Aircraft flight control system fault tolerance under structural and parametric uncertainties

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Abstract. The concept of an intelligent hybrid aircraft fault-tolerant flight control system operating under complete parametric and structural uncertainty is considered. Fault tolerance in the proposed system is ensured through the efficient integration of model-based and model-free health monitoring and reconfiguring methods.

1. Introduction

One of the most dangerous for aircraft (AC) flight safety are the faults of its flight control system (FCS). In the event of such faults the structure and parameters of direct or feedback AC control laws are changed leading to a loss of AC stability and controllability or an aviation accident. To prevent the evolution of an emergency in flight, it is necessary as fast as possible to detect and isolate the faulted elements for replacing them with redundant ones and to identify (estimate, quantify) the parameters of fault to accommodate (recover, compensate) it during the FCS functional reconfiguration [1–11]. The reconfiguration is realized by the redistribution (allocation) of signals from faulted control channels to healthy functionally redundant ones, preserving as much specified AC characteristics as possible [12–15].

There are a large number of methods for FCS health monitoring and reconfiguration. All of them can be divided into two different groups: model-based or parametric and model-free or nonparametric, which are also known as data-driven, data-based, signal-based or history-based [1–23].

Model-based methods, by definition, are directly or indirectly based on information about the parameters of real object model, the values of which are priori given or estimated in the process of identification [16–18]. Therefore, their use is hampered in practice by a number of factors caused by nonstationarity and nonlinearity of such model, inaccuracy in the determination of its parameters, inability to obtain a single solution in a closed-loop control, etc [24, 25]. As a result, the model-based methods are applicable only when the parameters and structure of the AC model are reliably known, and the uncertainties in the problem statement are essentially limited.

In contrast to the model-based methods, the model-less methods (neural network, cellular automata, support vectors, Markov, chaotic, fuzzy, genetic, etc.) are based on the measurements of FCS input and output signals only and need no a priori information on AC model parameters [19–23]. All widely known model-less methods either require preliminary long-term training and tuning for a particular AC or use the statistical algorithms requiring large amounts of data and time for the statistical properties extraction from analyzed variables. Therefore, such methods are not applicable, for example, to solve the problems of high-speed or highly maneuverable AC FCS reconfiguration.
In this paper we describe a concept and synthesis methodology of a hybrid AC fault tolerant FCS (FTFCS) based on the effective combination of original model-based and model-free methods, operating under complete structural and parametric uncertainties [26–32]. Model-based methods are based on the analytical solutions of linear matrix equations, developed by authors, allowing analyzing all inner dynamics relations and tuning reconfiguration law gains in the case of non-stationary environment. The proposed model-free methods are based on the algebraic solvability conditions for the AC model identification problems. They use FCS inputs and outputs only, do not require a priori information of the AC model parameters, training or statistical calculations. This makes it possible to significantly increase the efficiency of FCS fault tolerant problem solution by completely eliminating errors, associated with AC model uncertainties.

2. Fault tolerance problem statement
Let the dynamics of an AC with non-faulted FCS be presented by the discrete state space model

\[ x_{i+1} = Ax_i + Bu_i, \]  \hspace{1cm} (1)

where \( A \), \( B \) are the AC eigen dynamics and control efficiency matrices; \( x \) is the AC state vector of length \( n_x \); \( u_i = [u_i(1), u_i(2), \ldots, u_i(k), \ldots, u_i(n_u)] \) is the AC control or surface deflection vector of length \( n_u \); \( i \) is the discrete time.

