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Detection Filter Method in Diagnostic Problems for Linear Dynamic Systems

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In a presented research paper the problem of synthesis of the fault detection unit and failure occurrence locating in linear discrete dynamic time-invariant systems is considered. The result of synthesis is presented in the form of parallel type structure consisting of two independently functioning Kalman filter. The first of them calculates a system state vector estimation without taking note of faults, and the second – a degenerate type, creates a fault estimations. Linear combination of their exits forms the resulting state vector estimation. Both filters have dimensions smaller dimensions of the tested system and use the split procedure of an error differential signal. Splitting of the error signal is carried out before estimation process unlike Kitanidis filter. It allows to get a certain economy in computing costs, due to introduced restrictions and losses in accuracy. In general the obtained structure is suboptimal. Questions of stability and state vector estimation convergence of a dynamic system are briefly considered. Using of the computing resource of MatLab environment results of a functional methodcheck results are given.The article structure is constructed as follows. At first problem definition is executed and its resolvability from the mathematical point of view is analyzed. The following step is synthesis of the detection unit and localization of multiple faults then the convergence and stability of errors of estimation are analyzed. In final sections results of method operability check are given in the form of illustrative numerical example and the results of the performed research are summed up. In the conceptual plan research makes a generalization the known results for the continuous time systems.

Key words: model-oriented methods of fault detection; fail-safe control; discrete linear dynamic system; separate state estimation

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Introduction

It is not infrequent, in practice cases the dynamics of physical systems undergoes sudden changes. As a rule, it leads to degradation in their qualitative characteristics. As a first approximation these changes can be considered as faults or refusals. Faults are shown in the form of parameter deviations of the studied process (system) from their nominal values out of the operational service rate limits, and refusals – in the form abnormal process development due to changes either system parameters, or its structure. Owing to their influences the system appears incapable to carry out the tasks set for it often. Most often misoperation of separate techniques or subsystems is the reason of the specified deviations. To maintain constant operability of a system it is possible to use the theoretical concepts of the failsafe control theory based on very simple idea namely – compensations of fault influences due to hardware and (or) functional redundancy [1]. According to the separation theorem that is true for linear systemsonly, the general task of failsafe control can be separated into two rather independently solvable subtasks: problem of filtering and control task. The presented research solves a problem of timely fault detection and their localization by application of the corresponding methods and means, in particular model oriented. For rather small period of time (15-20 years) the set of approaches to the solution of the specified problem, for example, methods of the parity relations, the finding filters, observers with an uncertain input, etc. was developed. Features of many of them are elucidated in well-known review articles [2–8]. The applied questions connected with this direction are partially covered in researches [9–13]. Sufficiently plenty books and the monographs devoted to separate aspects of fault diagnostics in linear dynamic systems [14–17] are published recently. Thus, the model oriented methods of fault detection and their identification remain a hot topic of researches, both in theoretical, and in the applied plan.

Two various approaches to the solution of a filtering problem with faults and perturbations were so far created. The first of them is based on the idea of a system state vector expansion, due to inclusion in its mathematical model of dummy entered vector of the unknown input associated with fault influence and perturbations. Nevertheless such approach assumes that the model of dynamics of an unknown input is a priori known. In that case when statistical properties of unknown inputs are exactly known, the optimal solution of a filtering problem is provided with an expanded Kalman filter (EKF). However, at a large number of the considered faults and perturbations the dimension of an EKF exceeds dimension of the studied system much more. For the purpose of computing costreduction in [18] suggested to approximate EKF two-stage parallel structure of smaller dimension. This variation was only suboptimal in sense of exit equivalence of both structures. In further the basic idea of Friedland was extended to stochastic type of faults and perturbations [19–21]. In [22, 23] was developed adaptive option of a two-stage Kalman filter. The main efforts of researchers in this direction are focused on the methods of EKF approximation combining acceptable accuracy with the restrictions not too hard for practical applications.

The second approach is based on assumption of prior information absence about dynamic properties unknown input. First this problem was solved in [24] for the purpose of deduce of the linear unbiased estimations with minimum dispersion due to imposition of restrictions imposed on structure of the tested system. In [25] generalized results [24], having applied parametrical approach to deduce of optimum estimations. An optimum filter with minimum dispersion was obtained in [26] a little later. The problem of the characteristic degradation inherent in [24] was considered here. A problem of fault detection and localization by means of geometrical approach, creating at the same time difference signals with the directed properties was solved in [27, 28]. Afterwards, results of these researches were used in the [29] devoted to synthesis of the detecting filters. Relatively recently, in [30] the full order observer capable to find and localize multiple faults in a linear stationary system of continuous time was considered. The transfer matrix of the observer was chosen so that each element of a vector difference signal was connected only with one – specific fault, and at the same time was independent with other possible types of malfunctions from a priori set. The method was efficient only for a case when columns of a detectability matrix were expressed through eigenvalues of the observer transfer matrix. In the represented research the specified method gains further development for a case of a linear discrete system subject to influence of faults and (or) perturbations nevertheless thereof structure is indefinite. Without watching that faults and perturbations represent different physical processes, results of their impacts on the tested system in many respects are identical – they are directed to degradation its qualitative characteristics and in this sense they can be considered equivalent. Therefore in this research paper the main attention is concentrated on detection and localization of faults which are interpreted as additive perturbations of an unknown structure. The "extrapolator-corrector" of the device structure, similar to structure of the Kitanidis filter is result of the executed synthesis. It consist of two parallel independently functional Kalman type filter, one of them calculates a system state vector estimation without taking note of faults, and the second, the degenerate type, creates a fault estimations. Linear combination of their exits forms the resulting state vector estimation. It should be noted that both filters have dimensions smaller dimensions of the tested system and use the procedure of splitting procedure of an error differential signal.

