METHOD OF FAULT IDENTIFICATION IN MECHATRONIC SYSTEMS

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Abstract

This paper considers a method of synthesis of identification system for faults appearing in the various elements of complex mechatronic systems described by nonlinear differential equations. To solve this problem logic-dynamic approach and special feedback by residual signal is suggested. This approach consists of three main steps: replacing the initial nonlinear system by certain linear logic-dynamic system, obtaining the bank of linear logic-dynamic observers, and transforming these observers into the nonlinear ones. Logic-dynamic approach allows detecting and isolating faults in nonlinear dynamic systems by using the linear methods for diagnosis in nonlinear mechatronic systems. Feedback of special form introduced in the observers after the detection and isolation of faults. It is allowing to determine the value of faults in nonlinear systems with incomplete measurability of state vector. Efficiency and high performance of the proposed method is shown on example of identification of faults arising in electric drives of multilink manipulator.

Keywords: Fault identification; diagnostic; observers; mechatronic systems; nonlinear systems.

1. Introduction

Operative detection and localization of faults that may occur in elements and subsystems in the process of operation it is one of the perspective ways to improve the efficiency of operation of mechatronic systems (MS) in the event of minor defects in the sensor elements and actuators. Timely detection, localization and identification of the values of these faults allow the use of methods of fault-tolerant control and accommodation for the formation of specific control signals that allow to keep the most important characteristics of the system in the presence of faults in it providing guaranteed performance of specified operations and missions.

Currently, there are several different approaches to the synthesis of the system of identification of faults [1-9]. All these approaches are based on the procedures for the real-time identification and localization of faults via diagnostic observers (DO). Several methods for synthesis of diagnostic observers for nonlinear dynamical systems are known, including those based on the differential geometric approach [5], the algebra of functions [5], logic-dynamic approach [1-3, 9] and others [4, 6 - 8]. The first two allow obtaining the optimal solution with a minimum dimension of observer, however, have a rather complicated process of finding a solution, because of complex analytical calculations. Logic-dynamic approach does not guarantee a minimum dimension, but the process of finding a solution on its basis is quite

simple because of using of linear methods. The task of identifying the values of the faults on the basis of logic-dynamic approach has been solved in [2] and [3], by introducing into the diagnostic observers the signal of feedback by the residual. However, this approach is valid only for the case when the state vector of the diagnosing object fully measurable and diagnostic observers has the first order.

This paper considers solution to the problem of developing a method of synthesis of precise identification system for faults in a variety of complex MS, which use the DO, described by differential equations with the order above the first. In method a special feedback by the signal of residual is introduced in the diagnostic observers obtained with the logic-dynamic approach for real-time identification of values of faults.

2. Model of diagnosed object

In general, non-linear multidimensional diagnosed object (DO) can be described by a model of the form:

$$\begin{aligned}\dot{x}(t) &= Fx(t) + B(x(t), u(t)) + Gu(t) + Ld(t), \\ y(t) &= Hx(t),\end{aligned}\tag{1}$$

where $x \in R^n$ is state vector, n is dimensionality of DO; $y \in R^m$ is output vector; $u \in R^l$ is input vector, p -dimensional vector $d(t)$ describes the errors occurring in the system because of the appearance of faults in it (in the absence of faults all the elements of the vector are zero; in the presence of a fault corresponding element of the vector becomes unknown function of time); $F \in R^{n \times n}$ is matrix of system dynamics; $G \in R^{n \times l}$ is matrix that determines the effect of the input to the system; $H \in R^{m \times n}$ is matrix that determines the relationship of output with the state vector; $B(x(t), u(t))$ is a vector which determines a non-linear part of the system. In this paper a case where each of elements of vector $d(t)$ included only in one of the equations of (1) is considered, which means that there is only one nonzero element in each of the columns of matrix $L \in R^{n \times p}$. The task of detecting faults and determining their values are invited to decide on the basis of logic-dynamic approach (LDA) [1], which allows the construction of diagnostic observers using only linear methods. After synthesis of the diagnostic observers, the special feedback must be introduced in them to ensure stability and to determine the value of the faults occurring in the system.

The developed method provides a set of nonlinear diagnostic observers, each of which is sensitive to one of the faults and invariant to the others. The output signals of observers are the values of the corresponding faults.

