# TO CASCADE OR NOT TO CASCADE?

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Abstract: We describe an approach that is useful in deciding if significant benefits in terms of control loop performance index will be achieved by a change in control loop configuration from simple feedback (SFB) to cascade control. The problem is considered in a stochastic setting and solved using the Analysis of Variance (ANOVA) technique. The proposed methodology requires only routine operating data and knowledge of the process delay. Three simulation examples exemplify the utility of this approach.


Keywords: Analysis of variance (ANOVA), Control loop performance assessment, performance monitoring, minimum variance control, cascade control

## 1. INTRODUCTION

Cascade control is probably the single most important performance enhancement strategy over simple feedback loops. The potential improvements in performance possible and the ease of its implementation has led to its widespread use in the chemical process industries for over five decades now. Using extra output measurement(s) (in addition to the primary controlled variable), the cascade control scheme provides timely and calculated adjustment of the manipulated variable thereby decreasing the peak error as well as the integral error for disturbances affecting the process. The efficiency of the cascade control schemes in handling disturbances entering the inner loop has been well documented in several research articles and textbooks. What is relatively less appreciated is the fact that cascade control provides better performance (as compared to the single loop case) for all types of load changes. While the improvement for disturbances entering close to the process input (i.e. secondary disturbances) can be 10 to 100 fold, the improvement in performance for disturbances entering late into the process (i.e. primary disturbances) is about 2 to 5 times (Webb, 1961; Harriott, 1984). Marlin (2000) provides an excellent review of the principles of cascade control, details the criteria for cascade design and shows several industrial examples. It is shown that the cascade scheme provides practical benefits only if the secondary process is at least three times faster than the primary process even for disturbances entering the inner loop. Krishnaswamy *et al.,* (1990) relate the benefits afforded by cascade control to the parameters of the primary and secondary process models in a deterministic setting.

Industrial control loops are designed and implemented in order to achieve specific objectives. It is important to monitor the performance of these loops periodically and make sure they provide the best possible performance. In this regard, the performance monitoring of control loops has received much attention in the last decade. Many researchers have used the minimum variance controller (MVC) performance as the benchmark – this benchmark is appropriate if the goal of control is the reduction of the variance in the controlled variable (the variance of the manipulated variables, the complexity of the MVC or its robustness is not of concern). Harris (1989) showed that the minimum variance achievable (with a MVC) can be computed from routine operating data if the process time delay is known. Since then, there has been a multitude of research articles (e.g. Desborough and Harris, 1992; Stanfelj *et al.* 1993; Huang *et al.* 1997) that consider important extensions, alternate benchmarks (Tyler and Morari, 1996; Kendra and Cinar, 1997; Swanda and Seborg, 1999), applications (Thornhill *et al*., 1999) and industrial perspectives (e.g. Kozub, 1996; Desborough and Miller, 2001) on this topic. The user is also referred to the exceptional coverage provided by Huang and Shah (1999) and Qin (1998) to this topic. Recently, Agrawal and Lakshminarayanan (2003) described a method to determine the control loop performance achievable with PI type controllers, the optimal control settings that will yield the "best" performance and the expected robustness margins using closed loop transfer functions identified from closed loop experimental data.

Ko and Edgar (2000) established the basis of performance assessment of cascade loops. Desborough and Harris (1993) established a procedure to separate the variance contributions into components related to the controller and the disturbances by developing an analysis of variance (ANOVA) technique. Vishnubhotla *et al.* (1997) applied the ANOVA method to investigate the need for feedforward control on data sets provided by Shell, USA.

