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# Assessment and Diagnosis of Feedforward/Feedback Control System

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*Abstract*— **A sequence of statistical hypothesis procedures for assessing a feedforward/feedback control performance, diagnosing and removing its fault causes is proposed. Based on the controlled output, the current variance is contributed by the feedback only effect and the combination of feedback with feedforward effect, respectively. These effect variations are systematically conducted by a sequence of the statistic hypothesis testing and the isolation strategy to compare the current control performance and the achievable benchmark operating one. A diagnosis tree with hierarchical structure is constructed. The capability of the proposal is illustrated through a simulation case with multiple faults.**

## I. INTRODUCTION

Due to the rigorous demand in product quality, the duty of process engineers is not only to design a reliable control strategy but also to ensure the control objectives accomplishing within specifications. There has been growing interest in the monitoring and assessment of the control-loop performance during the last decade. It is important to construct an assessment technology for the industries to ensure the control performance in accordance with the customer request. In the previous work, the performance assessment based on the minimum-variance control (MVC) [1] as a performance benchmark has been widely applied due to the attractive theoretical properties associated with it. The theoretical best achievable bound under MVC can be estimated from the partial sum of squared coefficients in the first dead time terms of the time series model. Several researchers extended this theory to defining the feedforward/feedback performance in assessing the current control relative to the minimum-variance feedforward/feedback control [2,3,4,5,6].

Assessing whether current output variance is significantly deviated from the benchmark variance is solely the initial phase in performance monitoring. The next important phase is to find out and remove the root cause associated with the performance degradation. Thus, a comprehensive performance assessment tool not only detects the abnormal operation, but also isolates the root causes from routine data. Desborough and Harris [4] used analysis of variance table to investigate the variance contributions due to disturbances and controllers for a feedback/feedforward system. Stanfelj *et al*. [5] presented a method that utilized autocorrelation and cross-correlation functions for monitoring and diagnosing the cause of poor performance of feedforward and feedback control systems. When minimum variance under the current structure does not provide satisfactory performance, they suggested reducing the periods of delay and the variance of disturbance, and modifying the disturbance transfer function as solution in reducing minimum variance. In Stanfelj *et al.*'s work [5], the sources in poor performance are errors in the process model and/or poor controller tuning, but they do not consider the faults from the change of the dead time and the change of the unmeasured disturbance model.

According to Desborough and Harris' work [4], the output variance in a feedback/feedforward system can be classified into two variance effects from the unmeasured disturbance and the measured disturbance, respectively. Both effects can be further divided into the controller invariant term and the controller dependent term. Using the changes of the variances of these terms, the diagnosis tree of a feedforward plus feedback control system is developed in this paper. Any fault in feedback/feedforward systems might change either or both of the minimum invariance term and the controller dependent term for the unmeasured disturbance and the measured disturbance, respectively. Using these variance terms as fingerprints, a diagnostic tree is constructed. Following the hierarchy tree with a sequential hypothesis testing, the possible faults from making a comparison of the current variations and the variations with a benchmark control performance can be tracked.

The outline of this paper is organized as follows. The

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second section defines the diagnosis problem of a feedforward/feedback control system. The performance assessment bound based on the output variation is also given. Then, a diagnostic reasoning tree for detecting the fault sources is proposed in Section 3. In Section 4, a fault diagnosis problem with a feedforward/feedback control system from the computer simulation is presented. Conclusions are drawn in Section 5.

