HiSST: International Conference on High-Speed Vehicle Science Technology

26–29 November 2018, Moscow, Russia

Aircraft actuating system fault diagnosis under complete uncertainty

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Annotation

Nonparametric methods for aircraft actuating system fault detection, localization and identification are considered. The methods do not use any a priori information about the aircraft model and are capable of solving diagnostic problems in real time under conditions of complete uncertainty.

Keywords: *data-based, fault, detection, isolation, identification*

Notation

Latin
A – matrix of eigen-dynamics
B – matrix of control efficiency
F – matrix of faults
U – control matrix
X – state matrix
f – fault parameter
h – observation time
k – control channel index
r – element of the right zero divisor
u – control signal
x – state signal
Greek
ε – fault detection criterion
σ – fault localization criterion
Superscripts
+ – pseudoinversion of matrix
T – transposition of matrix
Subscripts
i – discrete time
q – time of fault occurrence

There are a large number of methods for faults diagnosing in dynamic object control systems. All of them can be divided into two different groups: parametric or model-based and nonparametric, which are also known as model-free, data-driven, data- based, signal-based or historical-based [1-4].

Parametric methods (regression, state space, etc.), by definition, are directly or indirectly based on information about the parameters of real objects models, the values of which are priori given or estimated during identification. Therefore, their use is limited in practice by a number of factors caused by nonstationarity and nonlinearity of such models, inaccuracy in the determination of their parameters, inability to obtain a single solution in a closed control loop, etc. [5, 6]. As a result, parametric methods are applicable in practice only when the parameters and structure of the mathematical model of the control object are reliably known, and the uncertainties in the statement of the problem are essentially limited.

Nonparametric methods are based on measurement of input and output signals only and need no a priori information about model parameters. The all widely known nonparametric methods either require preliminary training or tuning for a particular object, which causes their narrow focus (neural network, cellular automata, support vectors, Markov, chaotic, fuzzy, etc.) or use the statistical algorithms. All statistical algorithms require a large amount of data for ensuring the statistical properties of the analyzed variables, which inevitably leads to increasing the time required for problem solving. Therefore, such methods are not applicable, for example, to solve the problem of high-speed or high-maneuverable aircraft safe controlling - if the fault diagnosis time exceeds the control system critical response time, the aircraft can go into an unrecoverable state.

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This work is devoted to developing new universal nonparametric methods for diagnosing (detecting, localizing and identifying) faults in the actuating subsystem of an aircraft control system that are free of above mentioned limitations. The algebraic solvability conditions of aircraft dynamic linear model identification problems in various statements form the basis of the methods [7].

Let the discrete-time model of a non-faulted aircraft dynamics be represented in the state space as

$$\left[X_{i+h}\ \ x_{i+h+1}\right]=A\left[X_{i+h-1}\ \ x_{i+h}\right]+B\left[U_{i+h-1}\ \ u_{i+h}\right], \tag{1}$$

and q be a time when actuating system faults appear, which are modeled as a product $B_f=BF$ *with the help of fault* matrix $F=\operatorname{diag}\left[f(1)\ \cdots\ f(k)\ \cdots\ f(n_u)\right]$, where $f(*)=1$ – for the non-faulted control channels, $0\le f(*)<1$ – for the faulted ones:

$$\left[X_{i+h}\ \ x_{i+h+1}\right]=A\left[X_{i+h-1}\ \ x_{i+h}\right]+BF\left[U_{i+h-1}\ \ u_{i+h}\right], \tag{2}$$

where $i\ge q$. It's necessary without information on model A, B and faults F parameters, based only on measurements of control signals u and states x detect (determine the time of occurrence), localize (determine the place of occurrence) and identify (determine the quantitative values) faults.

Here, without proof, we give the final results. Fault detection is performed by calculating the Frobenius matrix norm [8]

$$\varepsilon=\left\|\left[X_{i+h}\ \ x_{i+h+1}\right]\begin{bmatrix} r_{i+h-1}\\ r_{i+h}\end{bmatrix}\right\|_2, \tag{3}$$

where the vector-column right zero divisor r is determined by the expressions

$$\begin{bmatrix} X_{i+h-1} & x_{i+h}\\ U_{i+h-1} & u_{i+h}\end{bmatrix}\begin{bmatrix} r_{i+h-1}\\ r_{i+h}\end{bmatrix}=0,\ \begin{bmatrix} r_{i+h-1}\\ r_{i+h}\end{bmatrix}^{\mathrm{T}}\begin{bmatrix} r_{i+h-1}\\ r_{i+h}\end{bmatrix}=1.$$