1 Problem definition and resolvability analysis

Let's assume that the linear discrete dynamic system subject to influence of unexpected perturbations and (or) faults can be described by the difference equation system:

$$\begin{aligned} &\mathbf{s}(k+1) = \mathbf{W}_s\mathbf{s}(k) + \mathbf{G}_s\mathbf{u}(k) + \mathbf{F}_s\mathbf{f}(k)\,; \\ &\mathbf{y}(k) = \mathbf{H}_y\mathbf{s}(k)\,, \end{aligned} \tag{1}$$

where $\mathbf{s}(0)=\mathbf{s_0}$; $\mathbf{u}(0)=\mathbf{0}$; $\mathbf{f}(0)=\mathbf{0}$ – initial conditions; $\mathbf{s}(k) \in \Re^n$ – a system state vector; $\mathbf{y}(k) \in \Re^m$ – a measurement vector; $\mathbf{u}(k) \in \Re^q$ – an exactly known control vector; $\mathbf{f}(k) \in \Re^p$ – a fault vector with indefinite structure; $\mathbf{F}_s = [\mathbf{f}_1, \mathbf{f}_2, \dots, \mathbf{f}_p]$ – a priori set direction matrix which describe possible fault signature in total. It is supposed that all system matrixes are known, have the corresponding dimensions and are full rank matrices. At the set initial conditions the exit system vector (1) during an arbitrary point of the time k is defined by the known ratio [15]

$$\begin{aligned} \mathbf{y}(k) = \mathbf{H}_y\mathbf{W}_s^k s(0) + \sum_{i=1}^{k-1}\mathbf{H}_y\mathbf{W}_s^{i-1}\mathbf{G}_s\mathbf{u}(k-i) + \\ + \sum_{i=1}^{k-1}\mathbf{H}_y\mathbf{W}_s^{i-1}\mathbf{F}_s\mathbf{f}(k-i). \end{aligned} \tag{2}$$

Basing on the main points of the paper [28], we will enter a failure detection factor:

$$\begin{aligned} &\theta_i \triangleq \min\left\{m : \mathbf{H}_y\mathbf{W}_s^{m-1}\mathbf{f}_i \neq 0;\ m = 1, 2, \dots\right\}; \\ &i = 1, 2, \dots, p\,, \end{aligned} \tag{3}$$

where $\mathbf{f}_i$ is a matrix column $\mathbf{F}_s$. This factor characterizes number of observations were the fault is displayed in an explicit form. If we could prove that in the considered system (1) the number of detection index is limited it would then be possible according to [30] to define of detection fault matrix in the form

$$\mathbf{Q}_\theta = \left[\mathbf{H}_y\mathbf{W}_s^{\theta_1-1}\mathbf{f}_1,\ \mathbf{H}_y\mathbf{W}_s^{\theta_2-1}\mathbf{f}_2, \dots,\ \mathbf{H}_y\mathbf{W}_s^{\theta_p-1}\mathbf{f}_p\right], \tag{4}$$

where $\mathbf{Q}_\theta \in \Re^{m\times p}, \theta_i,\ i=1,2,\dots,p$ the failure detection factor associated with the $\mathbf{f}_i$ vector direction. The entered method of a fault distribution description on a priori to the entered directions allows grouping and streamlining of the matrix columns $\mathbf{F}_s$ and the vector

$\mathbf{f}(k)$ according to a failure detection factor in each direction $\mathbf{f}_i$. Usually the set of the faults described by expression $\sum_{i=1}^{k-1} \mathbf{H}_y \mathbf{W}_s^{i-1} \mathbf{F}_s \mathbf{f}(k-i)$ is sorted from the greatest value of a factor θ_i to its smallest value. At the same time the matrix of fault detection $\mathbf{F}_\mathrm{s}$ and the fault vector $\mathbf{f}(k)$ undergo changes which can be described set of expressions:

$$\begin{aligned} &\mathbf{Q} = \left[\mathbf{H}_y \mathbf{F}_1 \;\; \mathbf{H}_y \mathbf{W}_s \mathbf{F}_2 \;\; \ldots \;\; \mathbf{H}_y \mathbf{W}_s^{z-1} \mathbf{F}_z\right], \\ &\mathbf{F}_l = [\mathbf{f}_m \ldots \mathbf{f}_l] : \mathbf{f}_m \neq \mathbf{f}_{l^\frown \theta_m = \theta_l}; \\ &\forall l = 1, 2, \ldots, z = \max(\theta_i), \\ &\forall m = 1, 2, \ldots, z = \max(\theta_i); \end{aligned} \quad (5)$$

$$\begin{aligned} &\omega = \left[\mathbf{f}^1(k-1) \;\; \mathbf{f}^2(k-1) \;\; \ldots \;\; \mathbf{f}^z(k-z)\right]; \\ &\mathbf{f}^l(k-l) = [\mathbf{f}_m(k-l) \ldots \mathbf{f}_l(k-l)]; \\ &\forall l = 1, 2, \ldots, z = \max(\theta_i), \\ &\forall m = 1, 2, \ldots, z = \max(\theta_i). \end{aligned} \quad (6)$$