## II. Performance Bound of Feedforward/Feedback Control Systems

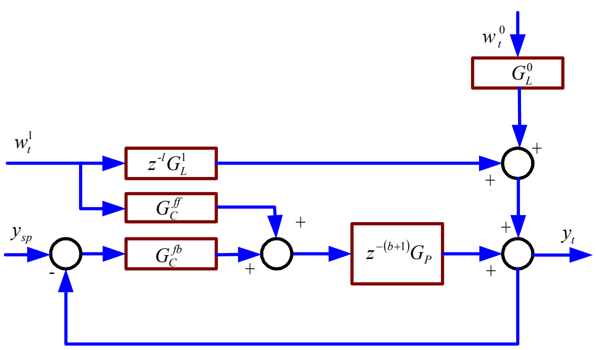


Fig. 1. The feedback/feedforward control system

Given a feedback/feedforward control system (Fig. 1), the closed-loop response ( $y_t$ ) to both unmeasured ( $w_t^0$ ) and measured disturbances ( $w_t^1$ ), both of which are a sequence of zero mean independent distribution with constant variance, can be derived as

$$y_t = \underbrace{\frac{G_L^0}{1+z^{-(b+1)}G_PG_C^{fb}}w_t^0}_{\text{Feedback}} + \underbrace{\frac{z^{-(b+1)}G_PG_C^{ff}+z^{-l}G_L^1}{1+z^{-(b+1)}G_PG_C^{fb}}w_t^1}_{\text{Feedback/Feedforward}} \tag{1}$$

where ($b$+1) and $l$ represent the dead time of the process and the measured disturbance, respectively. $G_p$, $G_L^0$, $G_L^1$, $G_C^{fb}$, and $G_C^{ff}$ represent the process, the unmeasured disturbance, the measured disturbance, the feedback controller and the feedforward controller models, respectively. The diagnosis is to analyze the measured output data ( $y_t$ ) and to find out the fault causes when the process faults come from the above elements of this system. Generally, it is difficult for operators who supervise the process to determine which part of the system is defective. A diagnostic tool is, therefore, required to assist the operators in keeping the system at the normal operation and in finding out the possible faults. Using the Diophantine identities, the output ( $y_t$ ) of Eq.(1) can be expressed as

$$y_t = \left[Q_L^0 + z^{-(b+1)}\frac{R_L^0 - Q_L^0G_PG_C^{fb}}{1+z^{-(b+1)}G_PG_C^{fb}}\right]w_t^0 + \begin{cases} \left[z^{-l}Q_L^1 + z^{-(b+1)}G_PG_C^{ff} + \dfrac{z^{-(b+l+1)}\left(R_L^1 - Q_L^1G_PG_C^{fb}\right) - z^{-(2b+2)}G_PG_C^{fb}G_PG_C^{ff}}{1+z^{-(b+1)}G_PG_C^{fb}}\right]w_t^1 & \text{if } l < b+1 \\ \left[z^{-(b+1)}G_PG_C^{ff} + \dfrac{-z^{-(2b+2)}G_PG_C^{fb}G_PG_C^{ff} + z^{-(b+l+1)}R_L^1}{1+z^{-(b+1)}G_PG_C^{fb}}\right]w_t^1 & \text{if } l \ge b+1 \end{cases} \tag{2}$$

The output variance ( $\sigma_y^2$ ) can be expressed as

$$\sigma_y^2\left(b, G_P, G_L^0, l, G_L^1\right) = \sigma_{y_{FB}}^2 + \sigma_{y_{FF}}^2 \tag{3}$$

and

$$\sigma_{y_{FB}}^2 = \underbrace{s_{FBI}\left(b, G_L^0\right)\sigma_{w_t^0}^2}_{\text{Feedback Invariant}} + \underbrace{s_{FBD}\left(b, G_L^0, G_P, G_C^{fb}\right)\sigma_{w_t^0}^2}_{\text{Feedback Dependent}} \tag{4}$$

$$\sigma_{y_{FF}}^2 = \begin{cases} \underbrace{s_{FBI/FFI}\left(b, l, G_L^1\right)\sigma_{w_t^1}^2}_{\text{Feedback Invariant/Feedforward Invariant}} + \underbrace{s_{FBI/FFD}\left(b, l, G_L^1, G_P, G_C^{ff}\right)\sigma_{w_t^1}^2}_{\text{Feedback Invariant/ Feedforward Dependent}} & \text{if } l < b+1 \\ \underbrace{s_{FBI/FFD}\left(b, G_P, G_C^{ff}\right)\sigma_{w_t^1}^2}_{\text{Feedback Invariant/ Feedforward Dependent}} & \text{if } l \ge b+1 \end{cases} + \underbrace{s_{FBD/FFD}\left(b, l, G_L^1, G_P, G_C^{fb}, G_C^{ff}\right)\sigma_{w_t^1}^2}_{\text{Feedback Dependent/ Feedforward Dependent}} \tag{5}$$

