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Stoustrup, Jakob

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AN OBSERVER PARAMETERIZATION APPROACH TO ACTIVE FAULT DIAGNOSIS WITH APPLICATIONS TO A DRAG RACING VEHICLE

Jakob Stoustrup *

* *Dept. of Electronic Systems, Automation & Control*
Aalborg University,
Fr. Bajers Vej 7C, DK-9220 Aalborg, Denmark,
E-mail: jakob@es.aau.dk,
URL: `http://es.aau.dk/staff/jakob`

Abstract:
An active fault diagnosis method for additive, parametric or multiplicative faults is proposed. It is assumed that the system considered is controlled by an observer based controller. The method is then based on a number of alternate observers, each designed to be sensitive to one or more faults. Periodically, the observer part of the controller is changed into the sequence of fault sensitive observers. This is done in a way that guarantees continuity of transition and global stability using a recent result on observer parameterization. The proposed active fault diagnosis method distinguishes itself from the existing literature in terms of not relying on an exogenous excitation signal. An illustrative example based on a drag racing vehicle is given.

Keywords: Active Fault Detection; Parametric Faults; Observer Parameterization

1. INTRODUCTION

The task of designing a fault diagnosis system share a number of challenges with that of performing a system identification, where the notion of persistent excitation is crucial to obtaining a high quality model. Similarly, if a detection approach is based on a 'passive' approach, i.e. only by logging the unmodified inputs and outputs, faults can easily remain undetected, particularly if they are parametric or multiplicative and reside in a part of the system, which is never excited.

To that end, recently there has been significant attention to so-called *active* fault diagnosis methods, see e.g. (Campbell *et al.*, 2002; Campbell and Nikoukhah, 2004; Niemann, 2006; Niemann and Poulsen, 2005; Nikoukhah, 1998; Nikoukhah *et al.*, 2000) and reference therein. (For general papers on FDI and FTC, the reader might confer with the following recent results: (Staroswiecki *et al.*, 2007; Yang *et al.*, 2007; Tao and Zhao, 2007)). In the active fault diagnosis methods, it is assumed to be admissible to superimpose the control input with a dedicated fault diagnosis signal, which is designed to excite the faults in such a way that they become better discernible at the output.

In this paper, another approach is suggested to make indiscernible faults temporarily visible. This method distinguishes itself from existing methods due to the fact that it does not require adding an external excitation signal.

The approach embarks from an observer based controller. The main idea is then to temporarily change the observer into one, which has been tuned to be maximally sensitive to one or more specific faults. This procedure is then repeated cyclically for all faults that should be detected.

The assumption of an observer based controller is without loss of generality, as all linear controllers can be (re-) written as an observer based controller, possibly extended by a Youla-Kucera parameter.

The proposed method can be used as an on-line algorithm, provided that emphasizing the faults is acceptable. Another approach is to apply the method as an off-line fault diagnosis approach. It will in many cases be possible to do a fault diagnosis on the system when it is out of work. This can e.g. be in connection with service of the system. It will then be possible to do the fault diagnosis in a controlled environment. In some cases, it will possible to place the system in a test bench.

A more radical approach along the same lines were presented in (Stoustrup and Niemann, 2006) where the controller was temporarily changed into one that would destabilize the system in the presence of a specific fault. Although effective, that method is clearly not admissible in as many cases

The rest of this paper is organized as follows. A problem formulation is given in Section 2. Section 3 include some preliminary results. The main results are given in Section 4 and an illustrative example is given in Section 5. The paper is closed with a conclusion in Section 6.

2. PROBLEM FORMULATION

Consider the following state space description of a given system:

$$\begin{aligned} \dot{x} &= Ax + B_u u + B_f f \\ y &= Cx \end{aligned} \tag{1}$$

where $u \in \mathcal{R}^m$ the control input signal vector, $x \in \mathcal{R}^n$ is the state vector of the system, and $y \in \mathcal{R}^p$ is the measurement vector. $f \in \mathcal{R}^q$ is the vector of potential fault signals (here modeled as additive faults).

