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Controller Modification Applied for Active Fault Detection

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Abstract— **This paper is focusing on active fault detection (AFD) for parametric faults in closed-loop systems. This auxiliary input applied for the fault detection will also disturb the external output and consequently reduce the performance of the controller. Therefore, only small auxiliary inputs are used with the result that the detection and isolation time can be long. In this paper it will be shown, that this problem can be handled by using a modification of the feedback controller. By applying the YJBK-parameterization (after Youla, Jabr, Bongiorno and Kucera) for the controller, it is possible to modify the feedback controller with a minor effect on the external output in the fault free case. Further, in the faulty case, the signature of the auxiliary input can be optimized. This is obtained by using a band-pass filter for the YJBK parameter that is only effective in a small frequency range where the frequency for the auxiliary input is selected. This gives that it is possible to apply an auxiliary input with a reduced amplitude. An example is included to show the results.**

Keyword: *Active fault detection, parametric faults, feedback controllers, YJBK parameterization, controller modification.*

I. Introduction

The area of fault diagnosis (FD) includes various methods based on passive observation of the systems and methods based on active excitation of the systems.

The passive faults diagnosis (PFD) approach have been investigated in a numbers of papers and books, see e.g. the books [3], [4], [7], [8] and the references herein. The active fault diagnosis (AFD) has not been investigated in the same level. The first AFD approach was developed by Zhang, [17]. Later a number of other approaches have been developed for both open-loop as well as closed-loop systems, [1], [2], [5], [10], [11].

In AFD, an auxiliary input is injected in the system. The residual output (or another output) from the residual generator is then investigated with respect to a signature from the injected auxiliary input. The investigation can be derived in different ways as e.g. using statistical test methods, [13].

One of the advantages by using AFD compared with PFD is a fast and more reliable fault diagnosis. A disadvantage with AFD is that an auxiliary input is injected into the system. The auxiliary input will in general affect the performance of the system in a negative way, especially in the fault free case.

The time for diagnosis (detection and/or isolation) in the AFD concept depends on a number of things. The key issue is how fast it is possible to detect and analyze the signature from the auxiliary input in the residual output. The detection time can be reduced by e.g. increasing the amplitude of the auxiliary input. It can also be reduced by applying one of the design methods as suggested in [5].

Another possibility is to modify the system with respect to fault diagnosis (FD). This will in general only be possible when a closed-loop setup approach is applied. Here, the controller can be changed with respect to FD. A preliminary result have been given in [15]. In this approach, the applied controller is modified such that it will destabilize the closed-loop system when faults have occurred. However, it is only relevant to use such a controller when the system is placed in test bench. Instead of destabilizing the system, the controller can be designed such that the residual outputs get more sensitive to parametric faults. Such a modification of the feedback controller will in general result in a performance degradation of the overall system. It is also here a trade-off between fast fault detection and minor performance degradation of the nominal closed-loop system.

However, it can still be relevant to modify the feedback controller in connection with active fault diagnosis (AFD). It will give an extra freedom in the design of the AFD and the associated auxiliary input. It will be shown in this paper that it is possible to reduce the closed-loop performance degradation caused by the auxiliary input in the nominal case and without increasing the fault detection time.

The focus in this paper will be at first to give an analysis of the consequence of modifying the feedback controller in connection with active fault diagnosis. Based on this analysis, the fault detection problem is investigated. It is shown that modifying the feedback controller by including a YJBK parameter, it is possible to minimize the performance reduction in the fault free closed-loop system due to the applied auxiliary input and at the same time reduce the time for detection of parametric faults when they occur in the system. This can be obtained by selecting the YJBK parameter as band-pass filters. The fault free closed-loop system will only be changed in a small frequency band and not in the whole frequency range. Further, the center frequency in the band-pass filter is also a design parameter. This has to be selected such that the closed-loop performance reduction is minimized in the fault free case. An example is included to illustrate the approach for fault detection using controller modification in connection with active fault diagnosis.

The rest of this paper is organized as follows. In Section II, the system set-up is given together with some preliminary results. Passive and active fault diagnosis is shortly considered in Section III followed by an analysis of using controller modification in connection with AFD in Section IV. The design problem of band-pass filters for the controller modification with respect to AFD is considered in detail in Section V followed by an example in Section VI. The paper is closed with a conclusion in Section VII.