As a result of the well-known procedure of synthesis of diagnostic observers based on the LDA [1] k -dimensional observer sensitive to one of the faults $d_i(t)$, $i = 1, p$, can be built in the following form:

$$\begin{aligned}\dot{x}^*(t) &= F^* x^*(t) + B^*(x^*(t), u(t)) + G^* u(t) + Jy(t), \\ y^*(t) &= H^* x^*(t),\end{aligned}\tag{2}$$

where $x \in R^k$ is state vector of observer; y^* is output signal of observer; $F^* \in R^{k \times k}$, $G^* \in R^{k \times l}$, $H^* \in R^{l \times n}$ are matrixes corresponding to matrices of system (1), $J \in R^{k \times m}$ is matrix, which defines the use of DO output in observer. All these matrices must be determined during the synthesis of the observer. It is known [1] that F^* и H^* can be chosen as:

$$F^* = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & 0 \end{bmatrix}, H^* = [1 \quad 0 \quad 0 \quad \dots \quad 0].\tag{3}$$

On the basis of the outputs of DO and observer following residual is generated:

$$r(t) = Cy(t) - y^*(t),\tag{4}$$

where C is m -dimensional vector, defining use of DO output in residual generation.

The state vectors of DO and observer are associated by the matrix $\Phi \in R^{k \times n}$, and, in the absence of a mismatch between the DO and the observer (if $r = 0$), satisfy the following equations[1]:

$$x^* = \Phi x, G^* = \Phi G, CH = H^* \Phi, \Phi F = F^* \Phi + JH.\tag{5}$$

In case of any fault the residual (4) becomes different from zero, and the equations (5) is no longer fulfilled. To solve the problem of identification of faults, consider how residual will change in the event of faults. After differentiating the expression (4) taking into account (1) and (2) it can be obtained:

$$\dot{r} = CH(Fx + Gu + B(x,u) + Ld) - H^*(F^*x^* + G^*u + B^*(x^*,u) + Jy).$$

In view of this and (5) it can be obtained:

$$\dot{r} = H^*(F^*(\Phi x - x^*) + \Phi B(x,u) - B^*(x^*,u) + \Phi Ld).$$

Denote the value of $\Phi x - x^*$ as a vector $e \in R^k$ of mismatch of states of DO and the observer: $e = \Phi x - x^*$. Considering introduced vector, it can be obtained:

$$\dot{r} = H^*(F^*e + \Phi B(x,u) - B^*(x^*,u) + \Phi Ld). \quad (6)$$

Consider the relationship of the vector of mismatch e with the residual r , in view of (4):

$$r = Cy - y^* = CHx - H^*x^* = H^*\Phi x - H^*x^* = H^*e. \quad (7)$$

Thus, taking into account the form of vector H^* , the residual r is the first element of mismatch vector e :

$$r = e_1.$$

Next, consider the impact of a fault not only on residual, but on the entire vector e . Then, taking into account (5) and (7) it can be obtained:

$$\dot{e} = F^*e + \Phi B(x(t), u(t)) - B^*(x^*(t), u(t)) + \Phi Ld. \quad (8)$$

From (8) it follows that the change of the mismatch vector depends on the element $\Phi B(x(t), u(t)) - B^*(x^*(t), u(t))$, which characterizes the non-linearity of DO and observer. In the case of incomplete measurability of DO, state vector x and the value of the element $\Phi B(x(t), u(t))$ can be unknown. It is making difficult identifying of value of faults. In LDA observer constructed in way to compensate the effect of non-linearity in the residual signal and $\Phi B - B^* = 0$. However, this condition is fulfilled only when there is no mismatch between the state vectors of DO and observer and $e = 0$. To determine the value of fault d_i , which we are interested, it is necessary to introduce feedback by residual signal formed in such way to provide mismatch elimination even in the case of faults.

3.Introduction of feedback

After the introduction of feedback by residual signal in the observer, its model assumes the form:

$$\begin{aligned} \dot{x}^*(t) &= F^*x^*(t) + B^*(x^*(t), u(t)) + G^*u(t) + w(r) + Jy(t), \\ y^*(t) &= H^*x^*(t), \end{aligned} \quad (9)$$

where $w(r) \in R^k$ is a vector specifying feedback by residual signal.

Taking into account the introduced feedback, change of the mismatch vector will be determined by the equation:

$$\dot{e} = F^*e + \Phi B(x,u) - B^*(x^*,u) + \Phi Ld - w(r). \quad (10)$$

If formed feedback ensures that the equalities (4) and $B^*(x(t), u(t)) = \Phi B(x^*(t), u(t))$ are performed, nonlinearity in the process of identification of faults will be compensated.