The study here is related to cascade loops. The scenario we consider is as follows: we have a process that is presently regulated by a simple feedback (SFB) controller. A control loop monitoring tool has flagged this loop as poorly performing when compared to MVC. We take a closer look at this loop and assess if the loop is performing to its full potential by taking into consideration factors such as the restricted structure of the controller – this is important because PID type controllers that are so common in the chemical process industries cannot provide minimum variance performance under many practical situations. Let us assume that such an analysis finds that the present controller is doing its best. If even better control performance is sought, the choices available are: (i) making process modifications or (ii) changing the controller structure. Two obvious enhancements to the SFB scheme are feedforward and cascade control. Feedforward control is more appropriate when measured disturbances are available. Cascade control is suited when suitable secondary measurements (the secondary measurement must be influenced by the manipulated variable; it must also have a direct impact on the primary variable) are available. Such a scenario has been mentioned in Stanfelj *et al.* (1993). Note that if the analysis had shown that the SFB loop is not performing as good as is possible, then retuning of the feedback controller would have been initiated.

In this paper, we assume that we are not satisfied with even the best performance that the SFB control system can provide and we would like to estimate the benefits that will accrue by migrating from SFB control to cascade control. Feedforward scheme is not an option due to the lack of measured disturbances. Routine operating data from the SFB control system will be utilized to perform an ANOVA decomposition of the process variance and speculate about the possible success of the cascade scheme.

This contribution is structured as follows. In the next section, we outline the basics of the performance assessment for simple feedback and cascade loops. We then discuss the ANOVA procedure as applied to a simple feedback loop and indicate the components of the variance that can be eliminated using cascade control. Examples will be used to demonstrate the utility of the proposed methodology.

## 2. THEORY

Consider the SFB control system shown in Figure 1. $y_1$ and $y_2$ represent the disturbance corrupted outputs of the primary and the secondary process respectively. The primary process is denoted by $T_1 = q^{-d1}\tilde{T}_1$ where d1 denotes the number of samples of time delay in the primary process and $\tilde{T}_1$ represents the delay free part of $T_1$. Along the same lines, the secondary process $T_2$ is represented as $T_2 = q^{-d2}\tilde{T}_2$. Q represents the feedback controller; $N_1$ and $N_2$ denote the disturbance transfer functions driven by zero-mean white noise sequences $a_1$ and $a_2$ respectively; disturbance $a_1$ is "closer" to the primary variable $y_1$ and disturbance $a_2$ is in proximity to the secondary variable $y_2$. 'u' represents the manipulated variable.

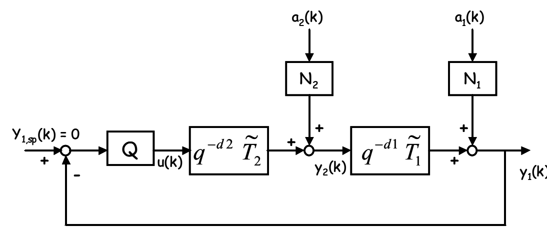


**Figure 1: Simple Feedback System**

Figure 2 shows a cascade system controlling the same process. In this case, $Q_1$ represents the primary controller and $Q_2$ represents the secondary controller. $u_2$ represents the manipulated variable that is set by the secondary controller $Q_2$. The setpoint for $Q_2$ comes from the primary controller $Q_1$.

