Nonparametric method for failures detection and localization in the actuating subsystem of aircraft control system

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Abstract. In this paper we design a nonparametric method for failures detection and localization in the aircraft control system that uses the measurements of the control signals and the aircraft states only. It doesn’t require a priori information of the aircraft model parameters, training or statistical calculations, and is based on algebraic solvability conditions for the aircraft model identification problem. This makes it possible to significantly increase the efficiency of detection and localization problem solution by completely eliminating errors, associated with aircraft model uncertainties.

1. Introduction
The most dangerous failures in the aircraft control system are the failures of the elements of the actuating subsystem of aircraft control system. For example: the failure of the actuator control unit, the failure of the communication link between the control unit and the actuator, the failure of the actuator itself, damage of the control surfaces. In the event of such failures, the aircraft aerodynamic coefficients and the control surfaces moment characteristics are changed, that can lead to an aviation accident. If the failure detection time exceeds the critical control system reaction time, the aircraft can move to nonrecoverable state. Therefore, the primary task is to detect of aircraft abnormal dynamics and localize the failure before an emergency. Fast failures detection and localization in the aircraft allows minimizing their consequences and taking early measures to prevent an accident.

The failures detection and localization methods can be classified into two broad groups: parametric and nonparametric [1–5]. As a rule, parametric methods are used to detect and localize failures, directly or indirectly implying a priori information about the parameters of the aircraft model. Using the parametric model-based methods involves a number of difficulties due to the nonlinearity of such models, inaccuracy in determining their parameters, multiply solutions, etc. The model parameter errors may often increase the threshold values of the failure detection criteria, thus increasing the time of failure detection and decreasing the accuracy of determining the time the failure occurred. In some cases, the accurate determination of the time that the failure occurred proves to be very difficult and time consuming [6–8].

In contrast to the parametric methods, the nonparametric methods of failures detection and localization based only on measurement of input and output signals and need no a priori information about model parameters [9–10]. These methods are based on the determination of specific qualitative or quantitative model characteristics. The all widely known nonparametric methods either require preliminary training/tuning for a particular plant or use the statistical algorithms, that themselves are subject to inevitable errors. Determining accurate and reliable solutions using such algorithms requires...
a large amount of data. They are characterized by high computational costs and low performance
indicators. These factors determine the high probability of false warning or missed failures in practice
[11–14].

The proposed method for aircraft control system failures detection and localization is based on the
measurements of the control signals and the aircraft states only. It doesn’t require a priori information
of the aircraft model parameters, training or statistical calculations, and is based on algebraic
solvability conditions for the aircraft model identification problem. This makes it possible to
significantly increase the reliability and speed of problem solution by completely eliminating
parametric errors.

2. Statement and solution of failures detection and localization problem
Let the model of a non-failure aircraft dynamics be represented in the state space as [15]

\[
x_{i+1} = Ax_i + Bu_i, \quad x'_{j+1} = Ax'_j + BFu_j,
\]

where \( A, B \) are the matrices of eigen-dynamics and control efficiency; \( x, u \) are the state and control
vectors of length \( n_x, n_u \); \( i = 0, l-1, j = l, l+1, \ldots \) are the discrete times before and after the occurrence
of failures; \( l \) is the instant a failures occur; \( F = \text{diag} \left[ f(1) \ldots f(k) \ldots f(n_u) \right] \) is the matrix of
failures (loss of efficiency), \( f(*) = 1 \) for a non-failure control channel, \( f(*) = 0 \) for a failure control
channel. It is necessary, based on the measurements of control signals \( u \) and states \( x \) only, to detect
the failures and localize the failure channels of the aircraft control system.

Suppose that observation of aircraft control signals and states is conducted for some time. Then the
aircraft models (1) will have the matrix forms:

\[
X_{i+1} = AX_i + BU_i, \quad X'_{j+1} = AX'_j + B_jU_j,
\]

where \( B_j = BF; \ X_i = \left[ x_0 \ldots x_{i+h} \right], \ X'_j = \left[ x'_0 \ldots x'_{j+h'} \right], \ U_i = \left[ u_0 \ldots u_{i+h} \right], \ U_j = \left[ u_j \ldots u_{j+h'} \right] ; \ h, h' \)
are the number of observations in non-failure and failure cases. Let’s represent the expressions (2) in
the form of the following matrix equations:

\[
\begin{bmatrix}
-A & I \\
0 & I
\end{bmatrix}
\begin{bmatrix}
X_i \\
X_{i+1}
\end{bmatrix} = BU_i, \quad \begin{bmatrix}
-A & I \\
0 & I
\end{bmatrix}
\begin{bmatrix}
X'_j \\
X'_{j+1}
\end{bmatrix} = B_jU_j,
\]

It’s known [16], that any linear matrix equation of the form

\[
YC = D
\]

with known matrices \( C, D \) is solvable for \( Y \) if and only if the solvability condition

\[
D\tilde{C}^R = 0,
\]

is satisfied, where \( \tilde{C}^R \) is the right zero divisor of maximal rank (matrix for which condition
\( \tilde{C}\tilde{C}^R = 0 \) is satisfied).