To ensure the sensitivity of observer to the fault d_i and the invariance of the rest, matrix Φ is constructed so that all the columns of matrix ΦL except i th were zero, so observer will be affected only by one element of fault vector d . Next, consider common case, when the equation (11) can be represented as:

$$\begin{aligned}
\dot{e}_1 &= e_2 - w_1(e_1), \\
\dot{e}_2 &= e_3 - w_2(e_1), \\
\dot{e}_3 &= e_4 - w_3(e_1), \\
&\dots \\
\dot{e}_v &= e_{v+1} + f_v d_i + a_v - w_v(e_1), \\
&\dots \\
\dot{e}_k &= -w_k(e_1).
\end{aligned} \tag{11}$$

where $a = \Phi B(x(t), u(t)) - B^*(x^*(t), u(t))$, f_v is element of the i th column of the matrix ΦL .

In this case, the fault and uncompensated nonlinear component a_v are present in only one of the equations (11). In the case of $w_{v+1}(e_1) = 0, \dots, w_k(e_1) = 0$ and the consistency of the initial conditions of DO and observer, $e_{v+1}, \dots, e_k$ are zero regardless of the occurrence of the fault. Then further, it is possible to consider only a part of the system of equations (11):

$$\begin{aligned}
\dot{e}_1 &= e_2 - w_1(e_1), \\
\dot{e}_2 &= e_3 - w_2(e_1), \\
\dot{e}_3 &= e_4 - w_3(e_1), \\
&\dots \\
\dot{e}_v &= f_v d_i + a_v - w_v(e_1).
\end{aligned} \tag{12}$$

Writing the system of equations (13) in the form of a differential equation we get:

$$f_v d_i + a_v = \dot{e}_v + w_v = \ddot{e}_{v-1} + \dot{w}_{v-1} + w_v = \ddot{e}_{v-2} + \dot{w}_{v-2} + \dot{w}_{v-1} + w_v = e_1^{(v)} + w_1^{(v-1)} + \dots + w^{(1)}_{v-1} + w_v.$$

Accepting elements of the vector of feedback, except the v th, proportional to the residual $w_j = \frac{T_j}{T_0} e_1$ ($j = \overline{1, v-1}$) and

$w_v = \frac{T_v}{T_0} e_1 + \frac{1}{T_0} z(e_1)$, it can be obtained:

$$f_v d_i + a_v = e_1^{(v)} + \frac{T_1}{T_0} e_1^{(v-1)} + \dots + \frac{T_{v-1}}{T_0} e_1^{(1)} + \frac{T_v}{T_0} e_1 + \frac{1}{T_0} z(e_1). \tag{13}$$

If value of $f_v d_i + a_v$ presented as input signal, and e_1 as output, equation (14) can be represented as a transfer function:

$$W = \frac{T_0}{T_0 s^v + \dots + T_v + Z(s)}.$$

Suppose that input $f_v d_i + a_v$ can be represented as a polynomial of degree q : $f_v d_i + a_v = b_0 + b_1 t + \dots + b_q t^q$. The Laplace

transform of such input is $Q = \frac{b_0}{s} + \frac{b_1}{s^2} + \dots + \frac{b_q}{s^{q+1}}$.

Then the steady value of e_1 can be found as: $e_1 = \lim_{s \rightarrow 0} W Q s = \lim_{s \rightarrow 0} \frac{T_0 (b_0 s^{q-1} + \dots + b_q) s}{(T_0 s^v + \dots + T_v) s^{q+1} + Z(s) s^{q+1}}.$

Assuming $Z(s) = \frac{T_{v+1}}{s} + \frac{T_{v+2}}{s^2} + \dots + \frac{T_{v+q}}{s^q} + \frac{T_{v+q+1}}{s^{q+1}}$ we get: $e_1 = \lim_{s \rightarrow 0} \frac{T_0 (b_0 s^{q-1} + \dots + b_q) s}{(T_0 s^v + \dots + T_v) s^{q+1} + T_{v+1} s^q + \dots + T_{v+q+1}} = 0.$

Thus introducing a feedback of indicated type result in a steady value of $e_1 = 0$. This also results in resetting of all elements of vector e . For many real systems value of the fault is constant or slowly changing and it is sufficient to introduce one integral of residual in feedback to achieve the required accuracy of the identification of faults:

$$z(e_1) = \int e_1 dt. \tag{14}$$

Thus, after the introduction of this kind of feedback, residual e_1 will tend to zero, after the completion of the transition process, including in the event of faults. This will ensure the synchronization of state vectors of DO and observer.