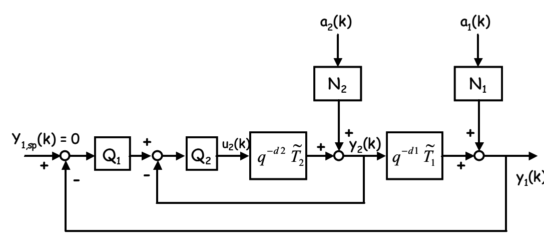


**Figure 2: Cascade Control System**

For a disturbance $a_2$ entering the system at t = 0, the output $y_1$ will be disturbed from 'time' d1 onwards. The controller Q in the SFB case will initiate control action at t = d1. The effect of this control action will be felt at $y_1$ only from (2d1+d2) onwards. $y_1$ will effectively be in open loop between d1 and (2d1+d2-1) samples. Under the cascade control system, $Q_2$ will initiate control action at t = 0, and the output $y_1$ will be in open loop condition only between d1 and d1+d2-1 samples. If d1 is large, the cascade scheme will provide better regulation of $y_1$ for the secondary disturbance $a_2$. Next, consider the 'primary' disturbance $a_1$ entering the system at t = 0. The primary controlled variable will remain in an open loop condition between t = 0 to t = d1+d2-1 for both the SFB and the cascade control system. In going from a SFB to a cascade scheme, we can hope to eliminate the effect of $a_2$ between t = d1+d2 and t = 2d1+d2-1. This does not mean that no more reduction in variance is possible as we change from SFB to cascade control. This aspect will be clarified later.

For the SFB, the closed loop relationship between the external signals and the output $y_1$ is given by:

$$y_1 = \left(\frac{N_1}{1+QT_1T_2}\right)a_1 + \left(\frac{N_2T_1}{1+QT_1T_2}\right)a_2 \qquad (2.1)$$

For the cascade scheme, this relationship is modified to:

$$y_1 = \left(\frac{N_1}{1+Q_1\,T_1\,T_2^*}\right)a_1 + \left(\frac{N_2^*\,T_1}{1+Q_1\,T_1\,T_2^*}\right)a_2 \qquad (2.2)$$

with $T_2^* = \dfrac{Q_2\;T_2}{1+Q_2\;T_2}$ and $N_2^* = \dfrac{N_2}{1+Q_2\;T_2}$.

For the SFB control scheme, the minimum variance is now computed. The disturbance and process transfer functions are expanded as follows:

$$N_1 = P_1 + R_1q^{-(d1+d2)} \qquad (2.3)$$

$$N_2 = P_2 + R_2q^{-(d1+d2)} \qquad (2.4)$$

$$P_2\widetilde{T}_1 = S + Vq^{-(d1+d2)} \qquad (2.5)$$

where $P_1$ and $P_2$ are monic polynomials (for $N_1$ and $N_2$ respectively) in $q^{-1}$ of order d1+d2-1.

In equation (2.3), $N_1$ is expanded into two parts $P_1$ and $R_1q^{-(d1+d2)}$. When noise $a_1$ enters the process at time 0, the controller action would not have any effect on $y_1$ until time d1+d2-1; this makes $P_1$ a feedback invariant term. In equation (2.4), $N_2$ is expanded into two parts $P_2$ and $R_2q^{-(d1+d2)}$. Note that the noise $a_2$ entering at time 0 will upset $y_2$ from time 0 to d1+d2-1 irrespective of any controller action. For our purposes, the effect of $a_2$ on $y_1$ is of interest. Therefore, in equation (2.5), the product of $P_2$ and $\widetilde{T}_1$ is expanded into S and $Vq^{-(d1+d2)}$, where S is a polynomial of order d1+ d2–1.

The closed loop transfer function shown in equation (2.1) can be divided into a feedback invariant part and feedback dependent part as shown in the following:

$$y_1 = \left(\frac{P_1 + R_1q^{-(d1+d2)}}{1+Q\widetilde{T}_1\widetilde{T}_2q^{-(d1+d2)}}\right)a_1 + \left(\frac{\left(P_2 + R_2q^{-(d1+d2)}\right)\widetilde{T}_1q^{-d1}}{1+Q\widetilde{T}_1\widetilde{T}_2q^{-(d1+d2)}}\right)a_2$$

$$= \left(\frac{P_1\left[1+Q\widetilde{T}_1\widetilde{T}_2q^{-(d1+d2)}\right] + q^{-(d1+d2)}\left[R_1 - P_1Q\widetilde{T}_1\widetilde{T}_2\right]}{1+Q\widetilde{T}_1\widetilde{T}_2q^{-(d1+d2)}}\right)a_1$$