Further, let the system be controlled by a full order observer based controller given by:

$$\begin{aligned} \dot{\hat{x}} &= A\hat{x} + Bu + L_0(y - C\hat{x}) \\ u &= F\hat{x} \end{aligned}$$

where $\hat{x} \in \mathcal{R}^n$ is the estimate of the state vector, $L_0 \in \mathcal{R}^{p\times n}$ is an observer gain for which $A + L_0C$ is Hurwitz, and $F \in \mathcal{R}^{m\times n}$ is a feedback gain for which $A + BF$ is Hurwitz. Then this controller is stabilizing according to the separation theorem.

The challenge is now for each possible fault in the system to find alternate parameters for the observer gain $L_1, \dots, L_q$, such that each of the corresponding observer becomes sensitive to one or more of the q faults.

Furthermore, we wish to find a procedure which enables us to tune the observer gain from the nominal one and to one of the faulty ones such that:

- the transition from the nominal observer with gain L_0 to any of the fault sensitized gains, L_i, should be performed such that no unacceptably large transients are created
- the transition should be performed such that stability is maintained throughout the transition

In the subsequent sections, we shall describe a method, which embarks from such a preliminary design of a nominal and a number of fault sensitized observer gains, and constructs an observer based feedback scheme which cycles through these observer gains in order to make sure that all faults are detected within a cycle, while at the same time preserving stability throughout the cycle.

3. PRELIMINARIES

The method proposed in this paper relies on the following recent result from (Stoustrup and Komareji, 2008).

Lemma 1. Let L_0 and L_1 be two different Luenberger observer gains for the following system:

$$\dot{x} = Ax + Bu\,, \quad y = Cx + Du$$

and suppose that

$$V_0(x) = x^*\ Z_0\ x \quad \text{and} \quad V_1(x) = x^*\ Z_1\ x$$

are the corresponding Lyapunov functions to $A + L_0C$ and $A + L_1C$, respectively, with $Z_i > 0$, $i = 0, 1$. Then a family of observer gains $L(\beta)$, $0 \leq \beta \leq 1$ is given by:

$$L(\beta) = \mathcal{F}_\ell(J_{L_0,L_1,Z}, \beta I) \tag{2}$$

where

$$J_{L_0,L_1,Z} = \begin{pmatrix} L_0 & I \\ Z(L_1 - L_0) & I - Z \end{pmatrix}, \; Z = Z_0^{-1}\, Z_1$$

and where $\mathcal{F}_\ell(M, X)$ denotes a lower fractional transformation of M by X (see e.g. (Stoustrup and Komareji, 2008)).

Moreover, $L(\beta)$ satisfies $L(0) = L_0$ and $L(1) = L_1$.

In (Stoustrup and Komareji, 2008) the dual result is proved. For completeness, we will give a direct proof of this (yet unpublished) result here.

Proof : The intermediate points admit the Lyapunov function given by

$$Z(\beta) = (1 - \beta)\; Z_0 + \beta\; Z_1$$

To verify the above claim, we have to show that

$$Z(\beta)(A + L(\beta)C) + (A + L(\beta)C)^* Z(\beta) < 0$$

The first term in left side of the Lyapunov inequality can be rewritten as:

$$\begin{aligned}
&Z(\beta)(A + L(\beta)C) \\
&\quad = ((1 - \beta)Z_0 + \beta Z_1) \\
&\qquad \big(A + \big(L_0 + \beta(I - \beta(I - Z))^{-1} \\
&\qquad\quad \times\; Z(L_1 - L_0)\big)\, C\big) \\
&\quad = ((1 - \beta)Z_0 + \beta Z_1) \\
&\qquad \times \big(A + L_0C + \beta(I - \beta(I - Z_0^{-1}Z_1))^{-1} \\
&\qquad\quad \times Z_0^{-1}\; Z_1(L_1 - L_0)C\big) \\
&\quad = ((1 - \beta)Z_0 + \beta Z_1) \\
&\qquad \big(A + L_0C + \beta((1 - \beta)Z_0 + \beta Z_1)\big)^{-1} \\
&\qquad\quad \times\; Z_1(L_1 - L_0)C\big) \\
&\quad = (1 - \beta)Z_0\,(A + L_0C) + \beta Z_1\,(A + L_1C)
\end{aligned}$$