The next step of solving the problem is estimation of value of the desired fault. Since the introduction of the feedback was able to arrange that $e = 0$, taking into account (12) it can be written:

$$d_i = \frac{w_v(e_1)}{f_v} \text{ or } d_i = \frac{1}{f_v T_0} \int e_1 dt. \quad (15)$$

Thus the output of the system of identification of faults after the of transient processes will be sought value d_i . The required system performance can be achieved by selection of $T_0 \dots T_v$ coefficients.

4. Example

Let us to consider multilink manipulator(MM) with n degrees of freedom which is driven by n actuators with DC motors. Each actuator has sensors of the position, speed and current. It is assumed that the following types of faults are possible in the actuators of MM: d_1 – fault caused by an increase of moment of viscous friction in the link of manipulator; d_2 – fault caused by an increase of moment of viscous friction in the actuator; d_3 – fault caused by the change of active resistance of rotor circuit of DC motors (for example, in case of significant changing of temperature). The presence of these faults significantly reduces the quality of the actuators and accuracy of performance of specific technological operations.

In the presence of these faults, each actuator of MM without feedback can be described by the nonlinear differential equations in form (1) where:

$$F = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -ci^2/H & -(k_{vn}+h)/H & ci/H & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ ci/J & 0 & -c/J & -k_{vd}/J & k_m/J \\ 0 & 0 & 0 & -k_\omega/L & -R/L \end{bmatrix}, B = \begin{bmatrix} 0 \\ (-M_E - M_{stn0} \text{sign}(x_2))/H \\ 0 \\ -M_{std0} \text{sign}(x_4)/J \\ 0 \end{bmatrix}, x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}, G = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ k_u/L \end{bmatrix},$$

$$L = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, H = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} d = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix},$$

where R, L, I are resistance, inductance and current of DC motor rotor circuits, accordingly; k_ω is a counter-EMF coefficient; k_u is an amplifier coefficients; k_m is a moment coefficient; J is a moment of inertia of DC motor shaft and rotating parts of reducers; c is rigidity of mechanical transmission; x_1 is a turn angle of link; i is a reducing ratio of the reducer; h, H, M_E are the variable components of torque influences on actuators, including the interactions between all the degrees of freedom of the manipulator; u is a input voltage of amplifiers.

In this case, the dimension of the output vector of the system less than dimension of state vector. Thus, only the value of x_1, x_4 and x_5 are measured, and x_2 and x_3 - no.

Next, consider the synthesis of the identification system for fault d_1 . Diagnostic observer of the third order, which is sensitive to this fault and insensitive to other faults, will be described by system of equations (10) and the following matrix:

$$F^* = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, G = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, J = \begin{bmatrix} -(k_{vn}+h)/H & 0 & 0 \\ -ci^2/H & 0 & 0 \\ 0 & ci/H & 0 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ -\frac{M_E + M_{stn0} \text{sign}(x_2)}{H} \\ 0 \end{bmatrix}.$$

Since $\Phi L = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$, the fault d_1 is affecting only second equation of observer, and feedback vector have the form:

$$w = \begin{bmatrix} w_1 & w_2 & 0 \end{bmatrix}^T.$$

Since the value of x_2 , a member of the vector B is not measured by sensors, it must be defined from (4):

$$x_2 = x_2^* - \frac{k_{vm} + h}{H} x_1^*.$$

In the synthesis of the third order observer is advisable to select feedback coefficients as follows:

$$T_0 = (6T_c)^3, \quad T_1 = 3(6T_c)^2, \quad T_2 = 18T_c,$$

where T_c is the time during which the output of the system enters the 5% area of the value of the desired fault. Accepting $T_c = 1s$ we get:

$$T_0 = 216, \quad T_1 = 108, \quad T_2 = 18.$$

Feedback vector in this case will be:

$$w = \begin{bmatrix} \frac{T_1}{T_0} e_1 \\ \frac{T_2}{T_0} e_1 + \int_0^1 \frac{1}{T_0} e_1 dt \\ 0 \end{bmatrix}.$$

To verify the functionality and effectiveness of the proposed method, the modelling of the synthesized faults accommodation system for the model of the actuator of the second degree of freedom (q_2) of PUMA-type manipulator (see Fig.1) was carried out.