When a fault occurs in the FCS the AC model is rewritten in the form

\[ x'_{i+1} = Ax'_i + Bu'_i, \]  \hspace{1cm} (2)

where \( x' \) is the state vector of AC with faulted FCS, and the faulted control vector is described as

\[ u'_i = Fu_i, \]  \hspace{1cm} (3)

where \( F \) is the FCS fault matrix

\[ F = \text{diag}[f(1), \ldots, f(k), \ldots, f(n_u)], \]  \hspace{1cm} (4)

\( f(k) = 1 \) – for \( k \)th non-faulted control channel, \( f(k) = 1 \) – for \( k \)th total faulted control channel, and \( 0 < f(k) < 1 \) – for partial loss of control effectiveness of \( k \)th control channel [1]. Substituting (3) into (2) we can write the dynamics model of the AC with faulted FCS

\[ x'_{i+1} = Ax'_i + B_fu_i, \]  \hspace{1cm} (5)

where \( B_f = BF \) is the control efficiency matrix of AC with faulted FCS.

Let us write the dynamics model of an AC with faulted and reconfigured FCS

\[ x'_{i+1} = Ax'_i + B_ju'_i, \]  \hspace{1cm} (6)

where the reconfigured control depends on non-faulted one and reconfiguration matrix \( H \) (Fig. 1):

\[ u'_i = (I + H)u_i. \]  \hspace{1cm} (7)

Then after substituting (7) into (6) the AC model looks like

\[ x'_{i+1} = Ax'_i + B_fu_i, \]  \hspace{1cm} (8)

where \( B_f = B_j(I + H) \) is the control efficiency matrix of AC with faulted and reconfigured FCS.
3. Mathematical framework

In this paper all problems of AC fault-tolerant system synthesis are reduced to either left-sided

$$CZ = D$$

(10)

or right-sided

$$YC = D$$

linear matrix equation for $Y$ with known matrices $C$ and $D$.

It’s known [33, 34], that these equations are respectively solvable if and only if

$$\bar{C}^L D = 0,$$

(11)

$$DC^R = 0,$$

(12)

and all sets of the solutions are defined as

$$Z = \tilde{C}D + \bar{C}^R \Omega,$$

(13)

$$Y = D\tilde{C} + \Theta \bar{C}^L,$$

(14)

where $\Omega$, $\Theta$ are arbitrary matrices; $\bar{C}^L$, $\bar{C}^R$ are left and right zero divisors satisfying $\bar{C}^LC = 0$,

$C\bar{C}^R = 0$; $\tilde{C} = \bar{C}^R \bar{C}^L$ is a generalized inverse matrix; $\bar{C}^L$, $\bar{C}^R$ are left and right unity divisors satisfying $\tilde{C}^\dagger C\bar{C}^\mathbf{R} = I$, defined by a canonical decomposition of the form

$$C = \begin{bmatrix} \bar{C}^L \\ \bar{C}^L \end{bmatrix}^{-1} \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \bar{C}^R \\ \bar{C}^R \end{bmatrix}^{-1}.$$  

(15)

Canonical decomposition (15) can be determined analytically; it is generally non-unique and actually formalizes the direct and inverse equivalent matrix transformations. When the solvability conditions (11) or (12) hold, the canonical decomposition produces analytical sets of solutions (13) or (14), that have the simplest forms, minimum ranks and number of arbitrary elements.

Under violation of solvability conditions the least squares solutions can also be determined by (13) or (14) with the help of the following analytical expression for pseudoinverse matrix

$$\tilde{C} = C^\dagger = \bar{C}^R LT \left[ \bar{C}^L RT C\bar{C}^R LT \right]^{-1} \bar{C}^L RT,$$

(16)

where $\bar{C}^L$, $\bar{C}^R$ are right and left zero divisors of matrices $\bar{C}^L$, $\bar{C}^R$.