where $s_{FBI} = \sum_{j=0}^{b}\left(\varphi_j\right)^2$ , $s_{FBD} = \sum_{j=b+1}^{\infty}\left(\varphi_j\right)^2$ , $s_{FBI/FFI} = \sum_{j=k}^{b}\left(\phi_j\right)^2$ , $s_{FBI/FFD} = \sum_{j=b+1}^{b+k}\left(\phi_j\right)^2$ and $s_{FBD/FFD} = \sum_{j=b+k+1}^{\infty}\left(\phi_j\right)^2$ . $\{\varphi_j\}$ and $\{\phi_j\}$ are the impulse response coefficients from the feedback and feedforward loops. In Eq. (3), the output variance of the feedback/feedforward system can be classified into the variances from feedback loop ( $\sigma_{y_{FB}}^2$ ) and from feedforward loop ( $\sigma_{y_{FF}}^2$ ). The feedback variance ( $\sigma_{y_{FB}}^2$ ) can be further expressed as the sum of the feedback invariant (FBI) term ( $s_{FBI}\sigma_{w_t^0}^2$ ) and the feedback dependent (FBD) term ( $s_{FBD}\sigma_{w_t^0}^2$ ). The feedforward variance ( $\sigma_{y_{FF}}^2$ ) can also be decomposed into the feedback /feedforward invariant (FBI/FFI) term ( $s_{FBI/FFI}\sigma_{w_t^1}^2$ ), the feedback-invariant/feedforward-dependent (FBI/FFD) term ( $s_{FBI/FFD}\sigma_{w_t^1}^2$ ) and the feedback/feedforward dependent (FBD/FFD) term ( $s_{FBD/FFD}\sigma_{w_t^1}^2$ ). These terms which are functions of the control elements of the feedback/feedforward system are also included in Eqs. (3)-(5).

Under the minimum variance control, the minimum variance bound of the feedforward/feedback system is

$$\sigma_{MVC}^2 = s_{FBI}\left(b, G_L^0\right)\sigma_{w_t^0}^2 + s_{FBI/FFI}\left(b, l, G_L^1\right)\sigma_{w_t^1}^2 \tag{6}$$

For practical consideration, the theoretical lower bound of the output variance is rarely achieved operationally. A more realistic performance bound for the fixed control structure can be solved by

$$\sigma^2_{achievable-MV} = \min_{\{k_i\}} E\left[y_t^2\right] \tag{7}$$

where $\{k_i\}$ is the controller parameters of $G_C^{fb}$, and $G_C^{ff}$.

## III. Fault Diagnostic and Isolated Procedures

Like a classical decision tree, a diagnosis tree structure consisted of internal and external nodes connected by branches is proposed. An internal node is a decision-making unit that is based on the hypothesis testing to find out the current possible fault element. After isolating and removing the fault element, the diagnosis tree further determines which child node to visit next. In contrast, an external node (or a terminal node) has no child nodes and is associated with a fault symptom that characterizes the operating data that leads to the fault problem.

