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Stability of Closed Loop Controlled Repetitive Periodic System applied to control of CD-Players

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Abstract— **In this paper a criterion for stability of specific control scheme for handling linear dynamic control systems with repetitive periodic sensor faults is derived. The given system and control scheme are described and defined. By combining these with the lifting technique a necessary and sufficient stability criterion is derived. This criterion is following applied to an example on a feature based control scheme for handling CD-players playing CDs with surface faults. This feature based control scheme is handling repetitive periodic sensor faults. The feature based control scheme approximates the repetitive sensor faults (surface faults). The fault approximations are subsequently subtracted from the measurements, and the influence from these repetitive sensor faults are thereby removed from the computed control signals.**

I. Introduction

In some control systems where sensor faults occur in such a way that the sensor information is partially false for short periods, standard fault tolerant control schemes are not usable. The standard fault tolerant control schemes, see [1], normally handle that parts of the system fail. These schemes subsequently use the non-faulty system parts to continue or stop the system in a stable way.

In the system in mind, the frequency content of these surface faults is either entirely or partly in the frequency range of sensitivity function of the controllers. A consequence of this it that this class of sensor faults cannot be handled as measurement noise. I.e. even though this problem seems simple it is not, since these repetitive sensor faults cannot be handled as noises.

An example of these control systems handling periodic repetitive sensor faults is the control of an optical disc player playing an optical disc with a scratch or a fingerprint. Fault tolerant control is often used to handle this specific problem. In the way the fault detection is used to detected fault, and subsequently handled when it is detected. The used scheme is often simple. The core idea is not to rely on sensor information during the fault. The sensor signals are simply fixed to zero as long a fault is detected, see [2], more advanced solutions are given in [3] and [4] where observers are designed to remove the fault from the measurements. However, these methods do not use the repetitive periodic nature of these surface faults.

The fault handling in question is designed to improve the performance of the system. The fault handling is not designed to ensure stability since these repetitive sensor faults do not destabilize the closed loop system. However, the fault handling can it self destabilize the closed loop system, if it increases the controller gain at critical frequencies. In [5] and [6] a method handling these repetitive periodic sensor faults (surface faults) called feature based control is presented. The feature based control method uses approximation of the faults to remove the fault components from the sensor signals and thereby remove the influence from the faults on the control signals. In order to use this method it is necessary to guarantee that this feature based control method is stable, given the model of the plant and the nominal controllers. It is possible to derive a necessary and sufficient condition by the use of lifting, see [7] and [8].

In this paper, the system with repetitive periodic sensor faults is defined, as well as the feature based control scheme. A stability criterion is derived based on the defined system and a feature based fault handling control scheme. This criterion is applied to an example of the focus control and the radial control loops in a CD-player playing a CD with a surface fault, which is handled by the proposed feature based control scheme. In the end an example on the improvements by using this fault handling scheme is presented.

II. System description

This paper deals with stability of closed loop control of linear discrete time systems with periodic repetitive sensor faults. Define the system as

$$\mathbf{x}[n+1] = \mathbf{A}\mathbf{x}[n] + \mathbf{B}\mathbf{u}[n] + \mathbf{E}\mathbf{d}[n], \tag{1}$$

$$e_{\mathrm{m}}[n] = \mathbf{C}\mathbf{x}[n] + \check{e}[n] + \mathbf{n}_{\mathrm{m}}[n], \tag{2}$$

where: $\mathbf{x}[n]$ is a vector of the discrete time states, $\mathbf{u}[n]$ is a vector of the control signals to the system, $e_{\mathrm{m}}[n]$ is the measured system output, $\check{e}[n]$ is the periodic repetitive sensor fault, $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$ and $\mathbf{E}$ are the system matrices. $\mathbf{d}[n]$ is a vector of disturbances. $\mathbf{n}_{\mathrm{m}}[n]$ is a vector of the measurement noises. $\check{e}[n]$ is periodic with the period p. It is zero in the fault free case. During a fault the frequency content of $\check{e}[n]$ is partly in the frequency region of $\mathbf{d}[n]$ and thereby in the region where sensibility is required of the controller. This means that these sensor faults cannot be