Figure 1. Closed-loop dynamics model of the AC with faulted and reconfigured FCS

The objective of FCS reconfiguration is the calculation of $H$, providing the best match of AC model parameters in non-faulted (1) and faulted (8) cases according to the reconfiguration equality

$$B_r = B_f \left( I + H \right) = B.$$  

(9)

It is necessary to detect, isolate, identify and accommodate faults in the FCS with the help of the model-based and health monitoring and reconfiguration methods.
4. Health monitoring problem solution

4.1. Model-based health monitoring methods

4.1.1. State prediction. The simplest way to solve the fault detection problem is to use model-based one-step-ahead prediction method with a priori known estimations of AC model parameters \( \hat{A} \), \( \hat{B} \):

\[
\hat{x}_{i+1} = \hat{A} x_i + \hat{B} u_i.
\]

Then we can calculate the difference between real (2) and predicted (17) AC state values

\[
\Delta x_{i+1} = x_{i+1}' - \hat{x}_{i+1} = A x_i' + B_i u_i - \hat{A} x_i' - \hat{B} u_i = (A - \hat{A}) x_i' + (B_i - \hat{B}) u_i.
\]

So if the AC model parameters are known exactly, then \( \hat{A} = A, \hat{B} = B \), and we can detect the fault by estimating the Fresenius norm of (18) at \( i \geq i_f \)

\[
\varepsilon_{\text{det}}^{ab} = \| \Delta x_{i+1} \|_2 = \| \Delta B_f u_i \|_2,
\]

where \( \Delta B_f = B_f - B \). In the absence of faults, computing and sensing errors or disturbances the real and predicted AC state values are the same, so the residual (5) is zero. When a fault occurs the value of (19) exceeds the critical one \( \varepsilon_{\text{det}}^{ab} > \varepsilon_{\text{max}} \), and the process of fault isolation and identification begins.

The main challenge of the model-based fault detection criterion (19) is that it requires the exact model parameters, which may be uncertain or even completely undefined in some cases. Moreover, it cannot in principle be used to isolate a faulted FCS channel.

4.1.2. Input restoration. For fault isolation it is necessary to solve the inverse dynamics problem of system input restoration. In this regard, let us rewrite (1) in the form of the following matrix equation

\[
B u_i = [I - A] \begin{bmatrix} x_{i+1} \\ x_i \end{bmatrix},
\]

which is solvable due to (11) if and only if

\[
\hat{B}^T [I - A] \begin{bmatrix} x_{i+1} \\ x_i \end{bmatrix} = 0,
\]

and the desired AC model input (or FCS output) can be restored from (20) according to (13) as

\[
\hat{u}_i = \hat{B} [I - A] \begin{bmatrix} x_{i+1} \\ x_i \end{bmatrix} + \hat{B}^\top \Omega.
\]

Then we can formulate the \( k \)th control channel fault isolation criterion as the difference between real \( u_i(k) \) and restored \( \hat{u}_i(k) \) input values

\[
\sigma_{\text{is}}^{ab}(k) = u_i(k) - \hat{u}_i(k),
\]

which is applicable due to (21) when the control uniqueness condition \( \hat{B}^\top = 0 \) holds only.

4.1.3. Model identification. Model-based method of fault identification is based on identification of AC model parameters \( B \) and \( B_j \) directly from (1) and (5). To solve identification problem the AC needs to be observed over a certain period, so the AC dynamics models with non-faulted (1) and faulted (5) FCS can be written in the matrix forms
\[ X_{i+1-h,i+1} = AX_{i-h,j} + BU_{i-h,j}, \quad X'_{i+1-h,i+1} = AX'_{i-h,j} + BU_{i-h,j}, \]  

where \( X_{i+1-h,i+1} = [x_{i+1-h} \ x_{i+2-h} \ldots \ x_{i+1} \ x_{i-h} \ x_{i+1-h} \ x_{i+2-h} \ldots \ x_{i+1}], \quad X'_{i+1-h,i+1} = [x'_{i+1-h} \ x'_{i+2-h} \ldots \ x'_{i+1} \ x'_{i-h} \ x'_{i+1-h} \ x'_{i+2-h} \ldots \ x'_{i+1}], \quad U_{i-h,j} = [u_{i-h} \ u_{i+1-h} \ldots \ u_{j}]. \) \( h \) is the number of observations.