So, we can conclude:

$$\begin{aligned}
&Z(\beta)(A + L(\beta)C) + (A + L(\beta)C)^* Z(\beta) \\
&\quad = (1 - \beta)(Z_0(A + L_0C) + (A + L_0C)^* Z_0) + \\
&\qquad \beta(Z_1(A + L_1C) + (A + L_1C)^* Z_1) \\
&\quad = (1 - \beta)Q_0 + \beta Q_1
\end{aligned}$$

where

$$Q_0 = Z_0(A + L_0C) + (A + L_0C)^* Z_0$$

and

$$Q_1 = Z_1(A + L_1C) + (A + L_1C)^* Z_1$$

According to the assumptions Z_0 and Z_1 are Lyapunov functions for $A + L_0C$ and $A + L_1C$, respectively, i.e.:

$$Q_0 < 0 \quad \text{and} \quad Q_1 < 0$$

from which we infer that

$$(1 - \beta)Q_0 + \beta Q_1 < 0$$

which completes the proof. ∎

4. MAIN RESULTS

The method proposed below is based on the following result:

Theorem 1. Consider a system given by a model of the form:

$$\begin{aligned}
\dot{x} &= Ax + B_u u \\
y &= Cx
\end{aligned}$$

Assume that a number of stabilizing observer gains $L_0, L_1, \ldots, L_q$ have been designed for this system, i.e. such that $A + L_iC$, $i = 0, 1, \ldots, q$ are all Hurwitz. Further, assume that Z_i, $i = 0, 1, \ldots, q$ are Lyapunov matrices for the matrices $A + L_iC$, $i = 0, 1, \ldots, q$.

Consider an observer based controller of the form:

$$\Sigma_C \;:\; \begin{cases} \dot{\hat{x}} = A\hat{x} + Bu + L(\beta(t))(y - C\hat{x}) \\ u = F\hat{x} \end{cases} \tag{3}$$

where:

$$L(\beta(t)) = \begin{cases} \mathcal{F}_\ell(J_{L_{i_0},L_{i_1},Z_{i_0,i_1}}, \beta(t)I) & \text{for } t_0 \leq t < t_1 \\ & \vdots \\ \mathcal{F}_\ell(J_{L_{i_{q-1}},L_{i_q},Z_{i_{q-1},i_q}}, \beta(t)I) & \text{for } t_{N-1} \leq t < t_N \end{cases}$$

where $Z_{i_k,i_{k+1}} = Z_k^{-1} Z_{k+1}$, and where $\beta(t)$ is a slowly varying continuous function, chosen such that $L(\beta(t))$ is continuous. This latter condition is equivalent to requiring that $\beta(t_i) = 0$ or $\beta(t_i) = 1$ for all $i = 0, \ldots, N$.

Then, Σ_C is a stabilizing controller.

Proof : Theorem 1 follows from Lemma 1. It should be noted, that as the controller in Theorem 1 time-varying that the Lyapunov inequalities will have an additional term. This term, however, will tend to zero as the rate of the time variation tends to zero. Note, that it is straightforward to evaluate whether a given solution is actually stable by evaluating the Lyapunov function. This is a sufficient condition only, so in principle the system could be stable even if this test fails. In practice, however, this test is very useful.

■

Based on this result, the fault diagnosis algorithm can now be formulated.

Algorithm 1. Let a system with a nominal model of the form (1) be given.

Step 1. Design (any) nominal observer based controller with observer gain L_0 and feedback gain F

Step 2. For each fault, design a new observer gain L_i, $i = 1, \ldots, q$, that makes the corresponding observer sensitive to that fault.

Step 3. Choose a sequence of these observer gains, such that every gain appears at least once in the sequence.

Step 4. Design $\beta(t)$ as a continuous function that varies between 0 and 1, where constant intervals with value 0 or 1 are intervals where a certain observer is fully active.

Step 5. Design Σ_C as given by (3).

The outputs of the observer needs subsequent signal processing in the standard fashion.

5. EXAMPLE

The example below is inspired by a drag race car project, see (Sørensen, 2003). The actual model is confidential, but the basic dynamics of the drive line is a second order system:

$$G(s) = \frac{1}{s^2 + as + b}$$

with two real poles having negative eigenvalues. In the numerical example, the two poles have been chosen as -10[rad/s] and -20[rad/s], so the nominal transfer function becomes:

$$G(s) = \frac{200}{s^2 + 30s + 200}$$

The car can be subjected to two faults which manifest as oscillations caused by two different physical phenomena. One type of oscillations is caused by micro-slip friction phenomena in the clutch of the vehicle, the other is caused by oscillations in the rubber of the tires.