II. System Set-up

In this paper we assume the system to be given by:

$$\Sigma_P \ : \ \begin{cases} e = G_{ed}(\theta)d + G_{eu}(\theta)u \\ y = G_{yd}(\theta)d + G_{yu}(\theta)u \end{cases} \tag{1}$$

where $d \in \mathcal{R}^{r_d}$ is an external disturbance input vector, $u \in \mathcal{R}^m$ the control input signal vector, $e \in \mathcal{R}^q$ is the external output signal vector to be controlled and $y \in \mathcal{R}^p$ is the measurement vector.

The parametric (or multiplicative) faults are modeled by θ_i, $i = 1, \cdots, k$, where k is the number of possible parametric faults. Further, let θ represent all the k parametric faults. θ can be either a vector or a diagonal matrix. $\theta = 0$ represent the fault free case. The single transfer functions in (1) will depend on the faults given by θ.

The above fault modeling with parametric faults gives a quite broad number of different types of faults. For further description of the fault modeling, see e.g. [11].

Further, let the system be controlled by a stabilizing feedback controller given by:

$$\Sigma_C \ : \ \{ \ u = Ky \tag{2}$$

A. The YJBK Parameterization

Let a coprime factorization of the nominal system $G_{yu} = G_{yu}(0)$ from (1) and the stabilizing controller K from (2) be given by:

$$\begin{aligned} G_{yu} &= NM^{-1} = \tilde{M}^{-1}\tilde{N}, \quad N, M, \tilde{N}, \tilde{M} \in \mathcal{RH}_\infty \\ K &= UV^{-1} = \tilde{V}^{-1}\tilde{U}, \qquad U, V, \tilde{U}, \tilde{V} \in \mathcal{RH}_\infty \end{aligned} \tag{3}$$

where the eight matrix transfer functions in (3) are stable proper rational functions that must satisfy the double Bezout equation given by, see [16]:

$$\begin{aligned} \begin{pmatrix} I & 0 \\ 0 & I \end{pmatrix} &= \begin{pmatrix} \tilde{V} & -\tilde{U} \\ -\tilde{N} & \tilde{M} \end{pmatrix} \begin{pmatrix} M & U \\ N & V \end{pmatrix} \\ &= \begin{pmatrix} M & U \\ N & V \end{pmatrix} \begin{pmatrix} \tilde{V} & -\tilde{U} \\ -\tilde{N} & \tilde{M} \end{pmatrix} \end{aligned} \tag{4}$$

Based on the above coprime factorization of the system G_{yu} and the controller K, we can give a parameterization of all controllers that stabilize the system in terms of a stable transfer function Q, i.e. all stabilizing controllers are given by [16]:

$$K(Q) = (\tilde{V} + Q\tilde{N})^{-1}(\tilde{U} + Q\tilde{M}), \ Q \in \mathcal{RH}_\infty \tag{5}$$

Using the Bezout equation, the controller given either by (5) can be realized as an LFT (linear fractional transformation) in the parameter Q:

$$K(Q) = \mathcal{F}_l\left(\begin{pmatrix} UV^{-1} & \tilde{V}^{-1} \\ V^{-1} & -V^{-1}N \end{pmatrix}, Q \right) = \mathcal{F}_l(J_K, Q) \tag{6}$$

The YJBK parameterization is shown in Fig. 1.

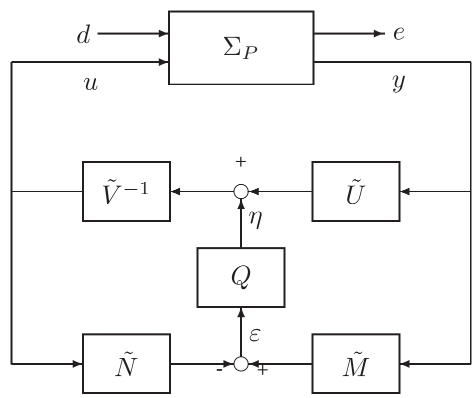

Fig. 1. The YJBK parameterization of all stabilizing controllers $K(Q)$ for a given system G_{yu}.

The YJBK parameterization will be applied in connection with controller modification for fault detection in the following sections.