Despite complexity of the general sorting algorithm description, its result is rather simple. As an example, for the matrix $\mathbf{F}_s = [\mathbf{f}_1, \mathbf{f}_2, \mathbf{f}_3]$, at the fault detection factors $\theta_1 = 1$; $\theta_2 = 2$; $\theta_3 = 3$ we have arrived at results $\mathbf{Q} = [\mathbf{H}_y \mathrm{f}_1, \mathbf{H}_y \mathbf{W}_\mathrm{s} \mathrm{f}_2, \mathbf{H}_y {\mathbf{W}_\mathrm{s}}^2 \mathrm{f}_3]$. Let's substitute parities (5)–(6) in the equation (2) and we will separate results of last observations $(k-i)$ of the presents connected with an instant k, then we will have arrive:

$$\mathbf{y}(k) = \mathbf{H}_y \mathbf{W}_s^k s(0) + \sum_{i=1}^{k-1} \mathbf{H}_y \mathbf{W}_s^{i-1} \mathbf{G}_s \mathbf{u}(k-i) + \\ + \sum_{i=2}^{k-1} \mathbf{Q}\omega(k-i) + \mathbf{Q}\omega(k-1). \quad (7)$$

It is easy to notice that the first two components of expression (7) describe evolution of a system according to a priori the set model, i.e. without fault influences. The third and fourth components consider only the influences of last and current faults. If to assume that to the instant k of the fault were absent, then it is obviously to take a component $\sum_{i=2}^{k-1} \mathbf{Q}\omega(k-i)$ equal to zero. Therefore for a nominal operating mode to the instant k the system exit equation (1) will be transformed to expression equivalent to this

$$\mathbf{y}(k) = \mathbf{H}_y \mathbf{W}_s^k s(0) + \sum_{i=1}^{k-1} \mathbf{H}_y \mathbf{W}_s^{i-1} \mathbf{G}_s \mathbf{u}(k-i) + \mathbf{Q}\omega(k-1).$$

It is easily shown that

$$\mathbf{y}(k) = \mathbf{H}_y s(k) + \mathbf{Q}\omega(k-1). \quad (8)$$

Finally the equivalent equation of the exit (8) where influence of the faults is separated from the influence of the control input and internal system dynamics is obtained as the result. It is the starting point in design of the modified observer capable to detect and localize the multiple faults appearing either is single-step, or sequentially in time.

2 Synthesis of the sensitive fault filter

It is well-known that the standard Kalman filter intended for estimation of a discrete linear dynamic system conditions allows the description in the form of the observer [29]:

$$\mathbf{s}^*(^{k+1}/_{k+1}) = \mathbf{W}_s \mathbf{s}^*(^{k+1}/_k) + \mathbf{G}_s \mathbf{u}(k) + \mathbf{K}\mathbf{r}(k); \quad (9)$$

$$\mathbf{y}^*(k) = \mathbf{H}_y \mathbf{s}^*(^{k+1}/_k), \quad (10)$$

where $\mathbf{x}^*(^{k+}/_k)$ – the extrapolated system state vector estimation; $\mathbf{y}^*(k)$ – the system exit estimation, $\mathbf{K}$ – the transfer observer matrix; $\mathbf{r}(k)$ – the difference signal determined by expression $\mathbf{r}(k) = \mathbf{y}(k) - \mathbf{y}^*(k)$. To synthesize a sensitive fault filter, it is necessary to consider earlier obtained parity (8) in the equation for a difference signal. From this we get

$$\mathbf{r}(k) = \mathbf{H}_\mathrm{y} \mathbf{e}(k) + \mathbf{Q}\omega(k-1), \quad (11)$$

where $\mathbf{e}(k) = s(k) - s^*(^k/_k)$ – the state estimation error.

It can easily be checked that at expression (11) there are two components. The first of them $\mathbf{H}_y \mathbf{e}(k)$ is the state vector system estimation error which ignores the considered faults and perturbations, and the second – $\mathbf{Q}\omega(k-1)$ has the distorting impact on the difference signal. The first component contains information necessary for correction performance of the state vector predicted value while the second component interferes with this correction by entering of shifts into the resulting estimation. It is quite obvious that for deduce of the unbiased state estimations filter transfer matrix it is necessary to separate influences of the second component. The two additional sequences $\mathbf{r}_0(k)$ and $\mathbf{r}_1(k)$, connected with an innovation process by a parity are for this purpose entered

$$\begin{bmatrix} \mathbf{r}_0(k) \\ \mathbf{r}_1(k) \end{bmatrix} = \begin{bmatrix} \mathbf{\Pi}_0 \\ \mathbf{\Pi}_1 \end{bmatrix} \mathbf{r}(k). \quad (12)$$

Matrixes $\mathbf{\Pi}_0, \mathbf{\Pi}_1$ will be defined a bit later. As a result we have two ratios

$$\begin{aligned} \mathbf{r}_0(k) &= \mathbf{\Pi}_0 \mathbf{H}_y \mathbf{e}(k) + \mathbf{\Pi}_0 \mathbf{Q}\omega(k-1); \\ \mathbf{r}_1(k) &= \mathbf{\Pi}_1 \mathbf{H}_y \mathbf{e}(k) + \mathbf{\Pi}_1 \mathbf{Q}\omega(k-1). \end{aligned} \quad (13)$$

For calculation of the state vector unbiased estimations, free from influences of faults and (or) perturbations it is necessary to use the first line of expression (13), and the lower line of the same expression intends for estimation of the extent of the above-stated faults or perturbations. For these purposes two restrictions for matrixes $\mathbf{\Pi}_0$ and $\mathbf{\Pi}_1$ are introduced:

$$\mathbf{\Pi}_0 \mathbf{Q} = \mathbf{0}; \quad \mathbf{\Pi}_1 \mathbf{Q} = \mathbf{I}. \quad (14)$$

If we introduce these restrictions in the equation (13) then the specified sequences it is possible to take a form

$$\mathbf{r}_0(k) = \mathbf{\Pi_0 H_y e}(k)\,; \\ \mathbf{r}_1(k) = \mathbf{\Pi_1 H_y e}\,(k) + \omega(k-1)\,. \quad (15)$$