Let’s rewrite (22) as the model identification left-sided matrix equations

\[
\begin{bmatrix} A & B \end{bmatrix} \begin{bmatrix} X_{i-h,i} \\ U_{i-h,j} \end{bmatrix} = X_{i+1-h,i+1}, \quad \begin{bmatrix} A & B_f \end{bmatrix} \begin{bmatrix} X'_{i-h,i} \\ U_{i-h,j} \end{bmatrix} = X'_{i+1-h,i+1}
\]  

(23)

at \( i < i_f \) and \( i \geq i_f + h \) respectively. Then if due to (12) the solvability conditions

\[
E_{id} = X_{i+1-h,i+1}^H = 0, \quad E_{id}' = X'_{i+1-h,i+1}^H = 0
\]  

(24)

hold, we can write according to (14) the identification problem solutions

\[
\begin{bmatrix} \hat{A} & \hat{B} \end{bmatrix} = \begin{bmatrix} X_{i-h,i} \\ U_{i-h,j} \end{bmatrix}^H \Psi \begin{bmatrix} A & B_f \end{bmatrix} \begin{bmatrix} X'_{i-h,i} \\ U_{i-h,j} \end{bmatrix}^H = X_{i+1-h,i+1}^H \Psi \begin{bmatrix} A & B_f \end{bmatrix} \begin{bmatrix} X'_{i-h,i} \\ U_{i-h,j} \end{bmatrix}^H
\]  

(25)

where \( \Psi, Y \) are arbitrary matrices, and the identification errors are determined as

\[
\epsilon_{id} = \|E_{id}\|_2, \quad \epsilon_{id}' = \|E_{id}'\|_2.
\]  

(26)

The main challenge of this method is the AC model unidentifiability and impossibility to get the unique solutions in (25) without test signals and a priori data to meet the identifiability conditions

\[
\begin{bmatrix} X_{i-h,i} \\ U_{i-h,j} \end{bmatrix}^H = 0, \quad \begin{bmatrix} X'_{i-h,i} \\ U_{i-h,j} \end{bmatrix}^H = 0.
\]  

(27)

Thus, the AC dynamics model identification problem is indeed a "gray box" identification problem.

4.2. Model-less health monitoring methods

Until recent, the conditions (24) based on a right zero divisor have usually been used for their intended purpose to analyze the solvability of identification equations (23). However, the analysis of the linear dependence of columns of the measurement matrices has a much broader potential for solving direct and inverse “black box” dynamics problems, which is currently incompletely fulfilled. Here we show how without a priori information on the parameters of model \( A, B \) and faults \( F \), based only on measurements of FCS inputs \( x \) and outputs \( u \) to detect, isolate and identify, determining the residuals in AC control efficiency parameters \( \Delta B_f = B - B_f \), FCS faults.

4.2.1. State error estimation. The norm of the matrix of AC state residuals caused by FCS fault can be estimated at \( i_f \leq i < i_f + h \) directly by the norm of the matrix similar to (24) with the help of orthogonal zero divisor [26, 28]

\[
\epsilon_{id}^{\text{det}} = \left\| \begin{bmatrix} X_{i-h,i} \\ U_{i-h,j} \end{bmatrix}^H \right\|_2.
\]  

(28)
For a non-faulted case, the value of the model-less fault detection criterion (28) is zero (or some small number caused by calculation and sensing errors or disturbances) due to model stationarity and will exceed it after FCS fault occurrence due to AC model parameters changing.