It is of ultimate importance to discover the possible presence of these two faults during test drives, as the added acceleration of these oscillations to the huge acceleration of the drag race drive itself might exceed that admissible to the human body, such that the inner organs of the driver might be damaged during the actual race.

In this example we shall describe these two phenomena as additive faults, i.e. the overall model becomes:

$$G_f(s) = G(s) \begin{pmatrix} 1 & G_{f_1} & G_{f_2} \end{pmatrix}$$

where G_{f_1} and G_{f_2} are second order resonant systems:

$$G_{f_1} = \frac{1}{s^2 + 2\zeta_1\omega_1 s + \omega_1^2}$$

and

$$G_{f_2} = \frac{1}{s^2 + 2\zeta_2\omega_2 s + \omega_2^2}$$

chosen with resonance frequencies of 5[Hz] and 20[Hz], and damping coefficients of 5% and 1%, respectively.

For this system, a nominal observer based controller is designed based on an LQG design, i.e. a second order controller.

In addition to the nominal observer, two observers are designed to be sensitive to the two faults, that are anticipated to occur. In this case, this is particularly simple, as the obvious choice is to assign poles for each of the two observers to coincide with the resonance frequencies.

Figure 1 shows single sided spectra of output from these three observers in three different cases. In all cases, the system is driven by a low frequency random reference with some measurement noise. In the plots shown in the first row, no faults have occurred. This is reflected in the FFTs, which all have LF components exclusively with exception from two almost undiscernible spikes at the resonance frequencies for the two sensitized observers. In the second and the third row of plots, either of the two faults are introduced (as random signals driving the two oscillators). In these cases, the observer sensitized at 5[Hz] has a clear spike at that frequency for the first fault, and likewise with the other observer. The two fault sensitized observers, however, has no significant spikes at the frequency of the non-occurrent fault. The nominal observer has only insignificant frequency contributions at the two fault frequencies.

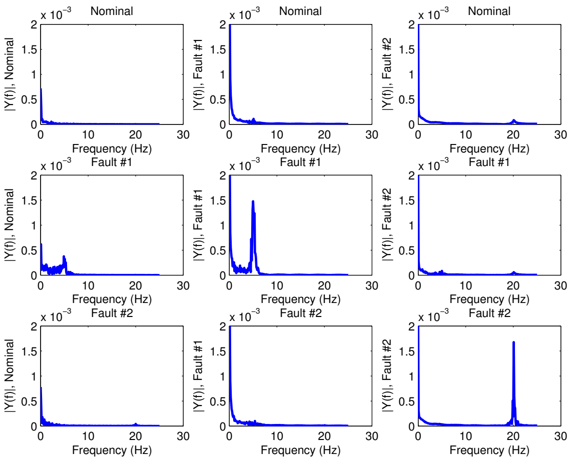

Fig. 1. Single sided spectra of output from observers. The title of each subplot indicate the state of the system, either nominal or in one of the faulty states. The vertical label indicate which observer has been applied, either the nominal or one designed to be sensitive to one of the faults. Spikes are clearly discernible in the diagonal where either of the two faults have occurred.

Next, we proceed with Step 3 of Algorithm 4, where the following sequence of observer gains are chosen for each cycle:

$$L_0\,,\,L_1\,,\,L_0\,,\,L_2\,,\,L_0$$

and the corresponding $\beta(t)$ is shown in Figure 2.

Based on these choices of observer gain sequence and selection parameters $\beta_1(t)$ and $\beta_2(t)$, we can now calculate Σ_C by (3). This has been done, and Figure 3 shows three simulations based on the same reference signal.

In the first subplot of Figure 3, the nominal situation is shown. No oscillations are seen in any period.

In the second subplot of Figure 3, the first fault has been introduced. An oscillations is clearly visible in the third period, where the corresponding fault sensitive filter is fully active. No oscillations are seen elsewhere.

In the third subplot of Figure 3, the second fault has been introduced. In this case, an oscillation is seen in the seventh period, which corresponds exactly to the period, where the observer that has been sensitized to the second fault is fully active.