In the same way, it is possible to derive a parameterization in terms of a stable transfer function S of all systems that are stabilized by one controller, i.e. the dual YJBK parameterization. The parameterization is given by [16]:

$$G_{yu}(S) = (\tilde{M} + S\tilde{U})^{-1}(\tilde{N} + S\tilde{V}), \ S \in \mathcal{RH}_\infty \tag{7}$$

An LFT representation of (7) is given by:

$$\begin{aligned} G_{yu}(S) &= \mathcal{F}_l\left(\begin{pmatrix} NM^{-1} & \tilde{M}^{-1} \\ M^{-1} & -M^{-1}U \end{pmatrix}, S \right) \\ &= \mathcal{F}_l(J_G, S) \end{aligned} \tag{8}$$

Further, S is given by, [16]:

$$S = \mathcal{F}_u(J_K, G_{yu}(S)) \tag{9}$$

The dual YJBK transfer function S will be a function of the system variations. Here we will consider parametric variations in terms of the parametric faults described by θ, i.e. $S = S(\theta)$. The connection between S and θ have been considered in details in [9]. Assuming that $\theta = 0$ is the nominal value of θ, then there exist the following simple relation, [9]:

$$S(\theta) = 0, \text{ for } \theta = 0$$

This relation is the central element in the active fault diagnosis approach described in [10], [11], [13]. By testing if $S(\theta)$ is zero or non-zero, parametric faults can be detected.

III. Fault Diagnosis

The YJBK set-up described in Section II-A can directly be applied in connection with fault diagnosis. This diagnosis can be derived in different ways, either by using passive methods [6], [7], active methods, [5], [10] or by using controller based methods. The controller based fault diagnosis methods will be described in the following.

Let us use the closed-loop set-up shown in Fig. 1 with $Q = 0$. The closed-loop transfer functions from inputs d and η to the outputs e and ε are given by:

$$\Sigma_{P,K} : \begin{cases} e = P_{ed}(S)d + P_{e\eta}(S)\eta \\ \varepsilon = P_{\varepsilon d}(S)d + \quad S\eta \end{cases} \tag{10}$$

where ($S = S(\theta)$)

$$\begin{aligned} P_{ed}(S) &= G_{ed}(\theta) + G_{eu}(\theta)(M + US)\tilde{U}G_{yd}(\theta) \\ P_{e\eta}(S) &= G_{eu}(\theta)(M + US) \\ P_{\varepsilon d}(S) &= (\tilde{M} + S\tilde{U})G_{yd}(\theta) \end{aligned}$$

Equation (10) can be derived by using the dual YJBK parameterization of $G_{yu}(\theta)$ together with the coprime factorization of the feedback controller.

In connection with fault diagnosis, the dual YJBK transfer function is also named the *fault signature matrix*, [10], [11], [13].

It has been shown in [10] that the vector ε in (10) is a standard residual vector as used in connection with (passive) fault diagnosis. In the case where the coprime factorization is based on a full order observer based feedback controller, ε is the output estimation error vector and the innovation vector in the case of using a Kalman filter.

A. Passive Fault Diagnosis

In passive fault diagnosis $\eta = 0$. The output vector ε in (10) is a residual vector, [6], [7], as pointed out above.

For the system without parametric faults ($\theta = 0$ or equivalently with $S = 0$), the transfer function from disturbance input d to the residual vector ε is given by:

$$\varepsilon = \tilde{M}G_{yd}d \tag{11}$$

When parametric faults are included $\theta \neq 0$, the residual vector ε is now given by:

$$\varepsilon = (\tilde{M} + S\tilde{U})G_{yd}(\theta)d \tag{12}$$

Assume that $d = 0$, then ε will be zero. Consequently, it will not be possible to detect parametric faults in the system. It is therefore relevant to consider active fault diagnosis methods.

B. Active Fault Diagnosis

AFD is derived by injection of an auxiliary input η. The diagnosis is then derived by considering the signature from the auxiliary input in an output vector or in a residual vector, [5], [10]. Here, let us use the AFD set-up described in [10].