As the parameters of free aircraft dynamics don’t change at emergence of failures in aircraft control
system, for the solvability of (3) in accordance with (4) the following conditions must be satisfied:

\[
BU_i \begin{bmatrix}
X_i \\
X_{i+1}
\end{bmatrix}^{R} = 0, \quad B_jU_j \begin{bmatrix}
X'_j \\
X'_{j+1}
\end{bmatrix}^{R} = 0 .
\]
If there is no functional redundancy in the actuating subsystem of aircraft control system \((\bar{B}^R = 0, \bar{B}^T_f = 0)\) the conditions (5) have an equivalent form, which does not depend on the parameters of the aircraft control efficiency:

\[
U \begin{bmatrix} X_i^R \\ X_{i+1}^R \end{bmatrix} = 0, \quad U \begin{bmatrix} X_f^R \\ X_{j+1}^R \end{bmatrix} = 0.
\]

(6)

But at the time of failures occur the solvability condition does not hold and looks like

\[
\begin{bmatrix} U_i \ U_j \end{bmatrix} \begin{bmatrix} X_i^R \\ X_{i+1}^R \\ X_f^R \\ X_{j+1}^R \end{bmatrix} = (B_j - B) \begin{bmatrix} 0 \ U_j \end{bmatrix} \begin{bmatrix} X_i^R \\ X_{i+1}^R \\ X_f^R \\ X_{j+1}^R \end{bmatrix} \neq 0.
\]

(7)

Having viewed (7) line by line, it can be seen that for the failure control channels \((f(\ast) \neq 1)\) the solvability conditions are not satisfied, and for the non-failure \((f(\ast) = 1)\) – are satisfied. This allows us to use the norms of conditions for the \(k\) of \(n\) control channels \(U_e = [u^{(1)}_e ... u^{(k)}_e ... u^{(n)}_e]^T\)

\[
\sigma^{(k)} = \left\| \begin{bmatrix} u^{(k)}_i \\ u^{(k)}_j \end{bmatrix} \begin{bmatrix} X_i^R \\ X_{i+1}^R \\ X_f^R \\ X_{j+1}^R \end{bmatrix} \right\|_2
\]

as nonparametric criterion for aircraft control system failures detection and localization.

3. Aircraft control system failures detection and localization example

Let’s assume that for one of the aircraft flight modes, the matrices of the eigen-dynamics and control efficiency of aircraft model (1) with in-phase deviation of elevator rudders and differential aileron deflection have the form:

\[
A = \begin{bmatrix}
0.9998 & -0.1021 & -0.0981 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\
-0.0001 & 0.9907 & 0.0000 & 0.0100 & 0.0000 & 0.0000 & 0.0000 \\
0.0001 & 0.0093 & 0.9999 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\
0.0000 & -0.0079 & 0.0000 & 0.9973 & 0.0000 & 0.0000 & 0.0000 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0003 & 0.0011 & 0.0099 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & -0.0344 & 0.9650 & -0.0090 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & -0.0199 & 0.0020 & 0.9896 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0100 & -0.0011 & 1.0000
\end{bmatrix},
\]

\[
B = \begin{bmatrix}
0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\
0.0003 & -0.0000 & 0.0000 & 0.0000 & 0.0000 \\
-0.0003 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\
-0.0067 & -0.0134 & 0.0000 & 0.0000 & 0.0000 \\
0.0000 & 0.0000 & -0.0000 & 0.0000 & 0.0000 \\
0.0000 & 0.0000 & -0.0019 & -0.0108 & 0.0000 \\
0.0000 & 0.0000 & -0.0314 & 0.0011 & 0.0000 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000
\end{bmatrix}.
\]
In this case, the vectors of states and control are written as $x = \begin{bmatrix} V & \theta & \omega_x & \omega_y & \omega_z & \gamma \end{bmatrix}^T$, $u = \begin{bmatrix} \delta_e, \delta_{stab}, \delta_{rud}, \delta_{ail} \end{bmatrix}^T$, where $\omega_x, \omega_y, \omega_z$ are the angular rates of roll, yaw, and pitch (deg/s); $\alpha, \theta, \gamma, \beta$ are the angles of attack, pitch, roll, and slip (deg); $V$ is the flight speed (m/s); $\delta_e, \delta_{stab}, \delta_{rud}, \delta_{ail}$ are the angles of elevators, stabilizer, rudder and ailerons deflections (deg).

Let us simulate the flight of the aircraft during 40 s with the following control signals:

- Elevator failure: $\delta_e = 5\sin(0.05 \cdot t)$
- Stabilizer failure: $\delta_{stab} = 2\sin(0.025 \cdot t)$
- Rudder failure: $\delta_{rud} = -5\sin(0.1 \cdot t)$
- Ailerons failure: $\delta_{ail} = 5\cos(0.05 \cdot t)$

Failures in the form of loss of efficiency of each control channel by 10% ($f(*) = 0.9$) will be entered on the 20th second of the flight ($i = 0:19$, $j = 20:40$).

The determination of the failure control channels is carried out by the failures detection and localization criterion (8) with $h = h' = 13$, the graphs of which for each failure case are shown in figure 1.

**Figure 1.** Graphs of failures detection and localization criterion.

It is clear that in each case of failure, its detection and localization are carried out fast and reliably.
4. Conclusion
As a result the new method of failures detection and localization in aircraft control systems, using only data of control signals and state measurements, is developed. The main advantage of it is its independence from the aircraft model parameters, which guarantees its efficiency in the absence of a priori information, does not require solving the problems of identifying model parameters and predicting its dynamics.

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