$$+\left(\frac{P_2\widetilde{T}_1q^{-d1}\left[1+Q\widetilde{T}_1\widetilde{T}_2q^{-(d1+d2)}\right] + q^{-(d1+d2)}\left[R_2 - P_2Q\widetilde{T}_1\widetilde{T}_2\right]\widetilde{T}_1q^{-d1}}{1+Q\widetilde{T}_1\widetilde{T}_2q^{-(d1+d2)}}\right)a_2$$

$$= \left(P_1a_1 + Sq^{-d1}a_2\right) + \left(C_{d1+d2}q^{-(d1+d2)} + C_{d1+d2+1}q^{-(d1+d2+1)} + \ldots\right)a_1$$

$$+\left(D_{2d1+d2}q^{-(2d1+d2)} + D_{d1+d2+1}q^{-(2d1+d2+1)} + \ldots\right)a_2 \qquad (2.6)$$

From equation (2.6), the minimum variance can be written as

$$\sigma^2_{mv,SFB} = \mathrm{var}\left(P_1a_1 + Sq^{-d1}a_2\right) \qquad (2.7)$$

For the cascade control system shown in Figure 2, the minimum variance can be computed as:

$$\sigma^2_{mv,CAS} = \mathrm{var}\left(P_1a_1 + S_2q^{-d1}a_2\right) \qquad (2.8)$$

with polynomial $P_1$ as defined in equation (2.3) and $S_2$ is a polynomial of order d2-1 defined by equations (2.9) and (2.10).

$$N_2^* = P_2^* + R_2^*q^{-d2} \qquad (2.9)$$

$$P_2^*\widetilde{T}_1 = S_2 + V_2\;q^{-d2} \qquad (2.10)$$

Remark 1: The only difference between $\sigma^2_{mv,SFB}$ and $\sigma^2_{mv,CAS}$ is in the term related to the secondary disturbance $a_2$.

Lemma: The d2–1 coefficients of the polynomial $S_2$ will be the same as the first d2-1 coefficients of the polynomial S.

Next, we seek to perform an analysis of variance for the SFB system. The variance of the primary controlled variable $y_1$ should be separated into an invariant component and a feedback dependent component. The result of this analysis would help in deciding if restructuring existing SFB system into cascade control system will be beneficial. In short, we are interested in predicting the *cascade achievable performance*.

The feedback invariant part for the SFB control system is given by

$$y_{1,SFB,FI} = \left(H_{10} + \ldots + H_{1(d1+d2-1)}q^{-(d1+d2-1)}\right)a_1 + \left(H_{20} + \ldots + H_{2(2d1+d2-1)}q^{-(2d1+d2-1)}\right)a_2 \qquad (2.11)$$

If a cascade control system were to be established, the feedback invariant part would be:

$$y_{1,CAS,FI} = \left(H_{10} + \ldots + H_{1(d1+d2-1)}q^{-(d1+d2-1)}\right)a_1 + \left(H_{20} + \ldots + H_{2(d1+d2-1)}q^{-(d1+d2-1)}\right)a_2 \qquad (2.12)$$

In equations (2.11) and (2.12), the $H_1$'s refer to the closed loop impulse response coefficients (analytically determined or identified from routine operating data) for the primary disturbance affecting $y_1$. The $H_2$'s refer to the closed loop impulse response coefficients for $a_2$. These coefficients are estimated by performing a multivariate autoregressive modelling using $y_1$ and $y_2$ measurements. In the SFB case, the first 2d1+d2 terms ($H_{20}$ to $H_{2d1+d2-1}$) are used while in the cascade case only the first d1+d2 terms ($H_{20}$ to $H_{d1+d2-1}$) are used. Keeping this difference in mind, the feedback invariant for simple feedback system can be split in to two parts as

