full order ($n = 10$) aircraft model in state-space form (17). The definition of state, input and output variables and the corresponding state space matrices are given in Appendix B of [19]. The aileron and rudder fault inputs are defined as

$$f = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \end{bmatrix} \left(\begin{array}{rl} right\ inner\ aileron\ fault & [rad] \\ left\ inner\ aileron\ fault & [rad] \\ right\ outer\ aileron\ fault & [rad] \\ left\ outer\ aileron\ fault & [rad] \\ upper\ rudder\ fault & [rad] \\ lower\ rudder\ fault & [rad] \end{array} \right)$$

For the two inner aileron faults $\{f_1, f_2\}$, two outer aileron faults $\{f_3, f_4\}$, and two rudder faults $\{f_5, f_6\}$, the FDIP with the specification

$$S_1 = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}$$

is achievable using a bank of three detectors with global order 3. The resulting specification for the fault-to-residual TFM is

$$R_f(s) = \begin{bmatrix} \frac{10}{s+10} & \frac{10}{s+10} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{10}{s+10} & \frac{10}{s+10} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{11.85}{s+10} & \frac{10}{s+10} \end{bmatrix}$$

The step responses from the faults are presented in FIG. 5.

We include now the actuator models and add three surface angle sensors for the two right ailerons and for the upper ruder. With this sensor location the complete FDIP with $S_2 = I_6$ can be solved to isolate all aileron and rudder failures. The resulting detector has order 9 and the achieved specification is

$$R_f(s) = \text{diag}\left(\frac{10}{s+10}, \frac{100}{s^2+20s+100}, \frac{10}{s+10}, \frac{100}{s^2+20s+100}, \frac{10}{s+10}, \frac{-0.0002566s+100}{s^2+20s+100}\right)$$

The step responses from the faults are presented in FIG. 6.

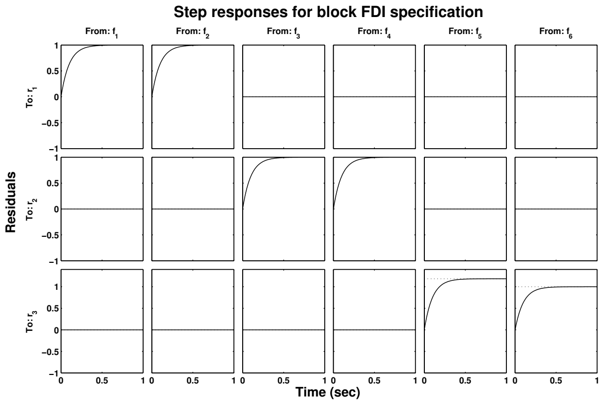

FIG. 5: Step responses from the aileron and rudder faults.

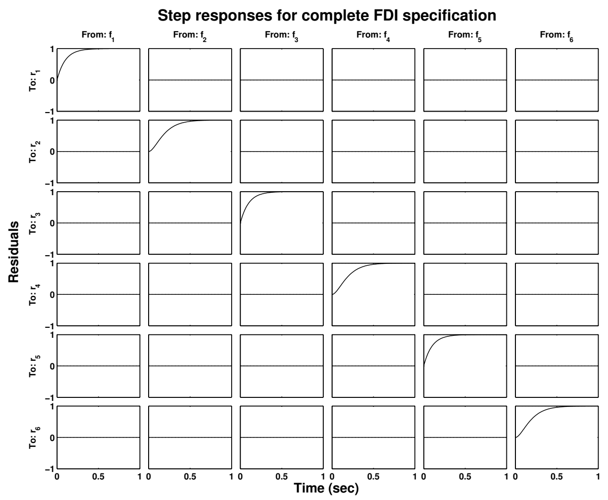

FIG. 6: Step responses from the aileron and rudder faults.