The sequence $\mathbf{r}_0(k)$ allows to carry out a correction of the predicted state estimations, and the sequence $\mathbf{r}_1(k)$ can be used for the estimation of the perturbations and (or) faults amount. Having substituted expressions (15) in expressions (9)–(10) and having executed simple operations, it is possible to write down the expression for the sensitive fault filter by a parity

$$\mathbf{s}^{*}(^{k+1}/_{k+1}) = \mathbf{W}_s\mathbf{s}^{*}(^{k+1}/_{k}) + \mathbf{G}_s\mathbf{u}(k) + \left([\mathbf{K}\ \Omega]\begin{bmatrix}\Pi_0\\ \Pi_1\end{bmatrix}\right)\mathbf{r}(k)\,; \\ \mathbf{r}_1(k) = \Pi_1\mathbf{r}(k)\,; \quad \mathbf{y}^{*}(k) = \mathbf{H}_y\mathbf{s}^{*}(^{k+1}/_{k})\,. \quad (16)$$

Were the matrix $\mathbf{\Omega}$ describes the channels of faults and (or) perturbations, defined as [29]:

$$\mathbf{\Omega} \triangleq \mathbf{W}_s\left[\mathbf{F}_1\ \ \mathbf{W}_s\mathbf{F}_2\ \ \ldots\ \ \mathbf{W}_s{}^{z-1}\mathbf{F}_z\right]. \quad (17)$$

If to enter additional designations, $\mathbf{H} = \mathbf{\Pi_0 H_y}; \mathbf{W} = \mathbf{W_s} - \mathbf{\Omega\Pi_1 H}$ that is possible to obtain the Kalman filter analog adapted to conditions of the considered task:

$$\mathbf{s}^{*}(^{k+1}/_{k+1}) = [\mathbf{W} - \mathbf{KH}]\,\mathbf{s}^{*}(^{k+1}/_{k}) + \mathbf{G}_s\mathbf{u}(k) + \\ + [\mathbf{K\Pi}_0 + \mathbf{\Omega\Pi_1}]\,\mathbf{y}(k)\,; \quad (18) \\ \mathbf{r}_1(k) = \Pi_1\mathbf{r}(k)\,; \quad \mathbf{y}^{*}(k) = \mathbf{Hs}^{*}(^{k+1}/_{k})\,.$$

This filter at the same time estimates the system state vector, the vector of the predicted measurements and the extent of faults and (or) perturbations. There was the choice problem of a matrix coefficient factor size. There are no special restrictions, except for stabilization of the matrix $[\mathbf{W} - \mathbf{KH}]$. For this purpose it is necessary to arrange observability poles within a circle of single radius that it is possible to make by means of the well-known package modeling team MatLab. In the absence of the system noise (the determined case) the synthesized filter transfer matrix becomes too unlimited by analogy with Kalman filter and it corresponds to the so-called, degenerate observer, but in a stochastic case it is regulated by the present noise levels.

3 Stability and estimation convergence

The offered structure contains two of discrete Kalman filters which function in parallel and independently. In this case such properties as estimations, stability and their convergence can be considered in the context of stability of the Rikkati equation solutions for a filter error covariation matrix at freeform transfer matrix:

$$\mathbf{P}(^{k+1}/_{k+1}) = (\mathbf{W}_s - \mathbf{KH}_y)\mathbf{P}(^{k}/_{k})(\mathbf{W}_s - \mathbf{KH}_y)^T + \mathbf{KRK}^T. \quad (19)$$

More thorough research of this subject can be found in paper [32] according to that the discrete Kalman filter will be steady in only case when: matrix eigenvalues $[\mathbf{W}_s - \mathbf{KH}_y]$ are located in a circle of the single radius; the couple $(\mathbf{W}_s, \mathbf{H}_y)$ has to be detected, and the couple $(\mathbf{W}_s, \mathbf{G}_s)$ – completely operated. In a condensed form it is expressed in the shape rank Rosenbrock's criterion:

$$rank\left(\begin{vmatrix} z\mathbf{I} - \mathbf{W}_s \\ \mathbf{H}_y \end{vmatrix}\right) = n, \quad \forall z \in C, \quad |z| \geq 1, \\ rank\left(\left[-e^{j\omega}\mathbf{I} + \mathbf{W}_s,\ \Omega^{1/2}\right]\right) = n,\ \forall\omega \in \Omega : 0 \leq \omega \leq 2\pi. \quad (20)$$

In relation to the case considered in this paper, the above-stated requirements are transformed to the following formulas:

$$rank\left(\begin{vmatrix} z\mathbf{I} - \mathbf{W} & \mathbf{F} \\ \mathbf{H} & 0 \end{vmatrix}\right) = n + p; \\ rank\left(\left[-e^{j\omega}\mathbf{I} + \mathbf{W},\ \mathbf{F},\ \Omega^{1/2}\right]\right) = n,\ \forall\omega \in \Omega : 0 \leq \omega \leq 2\pi. \quad (21)$$

4 Modelling result

As a test example we will consider an airplane landing system. Process of landing contains several stages. During the first of them, the airplane by means of the navigation set radio equipment direct to the required airport. At the second stage begins from the input moment of the airplane in contact of the a glide slope beacon beam, after that the pilot directs the air vehicle along the chosen line of planning at an angle approximately – 3° to a runway. At the height about 30 m the terminal phase – alignment begins. Here, in connection with close proximity of the earth, a radio beam alignment becomes inefficient. Further planning at an angle – 3° to the horizon plane also miss mark of comfort and flight safety. Therefore at an alignment stage the pilot is forced to operate the airplane in the manual mode, being guided at the same time by the visual observations of a runway and (or) following indications of autonomous onboard means, for example, of altimeters. Anyway, effective control of the air vehicle assumes availability of the operated object mathematical model. If to assume that the angle of bank at a stage of alignment is equal to zero, then the movement of the air vehicle is separated into two components: longitudinal and side. Further we will be limited to consideration only of a longitudinal component of the movement. On Fig. 1 the geometry of corners, a configuration of forces and the moments operating on the air vehicle in the vertical plane passing through its axis of symmetry is shown.