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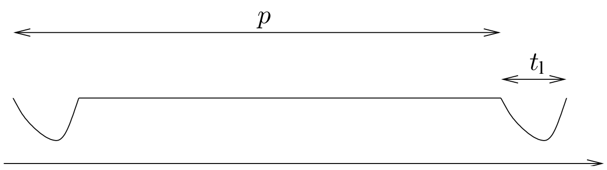

Fig. 1. Illustration of the relation between the period of the repetition of the fault, $\check{e}$, denoted p, and the length of the fault, t_l

viewed as being measurement noise. $\check{e}[n]$ does in addition not change dramatically from encounter to encounter. The interval, in which $\check{e}[n]$ takes values significant larger than zero, called length of the fault, t_l, is much smaller than p. This is illustrated in Fig. 1

In the following a periodic sensor fault is considered handled in a special way. This fault handling control scheme is derived and described in [5] and [6]. First the scheme detects the occurrence of the fault. The detection of the fault triggers a handling of the fault, which removes the fault component from the measurements by subtracting an estimate of the fault. The estimated fault is computed by the inner product of a fault approximating basis and the previous encounter of the fault. The approximations are represented by an approximating matrix $\mathcal{P}$. The operator computing the approximation is denoted $\mathcal{P}(\bullet)$. Since the fault handling scheme removes the fault components from the sensor signals, the used controllers can be the standard used PID-controllers. The controllers are in following denoted $\mathcal{K}$ and in most industrial applications these controllers are standard PID-controllers. These controllers are designed to suppress the disturbances and to reject the measurement noises. I.e. the controllers will react on the fault if nothing is done to accommodate the fault.

III. Stability of the control scheme handling periodic sensor faults

The control strategy handling these periodic repetitive sensor faults is illustrated in Fig. 2. This figure illustrates how the influence from the sensor fault is removed by the use of $\mathcal{P}(\bullet)$. This means that the controller, K, reacts on the sum of $\mathbf{e}[n]$ and the measurement noises, n_{m}.

In the following some stability issues of the algorithm will be discussed, in order to do so a lifting operator is defined. $\bullet^L[\vartheta]$ denotes in the following the lifted signals, where the ϑth fault encounter begins at sample no. n_ϑ.

A periodic system is defined as a system where specific signal sequences of constant window lengths are recurring with specific intervals. The length of these signal sequences are denoted l_w and the windows begin at samples $T_1, T_2 \cdots, T_{n+1} = T_n + p$.

A more detailed description of the lifting operator is given in [7] and [8]. The lifting operator L is an isometric isomorphism which transforms a linear periodic system to a time invariant representation defined as following

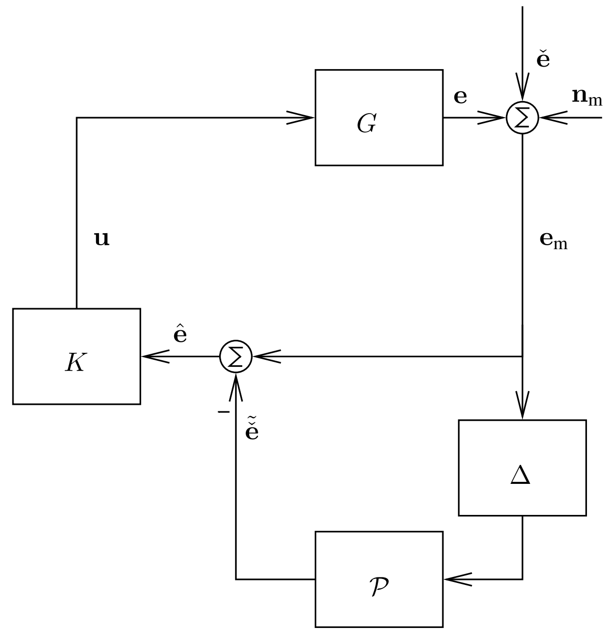

Fig. 2. Illustration of the closed loop with the feature based correction denoted by $\mathcal{P}$. K is the controller, and G is the system. Δ is the one period delay. $\mathbf{u}$ is a vector of the control signals, $\mathbf{e}$ is a vector of the distances, $\check{\mathbf{e}}$ is a vector of faulty sensor components due to the fault, $\tilde{\check{\mathbf{e}}}$ is a vector of the estimates of the faulty sensor components due to the fault, $\hat{\mathbf{e}}[n]$ is a vector of the corrected sensor signals. $\mathbf{e}_{\mathrm{m}}$ is a vector of the measured distance signals and $\mathbf{n}_{\mathrm{m}}$ is a vector of the measurement noises.

$$L : (y_0, y_1, \cdots)^T \mapsto \begin{bmatrix} (y_{T_1}, y_{T_1+1}, \cdots, y_{T_1+l_w-1}) \\ (y_{T_2}, y_{T_2+1}, \ldots, y_{T_2+l_w-1}) \\ \vdots \end{bmatrix}^T, \quad (3)$$

where y is the signal which shall be lifted.