The residual vector ε is now given by:

$$\varepsilon = (\tilde{M} + S\tilde{U})G_{yd}(\theta)d + S\eta \tag{13}$$

Let the auxiliary input η be a periodic input given by:

$$\eta = A_\eta \sin(\omega_0 t) \tag{14}$$

where A_η is constant vector, ω_0 is the frequency for the periodic excitation. The frequency ω_0 and A_η are free design parameters. Using the above auxiliary input, the residual vector given by (13) is then given by:

$$\varepsilon = S(\omega_0)A_\eta \sin(\omega_0 t) + (\tilde{M} + S\tilde{U})G_{yd}(\theta)d \tag{15}$$

In the normal situation the noise component in the residuals ε will be white noise. This can be obtained either by a filter on the residual or by incorporate a Kalman filter in the coprime factorization.

Fault detection and isolation based on a periodic auxiliary input vector have been investigated in [13].

IV. Controller based Fault Diagnosis

In this section, a preliminary analysis is given with respect to fault diagnosis when the feedback controller is changed. Instead of a direct modification of the feedback controller K, K is modified by including a feedback loop by Q using the YJBK parameterization. The advantage with this is that the nominal controller is unchanged and it is easy to return to the nominal controller. By using this concept, it is possible to apply different controllers for detection and isolation of the faults. Controller modification based on the YJBK parameterization have been considered in [12] in details.

Let us close the loop between ε and η by a suitable stable Q, i.e. the new input η is given by:

$$\eta = Q\varepsilon + \bar{\eta} = \eta_Q + \bar{\eta} \tag{16}$$

This is shown in Fig. 2.

Using η given in (16) in general equation for the residual vector ε from (10) gives:

$$\begin{aligned} \varepsilon_Q(Q) &= (I - SQ)^{-1}((\tilde{M} + S\tilde{U})G_{yd}(\theta)d + S\bar{\eta}) \\ &= (I - SQ)^{-1}\varepsilon_Q(0) \end{aligned} \tag{17}$$

where $\varepsilon_Q(0) = \varepsilon$ given by (10).

The residual vector in (17) is unchanged when the controller is changed by including a non-zero Q in the fault free case ($\theta = 0$), i.e. it is equal to the residual given by (11). The reason is that the fault signature matrix S is zero. When θ is non-zero, the residual vector will change due to a non-zero S. This gives a simple method to detect parametric

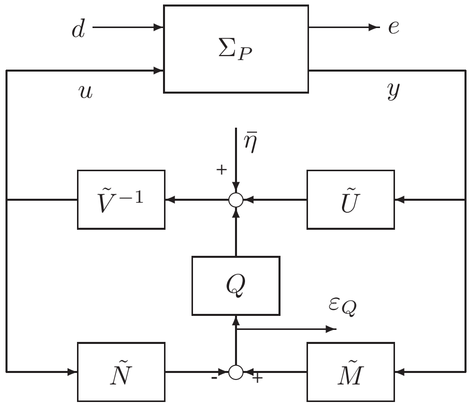

Fig. 2. Setup for controller modification in connection with fault diagnosis. $\bar{\eta}$ is the auxiliary input for AFD. The system Σ_P include parametric faults θ.

faults. Further, in this case, the controller modification can be applied for isolate parametric faults from the effect of input disturbance on the residual vector.

To summarize, we have the following results. In the fault free case, the residual vector $\varepsilon_Q(Q)$ is given by:

$$\begin{aligned} \varepsilon_Q(0) &= \tilde{M}G_{yd}(0)d \\ \varepsilon_Q(Q) &= \tilde{M}G_{yd}(0)d, \ Q \neq 0 \end{aligned} \tag{18}$$

In the faulty case, the residual vector is given by:

$$\begin{aligned} \varepsilon_Q(0) &= (\tilde{M} + S\tilde{U})G_{yd}(\theta)d + S\bar{\eta} \\ \varepsilon_Q(Q) &= (I - SQ)^{-1}\varepsilon_Q(0), \ Q \neq 0 \end{aligned} \tag{19}$$

It is clear from (18) and (19) that the residual vector is only changed in the faulty case. This result can also be used for fault detection, but will not be used directly in the following.

V. Active Fault Detection with Controller Modification

Now, let us consider the closed loop system $\Sigma_{P,K}$ given by (10). Further, applying the feedback controller from (16) gives the closed loop setup shown in Fig. 3.