1a) SFB and cascade invariant and
1b) Additional SFB invariant

The first part is defined as "SFB and Cascade invariant" – this variance component cannot be altered either by a simple feedback controller or a cascade control system. The second part labeled as "Additional SFB invariant" contains the variance contribution due to non-availability of the secondary controller. It is assumed that this contribution to overall variance can be reduced to zero if a *perfect* secondary controller is available. The invariant part of the SFB can hence be rearranged as follows

$$\underbrace{y_{1,SFB,FI} = \left(H_{10} + \ldots + H_{1(d1+d2-1)} q^{-(d1+d2-1)}\right) a_1 + \left(H_{20} + \ldots + H_{2(d1+d2-1)} q^{-(d1+d2-1)}\right) a_2}_{\text{SFB and Cascade invariant}}$$

$$+$$

$$\underbrace{\left(H_{2(d1+d2)} q^{-(d1+d2)} + \ldots + H_{2(2d1+d2-1)} q^{-(2d1+d2-1)}\right) a_2}_{\text{Additional SFB invariant}} \quad (2.13)$$

The variance component '1b' is given by

$$\left(H^2_{2(d_1+d_2)} + H^2_{2(d_1+d_2+1)} + \ldots + H^2_{2(2d_1+d_2-1)}\right)\sigma^2_{a_2} \quad (2.14)$$

where $\sigma^2_{a_2}$ is the estimated variance of secondary noise $a_2$.

We are now ready to analyze the feedback dependent variance or remainder variance. The feedback-dependent part can also be separated into two distinct parts:
2a) Variance arising due to noise sequence $a_1$
2b) Variance arising due to noise sequence $a_2$.

For single feedback control system, the feedback dependent part is

$y_{1,SFB,\,FD}$

$$= \underbrace{\left(H_{1(d_1+d_2)} q^{-(d_1+d_2)} + H_{1(d_1+d_2+1)} q^{-(d_1+d_2+1)} + \ldots\right) a_1}_{\text{Feedback-dependent from } a_1}$$

$$+ \underbrace{\left(H_{2(2d_1+d_2)} q^{-(2d_1+d_2)} + H_{2(2d_1+d_2+1)} q^{-(2d_1+d_2+1)} + \ldots\right) a_2}_{\text{Feedback-dependent from } a_2} \quad (2.15)$$

The individual terms in equation (2.15) can be used to determine the contributions to the variance in $y_1$ from the primary and secondary noise channels.

In summary, the total variance of the primary controlled variable ($y_1$) for a SFB system with an additional secondary output measurement $y_2$ can be split into four parts:

1a) The SFB and cascade invariant components
1b) Additional SFB invariant.
2a) Remainder variance due noise sequence $a_1$.
2b) Remainder variance due to noise sequence $a_2$

Out of these four parts, the cascade scheme should ideally eliminate (or reduce considerably) the variance contribution from two terms: 1b and 2b. The cascade strategy is designed specifically to reduce the overall time constant and delay to deal with a situation where the major disturbance hits the secondary process and minor stochastic disturbances hits the primary process. Hence the reason for elimination of variance contribution arising from 1b and 2b components can be easily understood. In addition, the cascade control scheme can reduce a portion of the variance attributed to component (2a). The exact amount of reduction possible with component (2a) is not easy to ascertain. We have noted in our simulations that a significant decrease (about 50% or more in all of the examples we have worked on) in the variance contribution due to $a_1$ (2a part) is also achieved along with practical elimination of the 1b and 2b components. The reduction in the variance contribution from the (2a) component in the cascade scheme could be due to one or more of the following reasons:

1) The severe control action applied by the primary controller along with the higher gain in secondary controller compared to SFB scheme effectively attenuates the primary disturbances (Harriott, 1984).

2) In the single loop system, the primary controlled variable ($y_1$) and the disturbance ($a_1$) are more tightly coupled than is desirable. The output $y_1$ will follow a load change $a_1$ too readily. In the cascade system, $y_1$ and $a_1$ are loosely coupled (Webb, 1961).