Assume the operating controllers ($G_C^{ff}$ and $G_C^{fb}$) with the achievable performance are given and the fault from these poor tuning controllers have been checked before starting diagnosis; the possible fault sources would come from the other elements ($b$, $l$, $G_P$, $G_L^0$ and $G_L^1$). However, whenever the fault is from one of these elements, the fault of the poor controller design ($G_C^{ff}$ and $G_C^{fb}$) would be indirectly affected. Thus, the controller should certainly be re-deigned. In the terms of the output variances of the feedforward and the feedback loops, the dead times ($b$ and $l$) are used to divide the variance into FBI, FBD, FBI/FFI, FBI/FFD and FBD/FFD. The dead times for the current operating data should be first estimated and checked if they are changed [7]. Now, the root causes ($G_P$, $G_L^0$ and $G_L^1$) would be dug by examining the corresponding sub-terms ($s_{FBI}$, $s_{FBD}$, $s_{FBI/FFI}$, $s_{FBI/FFD}$ and $s_{FBD/FFD}$) of $\sigma^2_{y_{FB}}$ and $\sigma^2_{y_{FF}}$. Since the number of elements of $\sigma^2_{y_{FB}}$ is less than that of $\sigma^2_{y_{FF}}$, the diagnostic procedures start from the feedback loop first.

### A. Feedback Control Loop

The output variance of the feedback control loop is

$$\sigma^2_{y_{FB}} = s_{FBI}\left(G_L^0\right)\sigma^2_{w_t^0} + s_{FBD}\left(G_L^0, G_P\right)\sigma^2_{w_t^0} \tag{8}$$

A diagnosis tree for the feedback loop is shown in Fig. 2. It is employed as follows. First, $m$ observations for achievable (*) benchmark condition and $n$ observations for the current (c) operating condition are presented to the starting node of the diagnosis tree. Note that the current dead time has been checked before starting the diagnosis tree. The current and the achieved variances are tested with the hypothesis ($s^c_{0,FBI} = s^*_{0,FBI}$ and $s^c_{0,FBD} = s^*_{0,FBD}$) as a decision function used by an internal node, the tree will branch to three child nodes ($\left(\mathrm{FBI}\right)_0^a \,\&\left(\mathrm{FBD}\right)_0^a$, $\left(\mathrm{FBI}\right)_0^a \,\&\left(\mathrm{FBD}\right)_0^r$, and $\left(\mathrm{FBI}\right)_0^r \,\&\left(\mathrm{FBD}\right)_0^r$, where the subscript a and r represent the accepted and rejected outcomes, respectively.

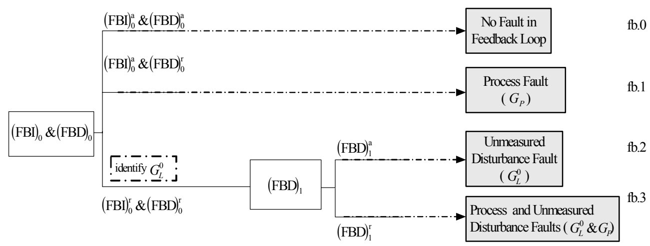


Fig. 2. Fault detection and diagnosis tree for the feedback control loop.

(a) $\left(\mathrm{FBI}\right)_0^a \,\&\left(\mathrm{FBD}\right)_0^a$.

It represents no fault in the feedback loop (fb.0 in Fig. 2).

(b) $\left(\mathrm{FBI}\right)_0^a \,\&\left(\mathrm{FBD}\right)_0^r$

$\left(\mathrm{FBI}\right)_0^a$ shows that $G_L^0$ has no fault and $\left(\mathrm{FBD}\right)_0^r$ indicates the only fault is $G_P$ error (fb.1 in Fig. 2).

(c) $\left(\mathrm{FBI}\right)_0^r \,\&\left(\mathrm{FBD}\right)_0^r$

$\left(\mathrm{FBI}\right)_0^r \,\&\left(\mathrm{FBD}\right)_0^r$ indicate $G_L^0$ error must exist. In order to re-construct the unmeasured disturbance model, the disturbance model ($G_L^0$) is identified based on the first $b$ closed loop impulse response coefficients obtained from the time-series modeling of the current output operating data [8]. After $G_L^0$ substituting into FBD, the only fault from $G_P$ can be examined using the hypothesis test ($\left(\mathrm{FBD}\right)_1$). Thus, the above node can be further branched to two child nodes:

(i) If $\left(\mathrm{FBD}\right)_1$ is accepted, only fault is $G_L^0$ (fb.2 in Fig. 2).