4.2.2. Input error estimation. Let us represent the expressions (22) in the form of the following matrix equations

\[
\begin{bmatrix}
-A & I
\end{bmatrix}
\begin{bmatrix}
X_{i-h,i}
X_{i+1-h,i+1}
\end{bmatrix}
= BU_{i-h,i},
\begin{bmatrix}
-A & I
\end{bmatrix}
\begin{bmatrix}
X^f_{i-h,i}
X^f_{i+1-h,i+1}
\end{bmatrix}
= BjU_{i-h,i}. \tag{29}
\]

As the AC eigen dynamics parameters do not change during the FCS fault, for the solvability of (29) due to (12) the following conditions must be satisfied at \(i < i_f\) and \(i \geq i_f + h\)

\[
BU_{i-h,i}
\begin{bmatrix}
X_{i-h,i}
X_{i+1-h,i+1}
\end{bmatrix}^R = 0, \quad B_jU_{i-h,i}
\begin{bmatrix}
X^f_{i-h,i}
X^f_{i+1-h,i+1}
\end{bmatrix}^R = 0. \tag{30}
\]

And if there is no AC FCS functional redundancy \((B^R = 0, B^R_j = 0)\) the conditions (30) have equivalent forms not depending on the AC control efficiency parameters:

\[
U_{i-h,i}
\begin{bmatrix}
X_{i-h,i}
X_{i+1-h,i+1}
\end{bmatrix}^R = 0, \quad U_{i-h,i}
\begin{bmatrix}
X^f_{i-h,i}
X^f_{i+1-h,i+1}
\end{bmatrix}^R = 0. \tag{31}
\]

But at the time when faults occur at \(i_f \leq i < i_f + h\), the solvability condition is not satisfied

\[
U_{i-h,i}
\begin{bmatrix}
X_{i-h,i}
X_{i+1-h,i+1}
\end{bmatrix}^R \neq 0. \tag{32}
\]

Moreover, having viewed (32) line by line, we can see that the violation of solvability condition corresponds to the faulted control channels only. This allows us to use the norms of lines in (32), determined with the help of orthogonal zero devisor, as the model-less FCS fault isolation criterion [28, 29]

\[
\sigma^\text{ml}_{i_{k}}(k) = \left\| U_{i-h,i}(k) \begin{bmatrix}
X_{i-h,i}
X_{i+1-h,i+1}
\end{bmatrix}^R \right\|. \tag{33}
\]

4.2.3. Fault identification. Let us write the identification equation solvability condition (24) in the following matrix-vector form

\[
\begin{bmatrix}
X_{i+1-h,i+1}
X_{i+1-h,i+1}
\end{bmatrix}
\begin{bmatrix}
X_{i-h,i-1}
x_i
\end{bmatrix}^R
= \begin{bmatrix}
X_{i+1-h,i+1}
x_{i+1}
\end{bmatrix}
\begin{bmatrix}
R
\end{bmatrix}^R = 0, \tag{34}
\]

where \(X_{i+1-h,i+1} = [x_{i+1-h} x_{i+2-h} \ldots x_i]\), \(X_{i-h,i+1} = [x_i x_{i+1-h} \ldots x_{i+1}]\), \(U_{i-h,i-1} = [u_{i-h} u_{i+1-h} \ldots u_{i+1}]\). Then (34) can be rewritten as the equation for next-step AC state

\[
x_{i+1}R^R_{i+1} = -X_{i+1-h,i}R^R, \tag{35}
\]

which is solvable due to (12) if and only if

\[
X_{i+1-h,i}R^R_{i+1} = 0,
\]
and has according to (14) uniquely defined solution [30]

\[ \hat{x}_{i+1} = -X_{i+1-k} \mathbf{R} \mathbf{r}_{i+1}. \]  
(36)