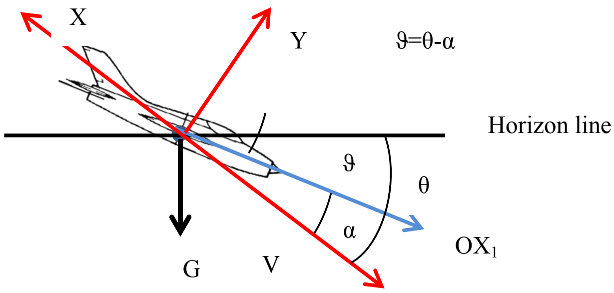


Fig. 1. Distribution of forces and the moments in the longitudinal movement of the air vehicle

As the oblique angle of a landing path is very small it gives the grounds to consider that the longitudinal movement of the air vehicle is defined by deviation angles of elevation rudders at an alignment stage completely. Besides we will assume that in the small range of height change the pilot hold down the accelerator lever handle in such state that the vessel airspeed remains to a constant. The entered assumptions allow to separate the longitudinal movement of the air vehicle into the short-period movement and long-period (phugoidal mode). Its time constants are different at ten times approximately. In terms of stability and controll ability flight on a planned trajectory the most major problem is implemented by a short-period component of the longitudinal movement which linearized equation is provided [32]:

$$\frac{d^3\vartheta\left(t\right)}{dt^3}+2\xi_\vartheta\omega_\vartheta\frac{d^2\vartheta\left(t\right)}{dt^2}+\omega^2{}_\vartheta\frac{d\vartheta\left(t\right)}{dt}= \\ =KT_0\omega^2{}_\vartheta\frac{d\delta_{\text{в}}\left(t\right)}{dt}+K\omega^2{}_\vartheta\delta_{\text{в}}\left(t\right), \quad (22)$$

where ϑ – a pitch angle; ξ_ϑ – damping coefficient in a pitch channel; ω_ϑ – self-resonant frequency; K – gain amount of short-period fluctuations; T_0 – trajectory constant of time; $\delta_{\text{в}}$ – elevation rudder deviation angle.

Parameters of the equation (22) are defined by design features of the air vehicle and depend from coefficients of aerodynamic forces and the moments which are very composite nonlinear functions of many parameters, change in time and depending on flight conditions. In practice these coefficients are defined experimentally for each aircraft type, and when carrying out engineering calculations use the corresponding schedules, see for example, [34] p. 24, [35] p. 120. However, processing of results of flight and bench tests shows that an overwhelming majority of pilots evaluate the air vehicle as control object by Cooper-Harper's scale on "well" or "satisfactorily" if his design data are in certain limits: $\xi_\vartheta=0.5-0.7$; $\omega_\vartheta=1-3.5\,s^{-1}$; $K=0.5-2$; $T_0=1-5\,s$. According to available data in [36] pp. 55-58, 149-150, we will stop on the following values of the above-named parameters:

$$\xi_\vartheta=0.5;\ \omega_\vartheta=2.0\,s^{-1};\ K=0,9;\ T_0=3.1\,s \quad (23)$$

that will be agreed with the recommendations of other research well, for example [33, 37].

As variables of a state we will choose height, speed of its change, a pitch angle and speed change of a pitch angle. Such option of the choice is favorable that all variable states allow measurements by technical means. For achievement of this purpose we will use communication between height and a pitch angle [33]

$$T_0\frac{d^2h(t)}{dt^2}=V_0\vartheta\left(t\right)-\frac{dh(t)}{dt}. \quad (24)$$

Further, we differentiate expression (24) twice

$$\begin{aligned} T_0\frac{d^3h(t)}{dt^3}&=V_0\frac{d\vartheta(t)}{dt}-\frac{d^2h(t)}{dt^2}; \\ T_0\frac{d^4h(t)}{dt^4}&=V_0\frac{d^2\vartheta(t)}{dt^2}-\frac{d^3h(t)}{dt^3}. \end{aligned} \quad (25)$$

Combining the equations (24)–(25), we obtain the result:

$$\frac{d^2\vartheta(t)}{dt^2}-\frac{1-2\xi_\vartheta\omega_\vartheta T_0}{T_0}\frac{d\vartheta(t)}{dt}+\frac{1-2\xi_\vartheta\omega_\vartheta T_0+(\omega_\vartheta T_\vartheta)^2}{{T_0}^2}\vartheta(t)-\frac{1-2\xi_\vartheta\omega_\vartheta T_0+(\omega_\vartheta T_\vartheta)^2}{V{T_0}^2}\frac{dh(t)}{dt}=K{\omega_\vartheta}^2T_0\delta_{\text{в}}(t). \quad (26)$$

Let's provide the equation (26) in the Cauchy form by definition of a state variables $s_1=h; s_2=dh/dt; s_3=\vartheta; s_4=d\vartheta/dt$. As the result we will obtain a matrix form of the equation (26)

$$\begin{bmatrix}\dot s_1\\ \dot s_2\\ \dot s_3\\ \dot s_4\end{bmatrix}=\begin{bmatrix}0 & 1 & 0 & 0\\ 0 & -\frac{1}{T_0} & \frac{V_0}{T_0} & 0\\ 0 & 0 & 0 & 1\\ 0 & \left(\frac{1}{V_0{T_0}^2}-\frac{2\xi_\vartheta\omega_\vartheta}{V_0T_0}-\frac{\omega^2{}_\vartheta}{V_0}\right) & \left(\frac{1}{{T_\vartheta}^2}-\frac{2\xi_\vartheta\omega_\vartheta}{T_\vartheta}-{\omega_\vartheta}^2\right) & \left({T_0}^{-1}-2\xi_\vartheta\omega_\vartheta\right)\end{bmatrix}\begin{bmatrix}s_1\\ s_2\\ s_3\\ s_4\end{bmatrix}+\begin{bmatrix}0\\0\\0\\K{\omega_\vartheta}^2T_0\end{bmatrix}\delta_{\text{в}}. \quad (27)$$