A. Stability

It is assumed that: The closed loop K,G is internally stable, and the nominal controller K stabilizes the plant G. The fault free sensor signal is estimated by

$$\hat{\mathbf{e}}[n] = \mathbf{e}[n] + \check{\mathbf{e}}[n] + \mathbf{n}_{\mathrm{m}} - \tilde{\check{\mathbf{e}}}[n], \quad (4)$$

where $\hat{\mathbf{e}}[n]$ denotes a vector of the approximations of the fault free distances, $\mathbf{e}[n]$ denotes a vector of the distance signals, $\tilde{\check{\mathbf{e}}}[n]$ denotes a vector of the estimated sensor fault components.

In case of a good approximation of the sensor fault, $\mathbf{e}[n]$ would be: $\mathbf{e}[n] \approx \hat{\mathbf{e}}[n] + \mathbf{n}_{\mathrm{m}}[n]$. I.e. the effect from the sensor fault would be removed from the position measurements fed to the controller. This means that the control signal would be the same as in the fault free case, meaning that the system would be stable since it is nominally stable. $\mathcal{P}$ reconstructs the periodic part of the measurement signals meaning that

$$\hat{e}[n] = \mathbf{e}_{\mathrm{m}} - \mathcal{P}(\mathbf{e}_{\mathrm{m}}) \approx= \mathbf{e} + \mathbf{n}_{\mathrm{m}}. \quad (5)$$

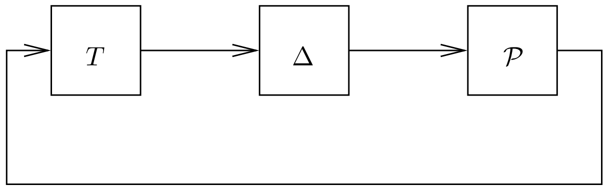

Fig. 3. Closed loop of the feature based control system. T is the complementary sensitivity of the nominal system, Δ is the one revolution delay, and $\mathcal{P}$ is the feature based fault handling.

This will be fulfilled if

$$\check{\mathbf{e}} \approx \mathcal{P}(\mathbf{e}_\mathrm{m}) \Rightarrow \tag{6}$$

$$\mathcal{P}(\mathbf{n}_\mathrm{m}) \approx 0 \ \wedge \ \mathcal{P}(\mathbf{e}) \approx 0 \ \wedge \tag{7}$$

$$\check{\mathbf{e}} = \mathcal{P}(\check{\mathbf{e}}). \tag{8}$$

This is fulfilled if $\mathcal{P}(\bullet)$ does approximate $\check{\mathbf{e}}[n]$ well and not $\mathbf{e}[n]$, and $\mathbf{n}_\mathrm{m}[n]$. On the other hand if $\mathcal{P}(\bullet)$ also approximates the system dynamics it can cause stability problems. This means that $\mathcal{P}(\bullet)$'s amplification of the system dynamic must be small, such that the energy in a given system response is decreased through $\mathcal{P}(\bullet)$ from revolution to revolution. In practice both (7) and (8) are not fulfilled, the question is how much can these assumptions be weaken before the feature based control scheme turns to be unstable.

By inspecting Fig. 2, it can be observed that the stability of the system can be analyzed by using the complementary sensitivity of the servo system. The influence from the fault handling scheme on the nominal servo system can be inspected if T denotes the complementary sensitivity of the nominal servo system, and Δ is the one revolution delay, see Fig. 3.

In order to combine these system parts, the complementary sensitivity of the nominal servo system and $\mathcal{P}$ are lifted, meaning that both part systems are represented by a discrete time series of a given length.