(ii) If $\left(\mathrm{FBD}\right)_1$ is rejected, it represents faults from $G_L^0$ and $G_P$ (fb.3 in Fig. 2).

### B. Feedforward Control Loop

As for the diagnosis tree of the feedforward loop (Fig. 3), two conditions are separated based on the difference of dead times between the process and the measured disturbance ($l < b+1$ and $l \geq b+1$), where the possible $b$ or $l$ errors have been checked before conducting the diagnosis procedure of the feedforward loop.

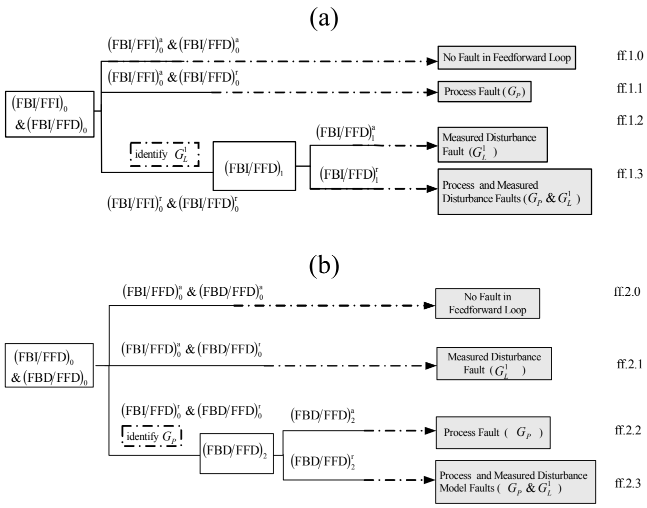


Fig. 3. Fault detection and diagnosis tree for the feedforward control loop: (a) $l < b+1$; (b) $l \geq b+1$.

**Condition 1:** $l < b+1$

$$\sigma^2_{y_{FF}} = s_{FBI/FFI}\left(G_L^1\right)\sigma^2_{w_t^1} + s_{FBI/FFD}\left(G_L^1, G_P\right)\sigma^2_{w_t^1} + s_{FBD/FFD}\left(G_L^1, G_P\right)\sigma^2_{w_t^1} \tag{9}$$

where $s_{FBI/FFD}$ and $s_{FBD/FFD}$ are functions of the same elements. To isolate the possible fault elements, only the hypothesis testing of $s_{FBI/FFI}$ and $s_{FBI/FFD}$ based on the achievable minimum and the current variances used here are evaluated. With the two null hypothesis testing, three possible outcomes would happen:

(a) $(\mathrm{FBI/FFI})_0^a$ & $(\mathrm{FBI/FFD})_0^a$:

It represents there is no fault in the feedforward loop (ff.1.0 in Fig. 3(a)).

(b) $(\mathrm{FBI/FFI})_0^a$ & $(\mathrm{FBI/FFD})_0^r$:

The acceptance of $(\mathrm{FBI/FFI})_0$ indicates that $G_L^1$ is no fault. This implies that the rejection of $(\mathrm{FBI/FFD})_0$ comes from the fault of $G_P$ (ff.1.1 in Fig. 3(a)).

(c) $(\mathrm{FBI/FFI})_0^r$ & $(\mathrm{FBI/FFD})_0^r$:

$(\mathrm{FBI/FFI})_0$ exceeds the critical value of the hypothesis testing and $(\mathrm{FBI/FFD})_0$ also cannot be accepted. One of the possible faults is from the disturbance model ($G_L^1$). The measured disturbance model should be re-estimated. With the estimated $G_L^1$, the new FBI/FFD of the achievable are updated. The node based on the new hypothesis testing of $(\mathrm{FBI/FFD})_1$ are further branched into two child nodes:

(i) If $(\mathrm{FBI/FFD})_1$ is accepted, only fault is $G_L^1$ (fb.1.2 in Fig. 3(a))

(ii) If $(\mathrm{FBI/FFD})_1$ is still rejected, it represents faults from $G_L^1$ and $G_P$ (fb.1.3 in Fig. 3(a)).