Expression (36) is indeed a model-less one-step-ahead state prediction algorithm equivalent to (17) in the absence of errors in the model parameters. So we can determine the state residual matrix

\[ \Delta \mathbf{X}_{i+1-k,i+1} = X_{i+1-k,i+1} - \hat{X}_{i+1-k,i+1}, \]

analogous to (18) and write fault identification matrix equation analogous to (19) [31]

\[ \Delta \mathbf{B} \mathbf{U} = \Delta \mathbf{X}_{i+1-k,i+1}, \]
(37)

which is solvable due to (12) if and only if \( \Delta \mathbf{X}_{i+1-k,i+1} \mathbf{U}_{i+1-k}^R = 0 \) and has according to (14) the solution

\[ \Delta \mathbf{B} = \Delta \mathbf{X}_{i+1-k,i+1} \mathbf{U}_{i+1-k}^R + \Theta \mathbf{U}_{i+1-k}^L. \]
(38)

Note that the solvability condition of (37) is always met in the absence of disturbances and its norm determined with orthogonal zero devisor can be used to test the computations

\[ \mathbf{E}_{\text{diag}} = \| \Delta \mathbf{X}_{i+1-k,i+1} \mathbf{U}_{i+1-k}^R \|_2. \]
(39)

So to identify a fault according to (38) it is necessary and sufficient to ensure the linear independence of control matrix rows (\( \mathbf{U}_{i+1-k}^L = 0 \)). This condition is significantly less severe than AC model identifiability conditions (27) and is always required for all fault identification methods.

Figures 2–4 show the examples of diagrams of the developed fault detection (28), isolation (33) and identification (38) algorithms. The moment of pulse deflection of the norms from zero in Fig. 2, 3 coincides with the time of fault occurrence. The forms of the pulses depend on the AC model parameters, the number of observations \( h \), types and quantitative characteristics of faults, the nature of controls and disturbances. The faults identification process is manifested in the form of a step deflection of the corresponding control effectiveness parameter, as shown in Fig. 4.

### 5. Reconfiguration problem solution

#### 5.1. Model-based reconfiguration methods

##### 5.1.1. Exact reconfiguration

To solve the FCS reconfiguration problem we need to solve according to (9) the left-sided linear matrix equation for reconfiguration matrix \( H \)

\[ B_f H = \Delta B_f, \]
(40)

which is solvable due to (11) if and only if the reconfigurability condition

\[ \bar{B}_f^L \Delta B_f = \bar{B}_f^L B = 0 \]
(41)
holds, and the set of all its solutions is derived according to (13) as [33]

\[ H = \tilde{B}_j \Delta B_j + \tilde{B}_j^\Xi, \]

(42)

where \( \Xi \) is an arbitrary matrix.

The exact solution (42) is analytical and simple, but the main disadvantage of the method based on matrix canonization is the need to satisfy the reconfigurability condition (41). In the event of FCS faults leading to inconsistency of the reconfiguration equation (40) and violation of condition (41), not all solutions from the set (42) are capable of reliably preventing the loss of AC stability and controllability. Moreover, the analysis of this set does not allow us to limit the amplitudes of compensating deviations of AC control surfaces.

5.1.2. Optimal reconfiguration. If it is impossible to ensure the exact equality \( B_j H - \Delta B_j = 0 \), we can find according to (42) and (16) the analytical optimal solution of the reconfiguration equation (40)

\[ \hat{H} = B_j \Delta B_j + \tilde{B}_j^\Xi = \overline{\tilde{B}_j^\Xi} \left( \overline{\tilde{B}_j^\Xi}^T B_j \overline{\tilde{B}_j^\Xi}^T \right)^{-1} \overline{\tilde{B}_j^\Xi}^T \Delta B_j + \tilde{B}_j^\Xi, \]

(43)

that minimizes the reconfiguration error

\[ \varepsilon_{rec} = \left\| B_j \hat{H} - \Delta B_j \right\|_2 = \left\| \overline{\tilde{B}_j^\Xi}^T \right\|_2^{0.5} \left\| \overline{\tilde{B}_j^\Xi}^T B_j \right\|_2 = \min, \]

(44)

and minimizes the reconfiguration power \( \mu_{rec} = \| \hat{H} \|_2 = \min \) at \( \Xi = 0 \).