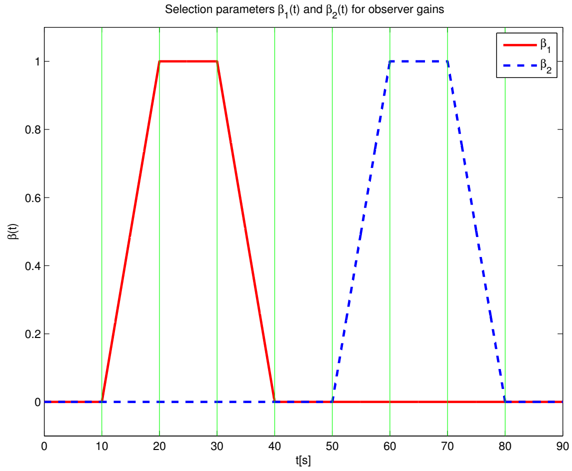

Fig. 2. Observer selection parameters $\beta_1(t)$ and $\beta_2(t)$. In this case, the transitional periods has been chosen of the same length as the stationary periods for each observer.

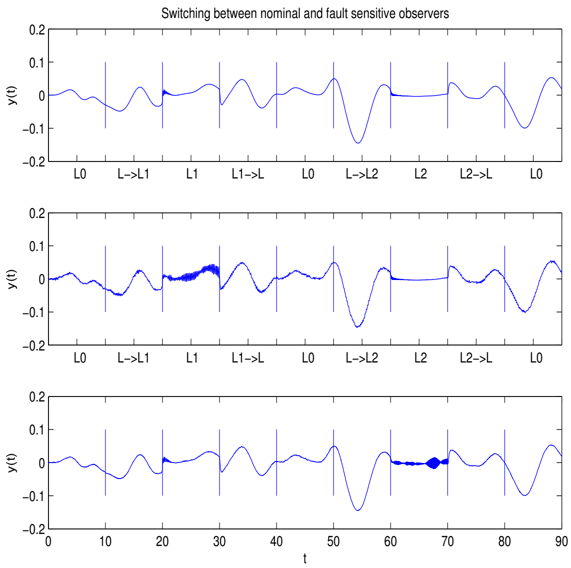

Fig. 3. Simulation of system with observer cycling controller. As indicated by the labels, the controller has transitions back and forth between the nominal observer and the two fault sensitive observers. In the first subplot, no fault occurs. In the second plot, Fault #1 has occurred and in the third subplot, Fault #2 has occurred. Oscillations are clearly discernible in the windows where the two sensitive observers are active and nowhere else.

In conclusion, the control scheme shown would clearly stimulate oscillations in the vehicle caused by the two faults in a test drive, even if they are present to an extent, where the driver would not notice them with the nominal controller. This gives a valuable dimension to the test drive, where the drive can be discontinued immediately, if one of the dangerous oscillations is discovered.

It should be noted, that the above example does in fact not disclose the full power of the method. Indeed, in the model approach taken, the faulty states are not controllable by the control signal. That means that the results displayed above are in a way obtained just by using the closed loop system as a "signal processor" for an oscillation of a fixed amplitude. In general, however, it could be anticipated that fault states would often be controllable, which means that they would be stimulated by the proposed controller, not just emphasized in the observer.

6. CONCLUSIONS

A method has been proposed for active detection of faults without an exogenous activation signal.

The method relies on a result on parameterization of observers that interpolate two given observers in such a way that all intermediate observers are guaranteed to be stable.

The approach proceeds by an initial design of a number of observers that are each sensitive to one or more faults and which together span all faults that should be detected.

The fault detection is then established through a transition cycle that encompasses all the observers in turn and thereby enables detection by emphasizing an occurred fault, that might otherwise have been indiscernible.

An important tuning parameter of the proposed method is the ratio of duration between the sensitized observers and the nominal observer. Clearly, it will have a performance degrading effect to have long durations of the sensitized observers, whereas it will give a greater risk of undetected false if they are made too short.

For a fault diagnosis system designed to handle a large number of faults, it would make sense to group faults and design one observer for each group only, otherwise the approach might be to cumbersome. Once, a group detection is active, the same detection scheme can be run with an observer bank that now consists of dedicated observers for the individual fault group members.

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