**Condition 2:** $l \geq b+1$

$$\sigma^2_{y_{FF}} = s_{FBI/FFD}\left(G_P\right)\sigma^2_{w_t^1} + s_{FBD/FFD}\left(G_L^1, G_P\right)\sigma^2_{w_t^1} \tag{10}$$

Like Condition 1, the evaluations of the hypothesis testing of $s_{FBI/FFI}$ and $s_{FBD/FFD}$ based on the achievable minimum and the current variances have three possible outcomes:

(a) $(\mathrm{FBI/FFD})_0^a$ & $(\mathrm{FBD/FFD})_0^a$:

It represents there is no fault in the feedforward loop (ff.2.0 in Fig. 3(b)).

(b) $(\mathrm{FBI/FFD})_0^a$ & $(\mathrm{FBD/FFD})_0^r$:

The acceptance of $(\mathrm{FBI/FFD})_0$ explains $G_P$ is no fault. This implies that the rejection of $(\mathrm{FBD/FFD})_0$ comes from the fault of $G_L^1$ (ff.2.1 in Fig. 3(b)).

(c) $(\mathrm{FBI/FFD})_0^r$ & $(\mathrm{FBD/FFD})_0^r$:

The $(\mathrm{FBI/FFD})_0$ exceeds the critical value of the hypothesis testing and $(\mathrm{FBD/FFD})_0$ also cannot be accepted. One of the possible faults from $G_P$ must exist. In order to confirm if the only fault is $G_P$, the process model should be re-estimated. Without any difficulty, the conventional closed-loop model identification [9] is applied here directly to obtain the new estimated process model. Then the new FBD/FFD of the achievable value is updated. The node based on the new hypothesis testing of $(\mathrm{FBI/FFD})_2$ is further branched into two child nodes:

(iii) If $(\mathrm{FBI/FFD})_2$ is accepted, only fault is $G_P$ (fb.2.2 in Fig. 3(b))

(iv) If $(\mathrm{FBI/FFD})_2$ is still rejected, it represents faults from $G_L^1$ and $G_P$ (fb.2.3 in Fig. 3(b)).

## IV. Simulation Study

A revised case based on Desborough and Harris [4] is depicted as

$$y_t = u_{t-3} + \frac{1-0.2z^{-1}}{1-z^{-1}} w_{0,t} + \frac{z^{-5}\left(1-0.6z^{-1}\right)}{1-z^{-1}} w_{1,t}$$

$$u_t = -\frac{K_{ff}}{1-z^{-1}} w_{1,t} + \frac{K_{fb}}{1-z^{-1}}\left(y_{sp} - y_t\right)$$

where the measured disturbance delay ($l = 5$) is larger than the process dead time ($b+1 = 3$). The achievable minimum variance of system is 3.5050 and the corresponding controller parameters are $K_{fb}^* = 0.2690$ and $K_{ff}^* = 0.4055$. According to the closed-loop data under optimal controllers, the variance terms of $\sigma^2_{y_{FB}}$ and $\sigma^2_{y_{FF}}$ can be evaluated. The achievable minimum variance benchmark can be separated as the feedback and/or the feedforward terms:

$$s^*_{FBI} = 2.2800 \;\; s^*_{FBD} = 0.4737$$

$$s^*_{FBI/FFD} = 0.6823 \;\; s^*_{FBD/FFD} = 0.0690$$

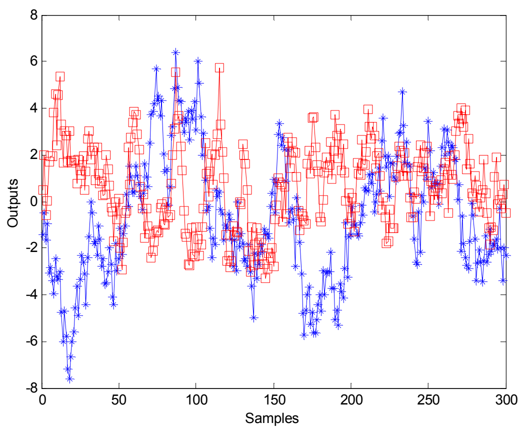


Fig. 4. The closed-loop simulation of the controlled output responses of the achievable benchmark (*), and multiple faults (□).