In a condensed form expression (27) will have an appearance:

$$\begin{aligned}\dot{\mathbf{s}}(t)&=\mathbf{W}_s\mathbf{s}(t)+\mathbf{G}_s\mathbf{u}(t)\,;\\ \mathbf{y}(t)&=\mathbf{H}_y\mathbf{s}(t)\,,\end{aligned} \quad (28)$$

where W_s – system matrix of size (4×4); G_s – a control matrix (4×1); $u(t)=\delta_{\text{в}}(t)$ – a scalar control signal; $y(t)$ – observation vector of size (4×1); H_y – a scalar observation matrix of the size (4×4) with units on the main diagonal. Believing the landing approach speed V_0 by the size of constant and equal $75\,\mathrm{ms}^{-1}$, and parameters of the longitudinal movement chosen according to expression (23), it is possible to obtain a discrete equivalent of the equation (28)

$$\begin{aligned} \mathbf{s}(k+1) &= \mathbf{W}_s\,(k+1,k)\,\mathbf{s}(k) + \mathbf{G}_s\,(k+1,k)\,\mathbf{u}(k)\,; \\ \mathbf{y}(k) &= \mathbf{H}_y(k)\,\mathbf{s}(k)\,, \end{aligned} \qquad (29)$$

where

$$\mathbf{W}_s\,(k+1,k) = \begin{bmatrix} 1.000 & 0.0249 & 0.0075 & 0.0001 \\ 0 & 0.9920 & 0.6010 & 0.0072 \\ 0 & 0.0001 & 0.9930 & 0.0235 \\ 0 & 0.0073 & -0.5457 & 0.8829 \end{bmatrix}$$

$$\mathbf{G}_s\,(k+1,k) = \begin{bmatrix} 0 \\ -0.0043 \\ -0.0209 \\ -1.6417 \end{bmatrix}$$

$$\mathbf{H}_y(k) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}; \qquad \mathbf{F}_s = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 1 \\ 1 & 1 \end{bmatrix}. \qquad (30)$$

In this example the sampling rate was chosen equal 40,5 Hz that corresponds to the scan frequency of the glide slope beacon in a landing system of the centimetric range. The fault vector formed according to expression

$$\mathbf{f}(k) = \begin{bmatrix} f_1(k) \\ f_2(k) \end{bmatrix} =$$

$$= \begin{bmatrix} if\ k \le 80 \quad f_1(k) = 0.0,\ else\, f_1(k) = -0.2; \\ if\ k \le 140\ f_2(k) = 0.0,\ else\ f_2(k) = -0.05 * \sin(0.1 * k) \end{bmatrix}.$$

The component $f_1(k)$ imitated fault in a hop damper, and $f_2(k)$ described process of gain factor K drift in the guidance subsystem. The analysis of these fault influence on variable states (27) allowed to create the fault distribution matrix given in the block of formulas (30). Components of a state vectors $s(k)$ were distorted by white Gaussian noises $w_s(k)$ for the purpose of accounting of modeling errors and influence of a wind turbulent component. Errors of measurements were considered by introduction of white Gaussian noises $v_y(k)$, uncorrelated to $w_s(k)$. The intensity of the specified noise was defined by a task of the corresponding covariation matrixes:

$$\mathbf{Q}_s(k) \triangleq E\left\{w_s {w_s}^T\right\} = diag\left[0.1^2 \quad 0.1^2 \quad 0.001^2 \quad 0.01^2\right];$$
$$\mathbf{R}_y(k) \triangleq E\left\{\mathbf{v}_y {\mathbf{v}_y}^T\right\} = 0.1 * eye\,(4)\,.$$

Initial conditions were defined by such values: $\mathbf{s}(0) = \begin{bmatrix} 30 & -1.2 & -0.1 & -0.002 \end{bmatrix}$; $\mathbf{u}(0) = -0.01$; $\mathbf{s}^*(\%) = \begin{bmatrix} 32 & -1.0 & -0.15 & 0.003 \end{bmatrix}$. The design order of the filter consisted of the such steps sequence:

1. Checks of feasibility of the separate estimation by calculation of a parity $rank({\mathbf{H}_y}^*\mathbf{F}_s) = rank(\mathbf{F}_s)$. In fact it means that the number of the localizable faults cannot be more the number of measuring means. For the reviewed example these restrictions are satisfied.

2. Definitions of a detectability fault factor in the set directions θ_i in compliance with formula (3). Established that $\theta_1 = \theta_2 = 1$.