The lifted $\mathcal{P}$ can be computed by

$$\mathcal{P}^\mathrm{L} = \mathbf{K}_{\check{e}} \cdot \mathbf{K}_{\check{e}}^T, \tag{9}$$

where $\mathbf{K}_{\check{e}}$ is a matrix in which the fault approximation vectors are columns, and the lifted representation of the complementary sensitivity is

$$T^\mathrm{L} = \begin{bmatrix} h_0 & 0 & \cdots & 0 \\ h_1 & h_0 & & \vdots \\ \vdots & & \ddots & \\ h_{l_\mathrm{w}-1} & \cdots & & h_0 \end{bmatrix}, \tag{10}$$

where $\mathbf{h} = \begin{bmatrix} h_0 & h_1 & \cdots & h_{255} \end{bmatrix}$ is time series of l_w samples of the impulse response of T.

By lifting the system illustrated in Fig. 3 one gets a set of discrete difference equations of the form, if :

$$\xi[N+1] = \mathbf{A}\xi[N] + \mathbf{K}\mathbf{u}[N], \tag{11}$$

where $\mathbf{A} = T^\mathrm{L}\mathcal{P}^\mathrm{L}$, and ξ is the related state vector. These definitions make it possible to state Theorem 1, which says that the linear system is stable.

1 Theorem *The feature based control system defined by Fig. 2 is stable if and only if:* *max* $\left(\left|eig\left(T^L\mathcal{P}^L\right)\right|\right) < 1$, *where* $\mathcal{P}^L$ *is defined in (9) and* T^L *is defined in (10).*

Proof:
Necessary and sufficient conditions:
The stability of the closed loop system shown in Fig. 2 is equivalent to stability of the system in (11), which is a standard LTI discrete time system, from which the result follows, the system is stable if and only if $\max\left(\left|\mathrm{eig}\left(T^\mathrm{L}\mathcal{P}^\mathrm{L}\right)\right|\right) < 1$. ■

This means that a criteria for stability of the feature based control scheme is derived. This criteria requires a relevant model of the plant, the controller, and the matrix representing the approximations of the sensor faults.

IV. An example: a CD-player playing a CD with surface faults

An example on a control scheme handling a system with a periodic repetitive sensor faults is the feature based control scheme. This scheme is designed to handle a CD-player playing a CD with a surface fault, see [5] and [6]. This means that the sensor faults in this case are the surface faults on the CDs.

The CD-player has two interesting control loops which are used to positioning the optical pick-up relative to the information track storing the information of the CD. These two controls called focus and radial tracking, have linear electro-magnetic actuators which are designed to be orthogonal to each other. The two directions are illustrated in Fig. 4. This figure shows the movement directions of the OPU enabling the positioning of the OPU correctly on the track.

The optical pick-up generates two sensor signals which are approximations of the position errors in the focus and radial direction. More information concerning the CD-player is given in [9] and [10]. In addition the optical pick-up generates a pair of residuals which can be used to detect the sensor faults, alternatively the residuals presented in [11] could be used. The two control loops in the CD-player are decoupled by construction, implying that the system can be examined as two SISO systems. The focus and radial models are very alike, they can both be modeled by second order models, see [10], [12], [9] and [4]. The discrete time focus model is

$$\mathbf{x}_\mathrm{f}[n+1] = \mathbf{A}_\mathrm{focus}\mathbf{x}_\mathrm{f}[n] + \mathbf{B}_\mathrm{focus}u_\mathrm{f}[n], \tag{12}$$

$$y_\mathrm{f}[n] = \mathbf{C}_\mathrm{focus}\mathbf{x}_\mathrm{f}[n], \tag{13}$$

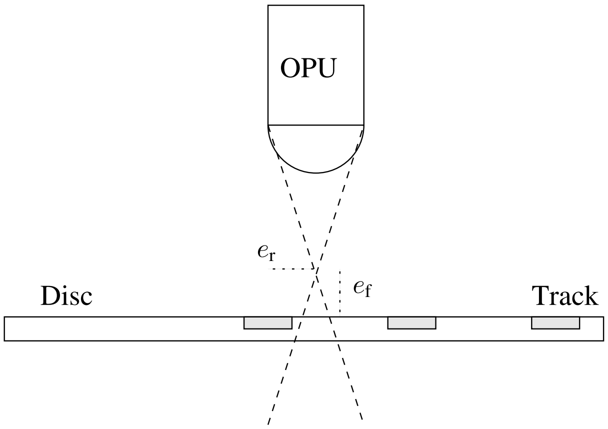

Fig. 4. The focus error e_f is the distance from the focus point of the laser beam to the reflection layer of the disc, the radial error is the distance from the center of the laser beam to the center of the track.