Assume that the control system with the multiple faults happens,

$$y_t = \frac{0.5}{1+0.8z^{-1}} u_{t-5} + \frac{1-0.2z^{-1}}{1-z^{-1}} w_{0,t} + \frac{0.2z^{-1}}{1-z^{-1}} w_{1,t}$$

The multiple faults are the change of the process, the change of the process dead time, the change of the measured disturbance dead time, and the change of the measured disturbance model. The control parameters of the closed loop are still based on the original achievable design values. The simulated closed loop outputs for the achievable normal operation condition and this fault is plotted in Fig. 4. From the figure, the output variance of this fault condition (5.7803) is a little far from that of the original benchmark condition; however, it is hard to diagnose the root faults solely from the closed-loop output response. To dig out the possible fault cause, the initial stage is to check if two dead times are changed using the cross-correlation analysis on input and output data. From Fig. 5, it is obvious that process dead time increases to 4 and the measured disturbance dead time decreases to 1. Now the feedback and/or the feedforward terms of the new achievable minimum variance benchmark are:

$$s^*_{0,FBI} = 3.5600 \;\; s^*_{0,FBD} = 3.4496$$

$$s^*_{0,FBI/FFI} = 1.4800 \;\; s^*_{0,FBI/FFD} = 0.00003075 \;\; s^*_{0,FBD/FFD} = 3.1377$$

(a)

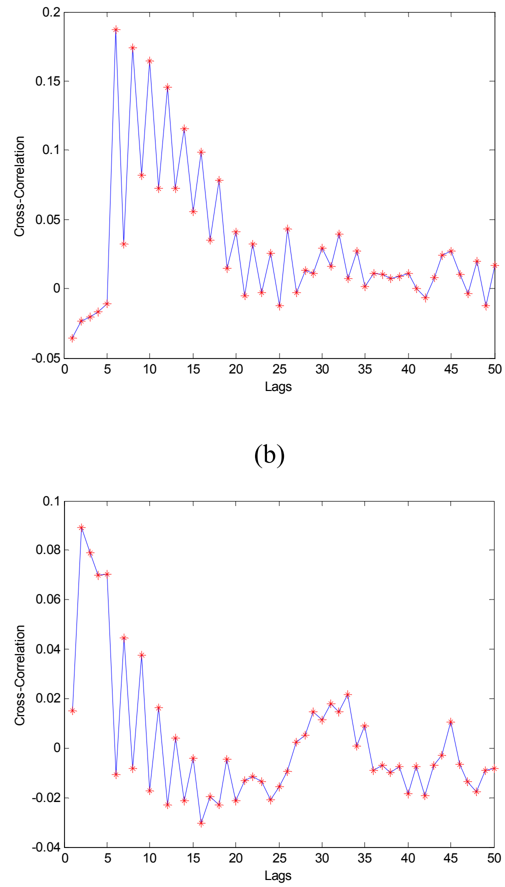


Fig. 5. Dead time estimations of (a) process and (b) measure disturbance process.