At the synthesis of faults accommodation system were used the following parameters of actuator with DC motor: $J=0.0001 \text{ kg}\cdot\text{m}\cdot\text{s}^2$, $k_\omega=0.02 \text{ V}\cdot\text{s}$, $k_u=100$, $R=0.4\Omega$, $L=0.004\text{Hr}$, $k_m=0.02 \text{ N}\cdot\text{m}/\text{A}$, $i=100$, $c=2\text{Nm}/\text{rad}$, $k_{vm}=10^{-2} \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$, $k_{vd}=10^{-5} \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$, $M_{sm}=0.06 \text{ N}\cdot\text{m}$, $M_{std}=0.0006 \text{ N}\cdot\text{m}$.

Fig. 1. Kinematical scheme of the manipulator

For the second degree of freedom mutual influence effects in the model are described by the following equations [10]:

$$\begin{aligned} H_2 &= J_{n2} + J_{n3} + m_2 l_2^{*2} + m_3 l_3^{*2} + (m_3 + m_g) l_2^2 + m_g l_3^2 + 2l_2(m_3 l_3^* + m_g l_3) \cos q_3, \\ h_2 &= -2l_2(m_3 l_3^* + m_g l_3) \dot{q}_3 \sin q_3, \\ M_{E2} &= [J_{n3} + m_3 l_3^{*2} + m_g l_3^2 + (m_3 l_3^* + m_g l_3) l_2 \cos q_3] \ddot{q}_3 - l_2(m_3 l_3^* + m_g l_3) \dot{q}_3^2 \sin q_3 + g[m_2 l_2^* + (m_3 + m_g) l_2] \sin q_2 + \\ &+ g(m_3 l_3^* + m_g l_3) \sin(q_2 + q_3) - \frac{1}{2}[(J_{n2} - J_{s2} + m_2 l_2^{*2} + (m_3 + m_g) l_2^2) \sin 2q_2 + (J_{n3} - J_{s3} + m_3 l_3^{*2} + m_g l_3^2) \sin 2(q_2 + q_3) + \\ &+ 2l_2(m_3 l_3^* + m_g l_3) \sin(2q_2 + q_3)] \dot{q}_1^2, \end{aligned}$$

where J_{si} is the moment of inertia of link i about its longitudinal axis; J_{ni} is the moment of inertia of link i of a transverse axis passing through its centre of mass; g is acceleration of gravity.

In modelling the following values of parameters of MM's links were used: $m_1=35.8\text{kg}$, $m_2=3.5\text{kg}$, $m_3=3\text{kg}$, $l_1=0.2\text{m}$, $l_2=0.5\text{m}$, $l_3=0.4\text{m}$, $l_1^*=0.1\text{m}$, $l_2^*=0.12\text{m}$, $l_3^*=0.1\text{m}$, $J_{s2}=0.0047\text{kg}\cdot\text{m}^2$, $J_{n2}=0.12\text{kg}\cdot\text{m}^2$, $J_{n3}=0.067\text{kg}\cdot\text{m}^2$, $m_g=0.5\text{kg}$.

Faults were simulated by introducing error signals $d_1=0.01$ from time $t_1=10$ s. to $t_3=20$ s. and $d_2=d_3=0.1$, from $t_2=15$ s. Output of observer is shown at Fig. 2.

Fig. 2. Output of observer at constant fault value.

As can be seen the proposed system accurately determines the presence or absence of a fault d_1 and its value. In addition, as required, faults d_2 and d_3 does not affect the determination of d_1 .

Conclusion

In this paper method of synthesis of accurate identification systems for occurring faults in a variety of complex MS, which use the DO described by differential equations with the order above the first was developed. This method consists of applying of logic-dynamic approach for synthesis of diagnostic observers, guaranteeing the independence of the detection and localization of possible faults and introducing of special feedback for diagnostic observers, allowing identifying values of faults. Efficiency of the proposed method of synthesis of diagnostic observers for identification of faults in nonlinear dynamic systems was confirmed by the results of mathematical modelling. The subject of further research will be application of the proposed method for synthesis of the fault accommodation and failsafe control systems for such objects as industrial manipulators and underwater vehicles.

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