where

$$\mathbf{A}_{\text{focus}} = \begin{bmatrix} 0.9998 & -1.0327 \\ 2.8569 \cdot 10^{-5} & 1.0000 \end{bmatrix}, \tag{14}$$

$$\mathbf{B}_{\text{focus}} = \begin{bmatrix} 33.6479 \\ 4.8070 \cdot 10^{-4} \end{bmatrix}, \tag{15}$$

$$\mathbf{C}_{\text{focus}} = \begin{bmatrix} 0 & 2.2235 \end{bmatrix}. \tag{16}$$

The discrete time radial model is

$$\mathbf{x}_{\text{r}}[n+1] = \mathbf{A}_{\text{radial}}\mathbf{x}_{\text{r}}[n] + \mathbf{B}_{\text{radial}}u_{\text{r}}[n], \tag{17}$$

$$y_{\text{r}}[n] = \mathbf{C}_{\text{radial}}\mathbf{x}_{\text{r}}[n], \tag{18}$$

where

$$\mathbf{A}_{\text{radial}} = \begin{bmatrix} 0.9998 & -2.7969 \\ 2.8569 \cdot 10^{-5} & 1.0000 \end{bmatrix}, \tag{19}$$

$$\mathbf{B}_{\text{radial}} = \begin{bmatrix} 5.7137 \cdot 10^{-6} \\ 8.16284 \cdot 10^{-11} \end{bmatrix}, \tag{20}$$

$$\mathbf{C}_{\text{radial}} = \begin{bmatrix} 0 & 2.2235 \end{bmatrix}. \tag{21}$$

A. The feature based control scheme handling systems with periodic sensor faults

In [5] and [6] a control scheme based on a fault tolerant control scheme is derived. This method is called feature based control. The idea in this method is as follows. Detect the occurrence of the fault. This detection triggers the fault handling scheme. The fault is estimated at encounter m and since the fault is periodic the fault is the similar at encounter $m+1$, meaning that the estimate can be used at encounter $m+1$ to remove the fault from the measurements. This method requires a good approximation of the fault, $\tilde{\breve{e}}[n]$, and a detection of the location of the fault.

The feature based control scheme is in [6] stated as

1) Detect the fault and locate its position in time, when the fault is detected at sample n, the detection signal, $f_{\text{d}}[n]$, $f_{\text{d}}[n] = 1$.
2) If $f_{\text{d}}[n] = 1$:

$$a = \begin{cases} 0 & \text{if } f_{\text{d}}[n-1] = 0, \\ a+1 & \text{if } f_{\text{d}}[n-1] = 1. \end{cases},$$

$$\hat{y}[n] = y[n] - \hat{f}_{\text{s}}[\iota],$$

where

$$\iota = ((256 - l_{\text{f}}) \text{ div } (2)) + a,$$

where a is a counter counting the number of samples, the given fault is present, and ι is a counter used to locate the given sample relative to the fault correction block.
3) When the fault has passed, find the beginning and end of the passed fault, and compute the fault length l_{f}.
4) Compute an estimate of the fault: $\tilde{\breve{e}} = \mathbf{K}_{\breve{\mathbf{e}}}\mathbf{K}_{\breve{\mathbf{e}}}^T \cdot \breve{e}[\upsilon]$ and, where υ is the interval of 256 samples in which the fault is present.

$\mathbf{K}_{\breve{\mathbf{e}}}$ is in this example the four most approximating Karhunen-Loève basis vectors supporting the surface fault and not $\mathbf{Cx}[n]$. These four most approximating Karhunen-Loève basis vectors are found based on a set of measured surface faults. The Karhunen-Loève basis, K, for more informations on the Karhunen-Loève basis see [13]. K is defined as

$$K = \text{eigenvector}\left(DD^T\right), \tag{22}$$

where D is a matrix in which each column vector is a measured encounter of surface faults. The four most approximating basis vectors for the given fault class are illustrated in Fig. 5.