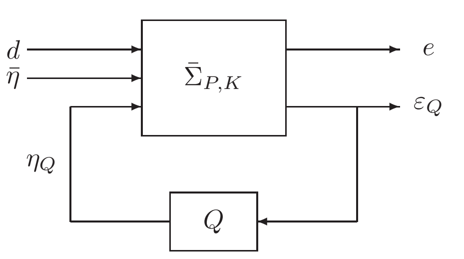

Fig. 3. The closed loop feedback system Q as the feedback controller.

The system $\bar{\Sigma}_{P,K}$ in Fig. 3 is given by (modification of (10)):

$$\bar{\Sigma}_{P,K} : \left\{ \begin{array}{ll} e &= P_{ed}(S)d + P_{e\eta}(S)\bar{\eta} + P_{e\eta}(S)\eta_Q \\ \varepsilon_Q &= P_{\varepsilon d}(S)d + \quad S\bar{\eta} \quad + \quad S\eta_Q \end{array} \right. \tag{20}$$

Closing the loop around $\bar{\Sigma}_{P,K}$ with Q gives

$$\bar{\Sigma}_{P,Q} : \left\{ \begin{array}{ll} e &= \bar{P}_{ed}(Q,S)d + \bar{P}_{e\bar{\eta}}(Q,S)\bar{\eta} \\ \varepsilon_Q &= \bar{P}_{\varepsilon d}(Q,S)d + \quad \bar{S}(Q)\bar{\eta} \end{array} \right. \tag{21}$$

where

$$\begin{aligned} \bar{P}_{ed}(Q,S) &= P_{ed}(S) + P_{e\eta}(S)Q(I - SQ)^{-1}P_{\varepsilon d}(S) \\ \bar{P}_{e\bar{\eta}}(Q,S) &= G_{eu}(\theta)(M + US)(I - QS)^{-1} \\ \bar{P}_{\varepsilon d}(Q,S) &= (I - SQ)^{-1}(\tilde{M} + S\tilde{U})G_{yd}(\theta) \\ \bar{S}(Q) &= (I - SQ)^{-1}S \end{aligned}$$

where $P_{ed}(S)$, $P_{e\eta}(S)$ and $P_{\varepsilon d}(S)$ are given by (10).

It is here important to note that the transfer function from auxiliary input $\bar{\eta}$ to the external output e in (21) is independent of Q in the nominal case. This mean that Q can now be included in the feedback controller for optimizing the fault detection speed without increasing the effect from the auxiliary input vector on the external output. It is clear from (21) that the transfer function from d to e will change by the introduction of Q in the feedback controller. Assume that the nominal feedback controller have been designed with respect to optimizing this transfer function. Including a non-zero Q will reduce this optimality of the transfer function from d to e. It is therefore important that including a Q will only change the transfer function from d to e as little as possible.

From (19) we have that the YJBK parameter Q can be used to detune the feedback controller and in this way increase the sensitivity from $\bar{\eta}$ to the residual output ε_Q. Using a periodic auxiliary input as given by (14) as applied in e.g. [10], [11], [13], this detuning only needs to be done in the frequency range around the frequency for the auxiliary harmonic input. This can be done by using a band-pass filter given by (for the SISO case but can be generalized to the MIMO case)

$$Q(s) = K_q \frac{\zeta s}{s^2 + 2\zeta\omega_q s + \omega_q^2} \tag{22}$$

where ω_q is the center frequency and ζ is the reciprocal quality factor.

Including a band-pass filter given by (22) in the fault free closed loop system will only have an effect around the center frequency ω_q in the band-pass filter. ζ can then be used for tuning the filter with respect to minimize the effect on the fault free closed loop system.

It is clear from the above that the center frequency ω_q and the frequency ω in the auxiliary input given by (14) should be the same. Following the line from [10], [11], [13], the frequency in the auxiliary input is selected in the frequency range where the fault signature matrix $S(\theta)$ has its maximal amplitude. Analysis in [10], [13] show that $S(\theta)$ will normally have a maximum around a certain frequency range for a given fault θ_i in a certain interval given by $[\theta_{i,min}, \ \theta_{i,max}]$. It is therefore naturally to select the auxiliary harmonic input with a frequency around the maximum of $S(\theta)$ for maximizing the effect of the signature from this input to the residual output ε_Q. Following the same line here, we can design Q with respect to where $S(\theta)$ has maximal amplitude. This gives that it will be possible to reduce the amplitude of the auxiliary input without reducing the detection time or reducing the detection time.