In the feedback loop, the diagnosis tree based on Fig. 2 guides the fault location which is transparent. In the hypothesis test of $\mathrm{FBI}_0$ & $\mathrm{FBD}_0$,

$$F_{0.975} = 0.8390 < (\mathrm{FBI})_0 = \frac{s^c_{0,\mathrm{FBI}}}{s^*_{0,\mathrm{FBI}}} = \frac{3.3612}{3.5600} = 0.9442 < F_{.025} = 1.1918$$

$$(\mathrm{FBD})_0 = \frac{s^c_{0,\mathrm{FBD}}}{s^*_{0,\mathrm{FBD}}} = \frac{2.4391}{3.4496} = 0.7071 < F_{0.975} = 0.8390$$

At the 0.05 level of significance, the null hypothesis of $(\mathrm{FBI})_0$ cannot be rejected ( $\mathrm{FBI}^a_0$ ) and the null hypothesis of $(\mathrm{FBD})_0$ cannot be accepted ( $(\mathrm{FBD})^r_0$ ). It indicates that the fault comes from the process.

In feedforward loop, the diagnosis tree based on Fig. 3 is applied because of $l < b+1$ . The hypothesis tests ( $\mathrm{FBI/FFI}$ & $\mathrm{FBI/FFD}$ ) are first used,

$$\left(\mathrm{FBI/FFI}\right)_0 = \frac{s^c_{0,\mathrm{FBI/FFI}}}{s^*_{0,\mathrm{FBI/FFI}}} = \frac{0.1431}{1.4800} = 0.0967 < F_{0.975} = 0.8390$$

$$F_{.025} = 1.1918 < \left(\mathrm{FBI/FFD}\right)_0 = \frac{s^c_{0,\mathrm{FBI/FFD}}}{s^*_{0,\mathrm{FBI/FFD}}} = \frac{0.00074}{0.00003075} = 24.0908$$

The null hypotheses of FBI/FFI and FBI/FFD are rejected. It indicates that the measured disturbance model ( $G_L^1$ ) error does exist. The re-identified disturbance model based on the time series of the input-output data under the closed-loop operation is

$$G_L^1 = \frac{0.2205z^{-1}}{1-0.9425z^{-1}}$$

The $\left(\mathrm{FBI/FFD}\right)_1$ statistics is then used to compare to the original achievable benchmark and the achievable benchmark $\left(\mathrm{FBI/FFD}\right)_1$ value that is obtained from the re-estimated disturbance model. The hypothesis test of $\left(\mathrm{FBI/FFD}\right)_1$ statistics

$$\left(\mathrm{FBI/FFD}\right)_1 = \frac{s^c_{1,\mathrm{FBI/FFD}}}{s^*_{1,\mathrm{FBI/FFD}}} = \frac{0.00074}{0.0536} = 0.0138 < F_{0.975} = 0.8390$$

also indicates another fault is the process change ( $G_P$ ).

The above procedures can find out four possible faults ( $G_P$, $G_L^1$, $l$ and $b$ ) to deteriorate the control performance. The last stage, but not the least one, is to recover the control performance after correcting the fault sources. After correcting these fault elements, the new achievable benchmark is 4.1040 and the corresponding controller parameters are $K^*_{fb} = 0.6203$ and $K^*_{ff} = 0.1426$ . The performance bound will be used as the new benchmark to keep the monitoring and diagnosis of the next coming operation feedforward/feedback system.

## V. Conclusions

In this work, the diagnosis tree based analysis approach via a sequence of the hypothesis testing is developed to examine the possible faults in a feedforward/feedback control system. On the basis of the closed-loop data only, without a major effort, this proposed data driven approach can systematically analyze the possible faults. With the decomposition of the control output variances into the feedback loop variance and the combination of feedforward and feedback loop variance, a sequence of hypothesis testing compares the current performance to the one that would be obtained by the a minimum achievable variance controller. It can systematically identify and isolate the system that contains the possible fault information. The hypothesis testing gives a good estimate of what the status of the current performance of the feedforward/feedback loop can be improved, which may be translated in terms of increased production. This is good for the complexity of a common industrial operating process. This prototype was used to verify the numerical simulation testing in this paper, and is now ready for field testing. It really remains to be confirmed that the proposed approach is robust enough for industrial applications, and in particular that all potential pitfalls can be avoid, like the estimated model error, and the estimated dead time error.

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