In practise the basis will support $\mathbf{Cx}[n]$ to some degree. In order to design bases such that this criteria is fulfilled one can use the following fact. A basis like Karhunen-Loève basis, see [13] and [14], can be used to design the approximating basis vectors $\mathbf{K}_{\breve{\mathbf{e}}}$. In the following section the stability of this method applied on the system defined in (1-2) is tested.

This feature based control scheme is to some degree related to schemes where faults or disturbances are removed based on estimation of the faults, e.g. see [15] and [16]. However, these schemes do not use the periodicity or recurrence of the fault and disturbance as used in this paper.

In this example two standard controller are used for focusing and radial tracking the optical pick-up, see [10]. These controllers are two PID-controller with a low-pass filter. The focus controller is as follows

$$u_{\mathrm{f}}[n] = \mathbf{k}_{focus,1} \cdot 10^3 \begin{bmatrix} y_{\mathrm{f}}[n-1] \\ y_{\mathrm{f}}[n-2] \\ y_{\mathrm{f}}[n-3] \\ y_{\mathrm{f}}[n-4] \end{bmatrix} - \mathbf{k}_{focus,2} \begin{bmatrix} u_{\mathrm{f}}[n-1] \\ u_{\mathrm{f}}[n-2] \\ u_{\mathrm{f}}[n-3] \\ u_{\mathrm{f}}[n-4] \end{bmatrix}, \tag{23}$$

where

$$\mathbf{k}_{focus,1} = \begin{bmatrix} 1.6668 & -4.7267 & 4.4682 & -1.4082 \end{bmatrix}, \tag{24}$$

$$\mathbf{k}_{focus,2} = \begin{bmatrix} -2.5152 & 2.2069 & -0.7756 & 0.084 \end{bmatrix}. \tag{25}$$

The radial controller is as follows

$$u_{\mathrm{r}}[n] = \mathbf{k}_{radial,1} \cdot 10^3 \begin{bmatrix} y_{\mathrm{r}}[n-1] \\ y_{\mathrm{r}}[n-2] \\ y_{\mathrm{r}}[n-3] \\ y_{\mathrm{r}}[n-4] \end{bmatrix} - \mathbf{k}_{radial,2} \begin{bmatrix} u_{\mathrm{r}}[n-1] \\ u_{\mathrm{r}}[n-2] \\ u_{\mathrm{r}}[n-3] \\ u_{\mathrm{r}}[n-4] \end{bmatrix}, \tag{26}$$

where

$$\mathbf{k}_{radial,1} = \begin{bmatrix} 126.7 & -359.2 & 339.6 & -107 \end{bmatrix}, \tag{27}$$

$$\mathbf{k}_{radial,2} = \begin{bmatrix} -2.5152 & 2.2069 & -0.7756 & 0.084 \end{bmatrix}. \tag{28}$$

In this example the length of the vectors in $\mathbf{K}_{\check{\mathbf{e}}}$ is 256, since typical surface faults are shorter than 256 samples, see [6], [17] and [5]. The set of surface faults on CDs are a large set. It is as a consequence helpful to separate these surface faults into a number of classes. In [17] a method is suggested for classifying the surface faults into three different classes of surface faults. The approximating bases are computed for each of the classes, and the approximating basis of the chosen class is used in the following.

Based on the models and the controllers and the Karhunen-Loève bases, it is possible to verify that $\mathrm{eig}\left(T_{\mathrm{l}} \cdot \mathbf{P}_{\mathrm{l}}\right) < 1$. The computed value in the focus case is 0.6894 and the computed value in the radial case is 0.499. I.e. it can be concluded that the stability criteria is fulfilled for both servo loops. The difference between the two values for each of the control loops, is due to two factors. The first factor is how well the fault is approximated, and the second is the amplification of the system dynamics through the approximations.

V. Practical Test

The feature based control scheme is tested on the modeled CD-player playing a disc with a scratch in classes for which the approximation base has just been proven stable, see [6] and [5]. An example on the improvement on the focus loop by the feature based control scheme can be seen in Fig 6. This figure compares a fault encounter not handled by the feature based control scheme (1st encounter), and one encounter handled by the feature based control scheme (5th encounter). From this comparison it is clear that the feature based control scheme clearly gives an improvement in the handling of surface faults.