The fault signature matrix $S(\theta)$ will not in general have maximal amplitude for all faults θ_i in the same frequency range. Therefore, we will in general need at number of YJBK parameters designed with respect to one or more faults. In the fault detection, we will need to change between a numbers of YJBK parameters with associated auxiliary inputs.

The design of the single YJBK parameters Q_i can be done with respect to a specified interval for the associated parametric fault θ_i given by $[\theta_{i,min},\ \theta_{i,max}]$. Based on this, the center frequency ω_q in the band-pass filter can be selected. The auxiliary input $\bar{\eta}$ need to be selected such that the effect on the external output e is limited in the nominal case. The norm of the effect on e from $\bar{\eta}$ is given by:

$$\|e\| = \|G_{eu}(0)M\bar{\eta}(\omega_p)\| \tag{23}$$

From (23) the gain of the auxiliary input can be selected such that it satisfy the limitation on $\|e\|$.

The ζ parameter in Q is then selected such that the change in the fault free case is minimal in $\bar{P}_{ed}(Q,0)$ and that the the detection is done in a reasonable time. This mean that the gain of $(I-S(\theta_i)Q_i)^{-1}S(\theta_i)$ is reasonable at the frequency for the auxiliary harmonic input. It is a condition that Q_i does not destabilize the closed loop system. Q_i will not destabilize the closed-loop system if, [16]

$$(I-S(\theta_i)Q_i)^{-1} \tag{24}$$

is stable. Using the small gain theorem, [14], on this problem, we get the following condition on Q_i:

$$\|S(\theta_i)Q_i\| \ < \ 1, \ \forall\theta_i \ \in \ [\theta_{i,min},\ \theta_{i,max}] \tag{25}$$

This will guarantee that the closed-loop is not destabilized by including Q_i. It is here assumed that both $S(\theta_i)$ and Q_i are stable.

Instead of selecting the frequencies for the auxiliary inputs based on where the fault signature matrix has maximal amplitudes, it can be selected from the nominal closed-loop system and the external disturbance. Based on this, a frequency range can be defined where the auxiliary input will have no effect or only a minimal effect on the external output e. Based on this frequency interval, the frequency for the auxiliary input can then be selected as the frequency where the fault signature matrix has maximal amplitude. Based on this selection the selection of the gain of $\bar{\eta}$ and ζ in Q is done in the same way as done above.

At last, let us summarize the two approaches for design of the YJBK parameters with respect to modifying the feedback for obtaining a better fault detection of parametric faults.

1) For every single parametric fault θ_i, select the relevant interval for the fault given by $[\theta_{i,min},\ \theta_{i,max}]$.
2) Select the frequency range for the frequency of the periodic auxiliary input $\bar{\eta}$.
3) For every single fault, calculate the maximal amplitude and the associated frequency of the fault signature matrix $S(\theta_i)$ for $\theta_i \in [\theta_{i,min},\ \theta_{i,max}]$ in the selected frequency range. This can be done based on the amplitude of the fault signature matrix or by considering the nominal closed-loop system.
4) Based on this analysis, select a minimal number of YJBK parameters for the controller modifications, such that it is possible to detect all parametric faults.
5) Based on the selected frequency for the auxiliary input $\bar{\eta}$, the gain is selected with respect to give a maximal effect on the external output e in the nominal case, see (23).
6) Select ζ for the single YJBK parameters with respect to reasonable performance degradation of the nominal closed-loop and reasonable detection time for the associated faults. Further, the design needs to satisfy the closed-loop stability condition.

If the design result in more than one YJBK parameter, the apply the YJBK parameters in a sequence with a single parameter Q_i and the associated auxiliary input $\bar{\eta}$ at the time.

VI. Example

To illustrate the methodology presented in this paper, we shall present a simple example. The system considered is given by the transfer function:

$$G(s) = \frac{s^2+1}{(s+1)(s+2)(s+3)}$$

It is assumed that the pole in -3 can change subject to a fault, such that its value changes to -4, i.e.:

$$G_f(s) = \frac{s^2+1}{(s+1)(s+2)(s+4)}$$

It can be seen that the both systems $G(s)$ and $G_f(s)$ has an imaginary pair of zeros at $\pm j$.