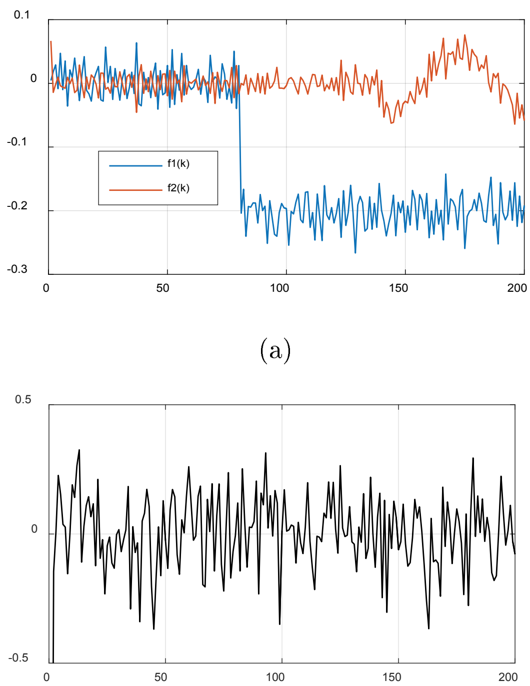
3. Calculation of the matrixes $\mathbf{Q}, \mathbf{\Pi_1}, \mathbf{\Omega}$ by expressions:

$$\mathbf{Q} = \mathbf{H}_y {\mathbf{W}_s}^{i-1} \mathbf{F}_s = \mathbf{H}_y \mathbf{I}\, \mathbf{F}_s;$$
$$\mathbf{\Pi_1} = \mathbf{I}\mathbf{Q}^{\#}; \quad \mathbf{\Omega} = \mathbf{W}_s \left[\mathbf{F}_1 \quad \mathbf{W}_s \mathbf{F}_2 \ \ldots \ {\mathbf{W}_s}^z \mathbf{F}_z\right],$$

where $\mathbf{Q}^{\#}$ – the pseudoinverse matrix of Moore-Penrose; the matrix $\mathbf{\Pi}_0$ was calculated on to the solution method of the not predetermined linear equation system, which demands the priori task of free parameters. The choice of these acceptable value parameters is dictated by specifically solvable task and its physical essence.

4. The filter transfer matrix was defined by a task of poles within a single radius circle.

Modeling results are presented on Fig. 2-3. On Fig. 2a fault estimations in the damper pitch channel $f_1^*(k/k)$ and perturbation $f_2^*(k/k)$ in a regulator subsystem. Until emergence of faults the offered filter was equivalent to a standard Kalman filter. Its difference signal is shown on Fig. 2b.



(a)

(b)

Fig. 2. Time history of difference signals before and after emergence of faults

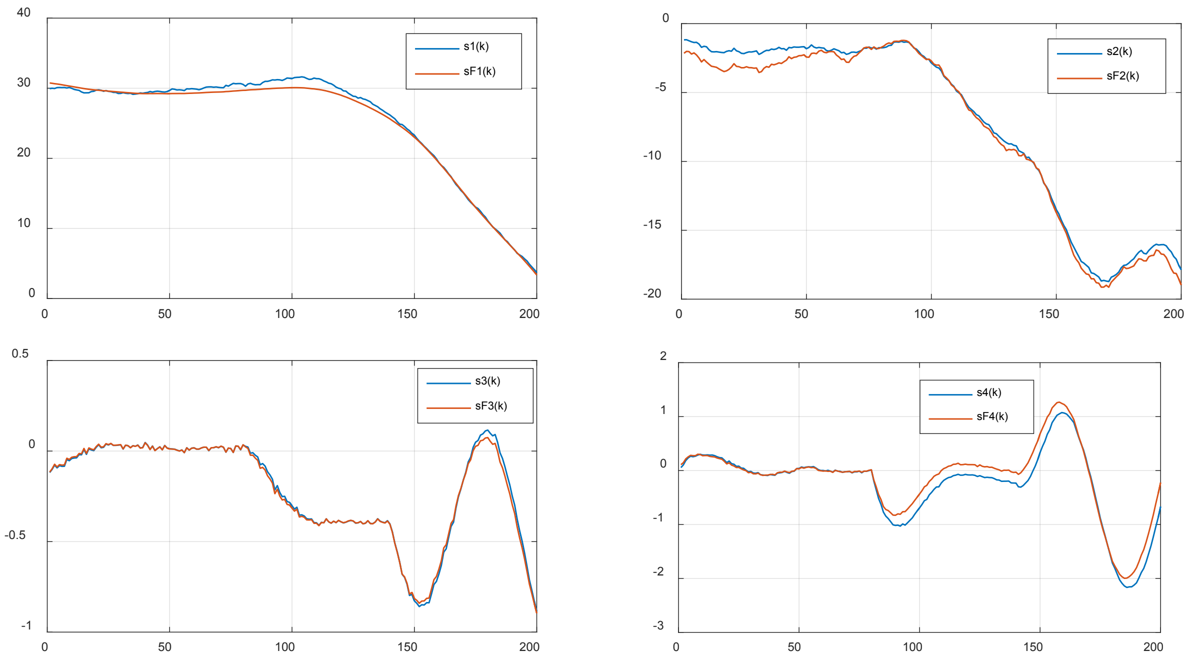


Fig. 3. The state vector estimations component and its actual values before and after emergence of faults

After emergence of faults, separate estimation mechanism operate trigger spuriously and the filter is split on two parallel of independent controlled type structure. One of them estimates faults, and the second estimates a state vector, ignoring at the same time the fact of fault emergence. The resulting estimation represents the weighed combination of the obtened private estimations. As everyone in parallel the functioning structure has dimension smaller than initial, it promotes reduction of computing costs. However, this economy is followed by accuracy loss in comparison by a nominal operational mode, and expansion of functionality is accompanied by introduction of additional rank restrictions. On Fig. 3 the components of a vector of state $s_1^*(k/k) - s_4^*(k/k)$ and their actual values $s_1(k) - s_4(k)$ before and after emergence.

It is possible to see that the obtened estimations meet and have acceptable quality throughout all computing experiment. However, it is even visually possible to notice that after emergence of fault in the damping channel, the pitch angle $s_3^*(k/k)$ approximately from the 90-th step goes beyond the regulated rates and begins to form the emergency situation which is followed by sharp altitude loss $s_1^*(k/k)$ of the air vehicle. There is an opportunity to avoid development of the emergency situation by performance of timely fault diagnostics. For this purpose, it is necessary to expose in channels $f_1^*(k/k)$ and $f_2^*(k/k)$ appropriately picked up threshold levels which exceeding would mean emergence of an alarm signal.