6. SUMMARY OF ACHIEVED RESULTS AND NEEDS FOR FURTHER ANALYSIS

The performed nominal analysis of the FDIP for a complete set of primary flight surfaces shows that a combination of component level monitoring with a system level monitoring allows the solution of this problem for a set of 11 actuator/surface failures. Our study demonstrated the interesting fact that by appropriately locating a minimal number of 6 surface angle sensors the complete isolation of faults is possible. The resulting orders of the residual generators are surprisingly low: order 7 for the pitch axis monitoring and 9 for gear/roll axis monitoring. These figures lower to 3 and 3, respectively, if no actuator models are included in the design.

By using the proposed least order detector design techniques implemented in reliable numerical software, a seamless switching among a large number of different sensor configurations was possible using a single global model of larger order. Interestingly, the reliability of employed numerical algorithms allowed us, to recover the same simple results in the case when sensors are used for all surfaces as those obtained working with each actuator/surface component individually.

The performed nominal design of residual generators provides valuable insight into the nature of the FDIP for aircraft actuator failures, demonstrates the feasibility of complete fault isolation, and provides filter specifications which can be useful in a more realistic design of robust residual generators.

For a reliable solution of the FDIP, the following aspects still need a careful consideration:

1. **Surface angle sensor faults.** To achieve a complete reliability of the fault monitoring system, it is important to also consider possible faults of the surface angle sensors. For example, by adding sensors to all surfaces, the complete isolation of all actuator faults is possible, while additionally the isolation of a sensor fault (e.g., stabilizer angle sensor) can be achieved. With three sensors (e.g., two for left elevators and one for stabilizer), to achieve the isolation of one sensor fault, we have to assume that sensor and actuator fault do not occur simultaneously. A complete analysis of this aspect is not intended here, but it is important for practical applications where using the minimum number of sensors and finding the appropriate location is always relevant. See Part II of [2] for a recent survey of sensor location and assignment aspects.

2. **Robustness against noisy inputs and noisy measurements.** The aspect of noisy inputs and noisy measurements must be considered in a realistic design. Typical noisy inputs for aircraft are gust turbulences, which can be taken into account by feeding white noise into the system via stable and minimum-phase Dryden spectra filters. Coloring filters driven by white noise can be used to model noise in sensor measurements. For further details see [8] and literature cited therein.

3. **Robustness against parametric uncertainties.** The robustness of the designed detectors against parametric uncertainties is important for practical applicability. Typical uncertain parameters to be considered for robustness studies are mass, coordinates of center of gravity, as well as flight conditions (speed, altitude). There are many possibilities to enforce the robustness of the designed detectors [1] and this challenging aspect will be considered in further studies. The results provided in this work can be seen as realistic specifications of what can be aimed to be achieved in the most favorable situation.

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A LINEARIZED BOEING 747 LONGITUDINAL MODEL

$$A = \begin{bmatrix} -0.4861 & 0.000317 & -0.5588 & 0 & -2.04\cdot 10^{-6} \\ 0 & -0.0199 & 3.0796 & -9.8048 & 8.98\cdot 10^{-5} \\ 1.0053 & -0.0021 & -0.5211 & 0 & 9.30\cdot 10^{-6} \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -92.6 & 92.6 & 0 \end{bmatrix}$$

$$B_u = \begin{bmatrix} -0.1455 & -0.1455 & -0.1494 & -0.1494 & -1.2860 & 0.0013 & 0.0035 & 0.0035 & 0.0013 \\ 0 & 0 & 0 & 0 & -0.3122 & 0.1999 & 0.1999 & 0.1999 & 0.1999 \\ -0.0071 & -0.0071 & -0.0074 & -0.0074 & -0.0676 & -0.0004 & -0.0004 & -0.0004 & -0.0004 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & -0.0199 & 3.0796 & -9.8048 & 8.98\cdot 10^{-5} \\ 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -92.6 & 92.6 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$D_u = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.3122 & 0.1999 & 0.1999 & 0.1999 & 0.1999 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$