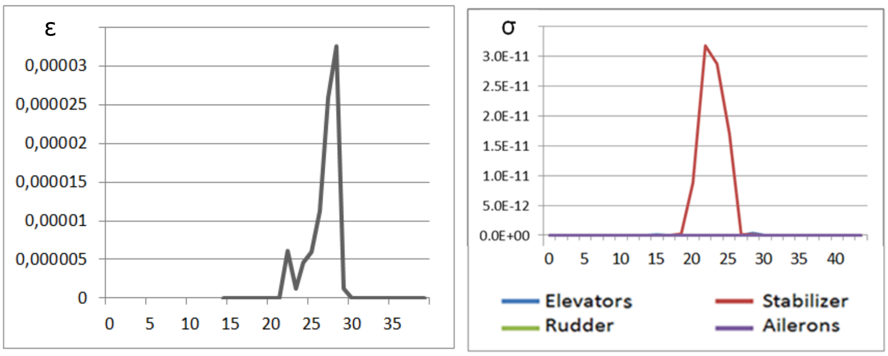
The faults are localized by calculating the norm for each control channel [9]

$$\sigma^{(k)}=\left\|\left[U^{(k)}_{i+h-1}\ \ u^{(k)}_{i+h}\right]\begin{bmatrix} \hat r_{i+h}\\ \hat r_{i+h+1}\end{bmatrix}\right\|_2, \tag{4}$$

where the vector-column right zero divisor $\hat r$ is determined by the expressions

$$\begin{bmatrix} X_{i+h} & x_{i+h+1}\\ X_{i+h-1} & x_{i+h}\end{bmatrix}\begin{bmatrix} \hat r_{i+h}\\ \hat r_{i+h+1}\end{bmatrix}=0,\ \begin{bmatrix} \hat r_{i+h}\\ \hat r_{i+h+1}\end{bmatrix}^{\mathrm{T}}\begin{bmatrix} \hat r_{i+h}\\ \hat r_{i+h+1}\end{bmatrix}=1.$$

In non-faulted case the values of the norms (3), (4) will be zero (or equal to some small number due to calculation errors or perturbations) and will exceed it in the faulted case, as shown in Fig. 1.



a) fault detection б) fault localization

Fig 1. Fault detection and localization criteria patterns

Zero norm rejection coincides with the time of fault occurrence, and this fact appears on the graphs in the form of pulse with characteristics depending on the f, u, and h.

Qualitative fault value identification is performed by the formula [10]

$$\Delta B = B(I - F) = \Delta X_{i+h+1} U^{+}_{i+h}, \tag{5}$$

where $i \geq q$ and the non-parametric one-step prediction algorithm

$$\hat{x}_{i+h+1} = -X_{i+h} r_{i+h-1} r^{-1}_{i+h}$$

is used to calculate the state residuals matrix $\Delta X_{i+h+1} = X_{i+h+1} - \hat{X}_{i+h+1}$.

In the absence of fault, the real and predicted aircraft state values are the same, and the value of (5) will be zero. The fault leads to control efficiency matrix ΔB step change, as shown in Fig. 2.

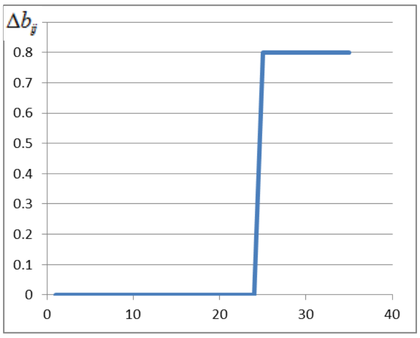


Fig 2. Control efficiency value changing identification pattern

The aircraft actuating system fault diagnosis scheme, functioning in accordance with (3)-(5), is shown in Fig. 3.

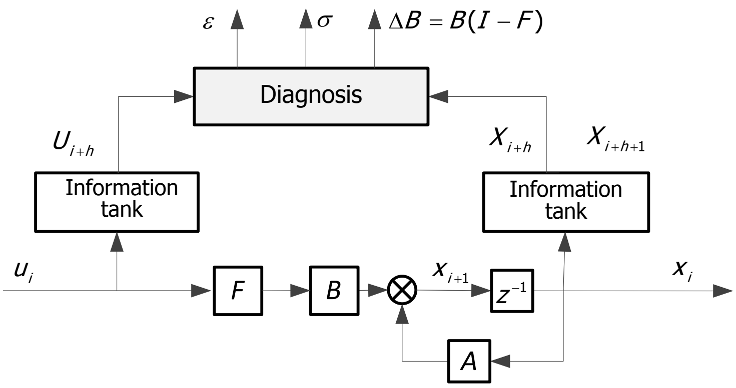


Fig 3. Aircraft actuating system fault data-based diagnosis

The proposed methods are based on input and output signals only, they don't require any information on aircraft model parameters, don't use statistical calculations, training or tuning, are not influenced by model errors and can be used to solve problems of fault diagnosing in complete uncertainty and model unidentifiability cases.

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