Such solution preserves all the advantages of the analytical solution and provides minimum deflection of the AC control surfaces, minimum deviation of the eigenvalues of closed-loop system and maximum preservation of the AC control stereotype [39, 40].

5.1.3. Robust reconfiguration. The above reconfiguration methods do not imply the presence of uncertainties in AC model parameters. To reduce the FCS sensitivity to such uncertainties we have to solve FCS robust reconfiguration problem [35–28]. For robust reconfiguration a finite set of AC dynamics models in various flight modes, for which fault tolerance must be provided a priori, are specified. The robust solution is found in the form of the intersection of the sets of solutions to each problem, corresponding to a specific realization of models. This approach is known as multi-model robust control [35, 36].

In the multi-model formulation, a FCS robust reconfiguration problem solution includes optimal solutions for each of the \( q \) studied AC flight modes

\[ B_j F H = B_j (I - F), \]
\[ B_2 F H = B_2 (I - F), \]
\[ \vdots \]
\[ B_q F H = B_q (I - F), \]

(45)

so that the reconfiguration errors for all modes have the minimum cumulative norm

\[ \varepsilon_{rec} = \left( \sum_{i=1}^{q} \left\| B_q F \hat{H} - B_q (I - F) \right\|^2 \right)^{1/2} = \min. \]

(46)

Let us present the system of equations (45) in the block-matrix form

\[ B_j H = \Delta B_j, \]

where
\[ B_f = \begin{bmatrix} B_1 \\ \vdots \\ B_q \end{bmatrix} F, \quad \Delta B_f = \begin{bmatrix} B_1 \\ \vdots \\ B_q \end{bmatrix} (I - F). \]

So analogous to equation (40) we can meet the requirement (46)

\[ e_{rec} = \| B_f \dot{\Delta} - \Delta B_f \|_2 = \left\| \left[ B_f^T \Delta \tilde{B}_f \right]^{0.5} \tilde{B}_f B_f \right\|_2 = \min, \]

by analogous to (43) robust reconfiguration expression

\[ \dot{\Delta} = \tilde{B}_f^T \Delta \tilde{B}_f + \tilde{B}_f^T \Xi. \]

5.2. **Model-less reconfiguration method**

A fundamentally unavoidable drawback of all the above reconfiguration methods is the need for a fault identification stage, which inevitably requires some time, when FCS operates with a maximum level of uncertainty. Moreover, in this case, a shock activation of the reconfiguration mode occurs with a sharp change in the moments and forces acting on the AC. Here we describe a new model-less method for AC FCS reconfiguration based on a model-less control method [32], that operates under complete parametric uncertainty and does not need health monitoring problem solving.

Let us separate the last column of matrices in the expression (31):

\[ \begin{bmatrix} U_{i-1} \ u_i \\ X_{i+1-h}^{\text{des}} \\ X_{i+1-h} \ x_i \end{bmatrix} = \begin{bmatrix} U_{i-1} \ u_i \\ \tilde{R} \end{bmatrix} = 0. \]

Then the model-less fault accommodation control

\[ u_i = -U_{i-1} R \tilde{\xi}_{i+1} \]

can be found directly from (47), while the desired states \( x_{i+1}^{\text{des}} \) may be estimated by model-based state prediction method with the help of AC aerodynamics database.

This method provides shock-free FCS reconfiguration activation under AC model nonidentifiability, arbitrary FCS functional redundancy and control exciting (Fig. 5).

![Figure 5. Model-less fault accommodation principle.](image-url)
To tune the proposed algorithm for fulfillment of (47), it is sufficient to observe the AC controls and flight parameters only for a time not exceeding the total order of the AC free and forced dynamics.

6. Intelligent hybrid fault-tolerant flight control system concept

Figure 6 shows the scheme of the proposed AC FTFCS based on a unified approach to the FCS health monitoring and reconfiguration, operating under complete structural and parametric uncertainties.