An example on the improvement on the radial loop by the feature based controls scheme can be seen in Fig 7. This figure compares a fault encounter not handled by the feature based control scheme (2nd encounter), and one encounter handled by the feature based control scheme (4th encounter). From this comparison it is clear that the feature based control scheme clearly gives an improvement in the handling of surface faults.

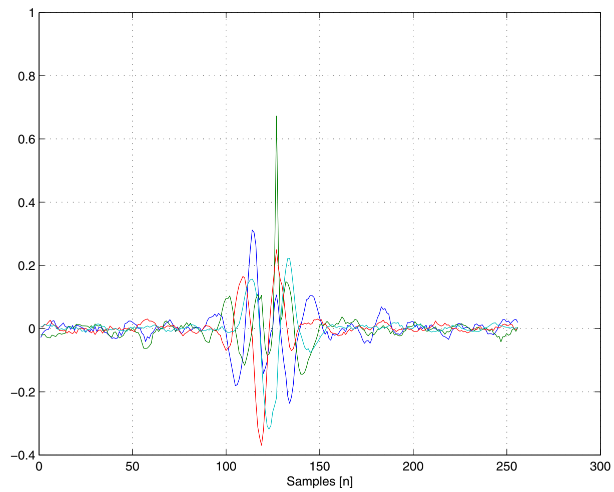

Fig. 5. The four approximating Karhunen-Loève basis vectors of a surface fault.

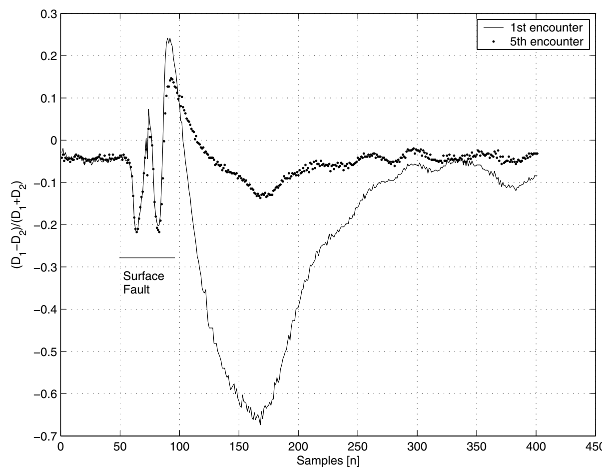

Fig. 6. A zoom on the 1st and 5th encounter of the fault. The 1st encounter is not handled by the feature based control scheme, where the 5th encounter is.

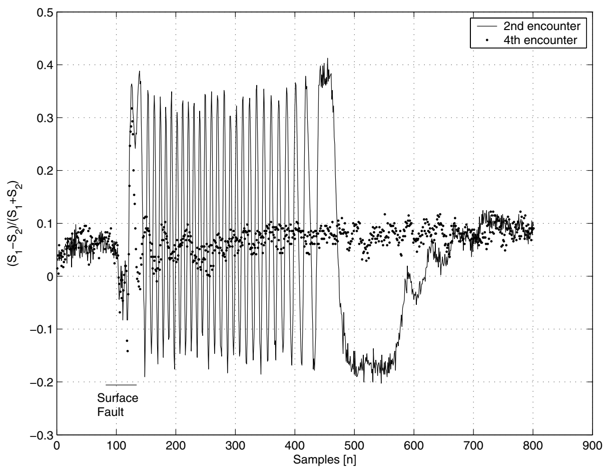

Fig. 7. A zoom on the 2nd and 4th encounter of the fault. The 2nd encounter is not handled by the feature based control scheme, where the 4th encounter is.

VI. CONCLUSION

This paper presents a method to prove the stability of a feature based control scheme for handling systems with repetitive sensor faults. A Theorem is stated and proved, which gives a necessary and sufficient condition for stability of the control system. The condition is applied to an example, a CD-player playing a CD with a surface fault. It is proven that this system is stable by the use of the derived Theorem. Performance of feature based control scheme proven stable is illustrated by an example of the CD-player playing a CD with a scratch. This example shows a clear improvement in the fault handling by the feature based control scheme.

VII. ACKNOWLEDGMENT

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