3) The multiple lags in the feedback path of the SFB causes the control action to be delayed. Hence the variance of $y_1$ remains large. These lags are greatly reduced in the cascade system so that any effect of $a_1$ on $y_1$ is greatly reduced (Webb, 1961).

## 3. EXAMPLES

Three simulation examples are used to demonstrate the utility of the proposed ANOVA method for predicting the possible improvement in control loop performance if cascade control is implemented and also for choosing the secondary variable (in case more than one candidate exists).

Example 1: The primary process ($G_{p1}$), the secondary process ($G_{p2}$), the primary noise transfer function ($N_1$), and the secondary noise dynamics ($N_2$) used in this example are given below. In this example, the noise dynamics affecting the primary process is purposefully kept severe compared to noise dynamics affecting the secondary process, to check the effectiveness of cascade in rejecting severe primary disturbance compared to secondary disturbance.

$$G_{P1} = \frac{z^{-2}}{1-0.9z^{-1}}; G_{P2} = \frac{z^{-1}}{1-0.5z^{-1}};$$
$$N_1 = \frac{z^{-1}}{1-0.9z^{-1}}; N_2 = \frac{z^{-1}}{1-0.5z^{-1}}$$

The PI achievable performance for the SFB is computed to be 0.29. With this "optimal" SFB control system, the variance of $y_1$ is 12.89; the breakup into the 1a, 1b, 2a and 2b components is 3.71, 4.03, 0.8 and 4.36 respectively. Components 1b and 2b are substantial – they make up about 65% of the variance in $y_1$. These are the components that can be targeted and reduced by the cascade control strategy. The analysis makes a strong case for implementing a cascade control scheme.

When a PI-P cascade scheme is implemented, the best CLPI achieved is 0.81. The improvement in performance index is about 200% and vindicates the prediction made by the ANOVA approach. With the PI-P cascade implementation, the variance in $y_1$ is 4.59; the breakup into the 1a, 1b, 2a and 2b components is 3.71, 0.45, 0.25 and 0.19 respectively. Note that there has been a substantial decrease (about 70%) in the 2a variance component also.

Remark 2: The proposed ANOVA approach uses only routine operating data; it cannot therefore predict the settings of the primary and secondary controller at which the optimal cascade loop performance is achieved. If suitable experimental data (collected either under open or closed loop conditions) is available and the process models are identified, the "optimal" settings of the primary and secondary controller leading to the best control loop performance can be obtained using parametric optimization.

Example 2: The transfer functions used in this example are:

$$G_{P1} = \frac{0.0038z^{-20}}{1-0.98z^{-1}}; G_{P2} = \frac{0.0278z^{-8}}{1-0.95z^{-1}};$$
$$N_1 = \frac{z^{-1}}{1-z^{-1}}; N_2 = \frac{z^{-1}}{1-z^{-1}}$$

The PI achievable performance for the SFB scheme is 0.43. At this "optimal" performance, the variance of $y_1$ is 55.52; the breakup into the 1a, 1b, 2a and 2b components is 23.95, 0.16, 30.86 and 0.55 respectively. The 1b and 2b components are small indicating that the benefits from a cascade control system should mainly come from the reduction of the 2a component, which accounts for about 56% of the total variance here. On the basis of our experience, we can predict that at least 50% of component 2a will be annihilated. We would expect the 2a component with the cascade scheme to be about 15 and the variance in $y_1$ to reduce to around 40. A more precise answer to the expected reduction in 2a component is not possible.

When a PI-P cascade scheme is implemented, the best CLPI achieved is 0.63. With the PI-P cascade implementation, the variance in $y_1$ is 39.71; the breakup into the 1a, 1b, 2a and 2b components is 24.99, 0.23, 13.94 and 0.55 respectively. Note that there has been a significant decrease in the 2a variance component. The overall increase in CLPI is 47%; this may be enough to justify the implementation of the cascade scheme.