For fault detection, isolation and identification we use a combination of model-based and model-less methods according to the accuracy of their inputs and outputs (Table 1).

Table 2 presents the functional logic of the fault accommodation module for FCS reconfiguration.

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**Table 1.** Fault detection, isolation and identification methods.

| Problem          | Method                                      | Inputs and outputs* |
|------------------|---------------------------------------------|---------------------|
|                  |                                             | x | u | A | B | F | Bf | ΔB | If | k |
| Fault detection  | Model-based state prediction                | + | + | + | – | – | – | v | v | – |
|                  | Model-less state error                      | + | – | – | – | – | – | v | v | – |
| Fault isolation  | Model-based input restoration               | + | + | + | – | – | – | v | v | v |
|                  | Model-less input error                      | + | – | – | – | – | – | v | v | v |
| Fault identification | Model-based identification              | + | + | v | v | – | – | – | – | – |
|                  | Model-based internal diagnostics            | – | + | – | v | v | – | – | – | – |
|                  | Model-based aerodynamic database            | + | – | v | v | – | – | – | – | – |
|                  | Model-less external diagnostics            | + | – | – | – | – | v | v | – | – |

*+ – inputs, v – outputs, – not used

Table 2. Functional logic of fault accommodation.

| Feature         | Passive | Active                  |
|-----------------|---------|-------------------------|
| Robustness      | to faults | unessential to flight modes | none |
| Accuracy        | min | mid | optimal | max |
| Adaptability    | none | real-time | to faults | full |
| Diagnostics error | $\epsilon_{\text{dgn}} \geq \epsilon_{\text{dgn}}^{\text{max}}$ | $\epsilon_{\text{dgn}} < \epsilon_{\text{dgn}}^{\text{max}}$ |
| Identification error | $\epsilon_{\text{idn}} < \epsilon_{\text{idn}}^{\text{max}}$ | $\epsilon_{\text{idn}} \geq \epsilon_{\text{idn}}^{\text{max}}$ | $\epsilon_{\text{idn}} < \epsilon_{\text{idn}}^{\text{max}}$ |
| Reconfiguration error | $\epsilon_{\text{rec}} \geq \epsilon_{\text{rec}}^{\text{max}}$ | $\epsilon_{\text{rec}} < \epsilon_{\text{rec}}^{\text{max}}$ |
Passive reconfiguration law meets all the criteria set both in non-faulted and faulted situations. It operates when it is impossible to obtain reliable flight, model and fault parameters. Active modes are based on the fault identification scheme and differ in the degree of robustness of the reconfiguration laws, which is determined by the operational availability of reliable data. The mode with maximum accuracy is based on the estimation of the optimal coefficients of the reconfiguration laws for any changes in the system. This mode is activated when reliable data both on the AC model and FCS fault parameters is available. The robust reconfiguration mode is activated in the absence of reliable AC model and the availability of accurate fault parameters. Real-time model-less reconfiguration mode is activated in the absence of reliable data on the AC model and FCS fault parameters, as well as when it is impossible to solve the reconfiguration problem with a given accuracy.

7. Conclusions
As a result a new concept of an intelligent hybrid AC fault tolerant FCS based on the effective combination of original model-based and model-free fault detection, isolation, identification and accommodation methods is presented. Model-based methods based on the analytical solutions of linear matrix equations are the most accurate ones, but are applicable only when the parameters and structure of the AC mathematical model are reliably known and the uncertainties are essentially limited. The model-free methods based on the algebraic solvability conditions for the AC model identification problems use FCS inputs and outputs only. These methods are considered to be intelligent as they make it possible to solve direct and inverse “black box” dynamics problems completely without errors, associated with AC model uncertainties. The implementation of the hybrid AC FTFCS operating in all flight modes under complete structural and parametric uncertainties can significantly increase the efficiency of health monitoring and reconfiguration processes while decreasing the requirements to AC priori information and control exciting.

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