For the nominal system, a standard LQG controller $K(s)$ is designed. The state feedback gain F and the Kalman gain L are given by:

$$\begin{aligned} F &= \begin{bmatrix} -0.4808 & -0.9071 & -2.5511 \end{bmatrix} \\ L &= \begin{bmatrix} -5.7405 \\ 4.1245 \\ -0.6956 \end{bmatrix} \end{aligned}$$

This means that the YJBK parameterization can be implemented as an observer based controller with $Q(s)$ feeding back from the estimation error to the joint input for system and observer, see e.g. [18].

The band-pass filter $Q(s)$ given by (22) is designed such that it emphasizes the loop gain around the frequencies where $S(\theta)$ is maximal in the presence of the above mentioned fault.

The reciprocal quality factor ζ can be used as a trade-off between on one hand minimizing the effects of defining and on the other hand limiting potential adverse effects in terms of robustness issues caused by the significant phase lag (although unobservable from the nominal system). In the simulation described below, $\zeta = 0.1$ was found as a good compromise between these objectives.

The resulting effect of the detuning in terms of the ability of the system is depicted in Fig. 4. It can be seen that the ability to suppress high frequency disturbances have been slightly decreased.

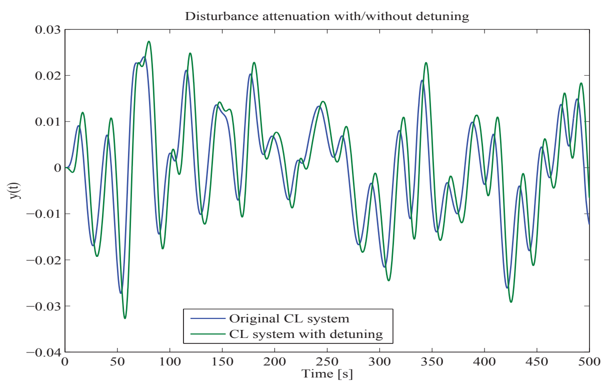

Fig. 4. Simulation showing disturbance attenuation at output both with and without the detuning parameter Q. It can be seen that the detuning causes a slight decrease in performance. This performance loss can be made arbitrarily small by controlling the quality factor of the bandpass filter of Q.

On the other hand, the introduction of the Q parameter has increased the sensitivity for the active fault diagnosis signal significantly as seen in Fig.5.

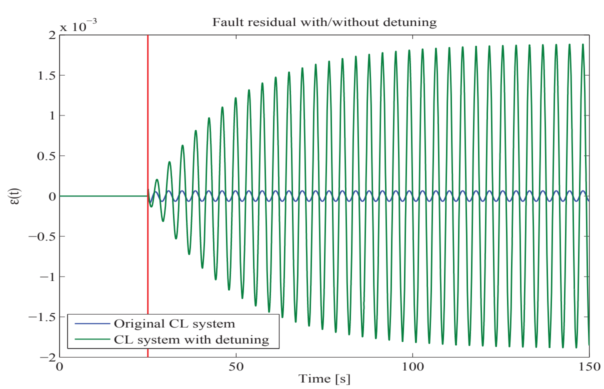

Fig. 5. Simulation showing the response of the fault residual to a parametric fault occurring at $t = 25s$. It can be seen that the detuning sensitizes the fault residual with approx. a factor of 30 compared to the situation without Q.

In this case, an active diagnosis signal in terms of a harmonic signal with $\omega = 1.66\ rad/s$ was applied. With the design parameters mentioned above, the sensitivity was improved with a factor of approximately 30. This means that the probability of detection given a certain signal-to-noise ratio will improve significantly. Alternatively, the amplitude of the active fault diagnosis signal can be reduced correspondingly, so as to avoid adverse spill-over effects on the output.

VII. Conclusion

The concept of using active fault detection (AFD) for detection of small parametric faults have been considered in this paper. It have been showed that using the YJBK controller architecture will allow a modification of the controller with a minor effect on the external output in the fault free case. In the faulty case, the effect of the auxiliary input on the residuals can be optimized. This is obtained by using a band-pass filter for the YJBK parameter that is only effective in a small frequency range where the frequency for the auxiliary input is selected. This gives that it is possible to apply auxiliary inputs with a smaller gains.

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