Conclusion

In the submitted paper the synthesis of the fault sensitive filter intended for detection and localization of the faults and (or) perturbations in linear discrete time-invariant systems is executed. The detecting filter was designed so that by means of the directed properties, previously created the residual differences it was possible to separate one type influence of faults (perturbations) which is interest, from other types influence of faults (perturbations).

The structure of the "extrapolator-corrector" device similar to Kitanidis filter structure is result of synthesis. It consist of two independently parallel functioning adaptive device of Kalman filter type. The first of them calculates a system state vector estimation without taking note of faults, and the second - a degenerate type, creates a fault estimations. Linear combination of their exits forms the resulting state vector estimation. Both filters have dimensions smaller dimensions of the tested system and use the split procedure of an error differential signal. Splitting of the error signal is carried out before estimation process unlike Kitanidis filter. It allows to get a certain economy in computing costs, due to introduced restrictions and losses in accuracy. In general the obtained structure is suboptimal. Issues of convergence and stability of the obtained estimations are discussed briefly. Results of a functional check method are given by an informative numerical example using of the computing MatLab environment. Modeling results confirmed operability of the method, and the synthesized filter is capable to create the state estimations of satisfactory quality and to perform correct functionality on diagnostics of anticipated perturbations and (or) faults. All above shows that the submitted paper to brings a novelty aspect in the general perspective associated to detection and recognition of multiple faults in linear discrete dynamic systems.

It should be noted that out of sight of this research there were such important issues as diagnosing of slowly arising faults, resistance to parametrical uncertainty of the diagnosed object, diagnosing of faults in nonlinear systems and of course, expansion of the sphere of the applications developed methods. All this can be a subject of further researches.

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Метод виявляючого фільтра в задачах діагностики лінійних динамічних систем

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На практиці досить частими є випадки, коли динаміка фізичних систем зазнає раптових змін, що в свою чергу, призводить до погіршення їх якісних показників. Ці зміни, у першому наближенні, можна характеризувати або як несправності, або як відмови. У представленій роботі розглянуте завдання синтезу пристрою виявлення несправностей і їх розпізнавання в лінійних дискретних динамічних системах з постійними параметрами. Результат синтезу представлений у вигляді паралельної структури, що являє собою два незалежно працюючих фільтри калмановського типу. Перший з них обчислює оцінку вектора стану системи без врахування впливу несправностей, а другий – виродженого типу, формує оцінку несправностей. Лінійна комбінація їх виходів утворює результуючу оцінку вектору стану. Обоє фільтра мають розмірності менші за розмірності системи, що досліджується й використовують процедуру розщеплення сигналу нев'язки. Розщеплювання нев'язки, на відміну від фільтра Кітанідиса, здійснюється до процесу оцінювання. Це дозволяє одержати певну економію в обчислювальних витратах, але за рахунок додатково введених обмежень і втрат у точності. У цілому отримана структура є квазиоптимальною. Коротко розглянуті питання стійкості й збіжності оцінок вектора стану динамічної системи. Наведені результати перевірки працездатності методу на змістовному числовому прикладі з використанням обчислювального середовища Matlab. Структурно робота побудована в такий спосіб. Спочатку виконана постановка завдання й аналізується її можливість розв'язання з математичної точки зору. Наступним кроком є синтез пристрою виявлення й локалізації множинних несправностей, після чого проаналізовані збіжність і стійкості помилок оцінювання. У заключних розділах наведені результати перевірки працездатності методу на ілюстративному прикладі й підведені підсумки виконаної роботи.

Ключові слова: модельно-орієнтовані методи виявлення несправностей; відмовостійке керування; дискретна лінійна динамічна система; роздільне оцінювання вектору стану

Метод обнаруживающего фильтра в задачах диагностики линейных динамических систем

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На практике нередки случаи, когда динамика физических систем претерпевает внезапные изменения, что приводит к ухудшению их качественных показателей. Эти изменения, в первом приближении, можно характеризовать либо как неисправности, либо как отказы. В представленной работе рассмотрена задача синтеза устройства обнаружения неисправностей и их распознавания в линейных дискретных динамических системах с постоянными параметрами. Результат синтеза представлен в виде параллельной структуры, состоящей из двух независимо работающих фильтров калмановского типа. Первый из них вычисляет оценку вектора состояния системы без учета влияния неисправностей, а второй – вырожденного вида, формирует оценку неисправностей. Линейная комбинация их выходов образует результирующую оценку вектора состояния. Оба фильтра имеют размерности меньшие размерности исследуемой системы и используют процедуру расщепления сигнала невязок. Расщепление невязок, в отличие от фильтра Китанидиса, осуществляется до процесса оценивания. Это позволяет получить определенную экономию в вычислительных издержках, но за счет дополнительно введенных ограничений и потерь в точности. В целом полученная структура является квазиоптимальной. Кратко рассмотрены вопросы устойчивости и сходимости оценок вектора состояния динамической системы. Приведены результаты проверки работоспособности метода на содержательном числовом примере с использованием вычислительной среды MatLab. Структурно работа построена следующим образом. Сначала выполнена постановка задачи и анализируется ее разрешимость с математической точки зрения. Следующим шагом является синтез устройства обнаружения и локализации множественных неисправностей, после чего проанализированы сходимость и устойчивости ошибок оценивания. В заключительных разделах приведены результаты проверки работоспособности метода на иллюстративном примере и подведены итоги выполненной работы.

Ключевые слова: модельно-ориентированные методы обнаружения неисправностей; отказоустойчивое управление; дискретная линейная динамическая система; раздельное оценивание вектора состояния