Example 3: The system considered next is described by the following equations:

$$y_3 = \frac{e^{-6s}}{(5s+1)(2s+1)} u + \frac{1}{(15s+1)} a_3$$
$$y_2 = \frac{e^{-2s}}{(10s+1)} y_3 + \frac{1}{(50s+1)} a_2$$
$$y_1 = \frac{e^{-3s}}{(20s+1)} y_2 + \frac{1}{(32s+1)} a_1$$

Here, $y_1$ is the primary controlled variable and $y_2$ and $y_3$ represent possible secondary variables. U is the manipulated variable; $a_1$, $a_2$ and $a_3$ represent zero mean white noise sequences with variances $\sigma^2_{a1}, \sigma^2_{a2}$ and $\sigma^2_{a3}$ respectively. The process is controlled by a PI controller with $K_c = 1$ and $\tau_I = 40$. We will examine the ANOVA results for various combinations of the noise variances and suggest the "best" secondary variable in each of those cases. In each case, 5000 samples of routine closed loop data sampled at intervals of 1 time unit were used.

Case 1: $\sigma^2_{a1} = \sigma^2_{a2} = 1$ and $\sigma^2_{a3} = 100$

If $y_2$ is considered as the secondary variable in the cascade scheme, the ANOVA estimates the overall variance in $y_1$, 1a, 1b, 2a and 2b components to be 1.38, 0.02, 0.02, 0.03 and 1.31 respectively. If $y_3$ were to be chosen as the secondary variable, these values are 1.40, 0.06, 0.02, 0.01 and 1.31 respectively. In this case, it does not matter whether $y_2$ or $y_3$ is chosen as the secondary variable. Since 2b component is very strong, cascade control using either $y_2$ or $y_3$ as the secondary variable will provide a vastly improved control loop performance. Between $y_2$ and $y_3$, we can choose the one that engulfs most of the disturbances as the secondary variable.

Case 2: $\sigma_{a2}^2 = \sigma_{a3}^2 = 1$ and $\sigma_{a1}^2 = 100$

If $y_2$ is considered as the secondary variable in the cascade scheme, the ANOVA estimates the overall variance in $y_1$, 1a, 1b, 2a and 2b components to be 1.83, 0.87, 0.001, 0.94 and 0.02 respectively. If $y_3$ were to be chosen as the secondary variable, these values are 1.83, 0.87, 0.002, 0.92 and 0.04 respectively. The 1a and 2a components are dominant in this case. Based on our experience, we conjecture that more than 50% of the 2a component will be consumed by the cascade scheme that could use either $y_2$ or $y_3$ as the secondary variable. Between $y_2$ and $y_3$, the choice will depend on their relative "location" with respect to the anticipated disturbances.

Case 3: $\sigma_{a1}^2 = \sigma_{a3}^2 = 1$ and $\sigma_{a2}^2 = 100$

If $y_2$ is considered as the secondary variable in the cascade scheme, the ANOVA estimates the overall variance in $y_1$, 1a, 1b, 2a and 2b components to be 0.445, 0.062, 0.014, 0.007 and 0.362 respectively. The 2b component is dominant here and a cascade control scheme with $y_2$ as the secondary variable can eliminate this variance component very effectively. If $y_3$ were to be chosen as the secondary variable, these values are 0.378, 0.023, 0.000, 0.342 and 0.013 respectively. Interestingly, with $y_3$ as the secondary variable, the 2a component is the dominant one. With cascade control we *may* not be able to eliminate this component completely (as much as we can do with the 1b or 2b components). In this case, the use of $y_2$ as the secondary variable seems to be a more prudent choice.

## 4. CONCLUSIONS

The proposed ANOVA method provides an estimate of the variance reduction possible by moving from a SFB scheme to a cascade scheme using only routine operating data and knowledge of the process time delays. Our simulations show that it is possible to achieve this predicted cascade achievable performance with a PI-P configuration or a PI-PI (when the secondary noise is non-stationary) cascade scheme.

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