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Improved Dead-Time Compensator Controllers

It is shown that the conventional Smith dead-time compensator can be modified in a fashion which leads to significant improvements in its regulatory capabilities for measurable disturbances or inputs. The proposed modification utilizes effectively the existing prediction capabilities of the conventional dead-time compensator and eliminates the need for a separate feedforward controller in many circumstances under which it is normally employed. The modified dead-time compensator possesses simultaneous feedforward and feedback actions. An additional tuning parameter which controls the degree of dead-time cancellation allows the designer to shape the response according to requirements. Illustrative examples show the advantages of the modified scheme.

Z. J. PALMOR
Faculty of Mechanical Engineering, Technion Israel Institute of Technology Haifa, Israel

D. V. POWERS
Taylor Instrument Company Rochester, NY 14692

SCOPE

A long-standing problem in process control is that of controlling processes with significant deadtimes between inputs and outputs. A considerable improvement in the control in these cases may be obtained via the O. J. M. Smith dead-time compensator (DTC) which recently has been extended to systems with multiple dead times. While the inclusion of the DTC considerably improves the performance of the controlled loop for setpoint changes, as has been shown by numerous experimental and simulation studies, the enhancements in disturbance rejection capabilities are not as apparent.

This paper reveals the reason for this and presents a simple, yet novel, modification of the DTC. With this modification, the dead time of the system to measurable disturbances is also compensated. This leads to significant improvements in the regulation capabilities of the DTC while retaining all its other properties.

By treating the degree of compensation as a design parameter, it is shown that the overall performance may be further improved in certain cases. Analytical approach to the determination of the degree of compensation is also discussed.

The main features of the new design are demonstrated through simulated responses.

CONCLUSIONS AND SIGNIFICANCE

The servomechanism properties of process controllers are considerably improved by the inclusion of a conventional dead-time compensator. DTC-based controllers traditionally have been considered and treated as feedback-only control schemes, and therefore no attention has been paid to the possibility of extending their properties to those of feedforward controllers. The modified DTC proposed in this paper utilizes the existing process model contained in the conventional DTC to predict the effect of the disturbances on the outputs. These predictions are further used in the new DTC to cancel the long dead times that usually exist between the disturbance and its effect on the output. Consequently, the control actions taken counteract the effect of the disturbances before they can appreciably change the output. In this fashion, the conventional DTC is extended to encompass features of feedforward controllers without the employment of separate controllers. This leads to significant improvements in the regulation properties while the servomechanism properties of the conventional DTC are clearly preserved, and the sensitivity to modeling errors is unaltered.

The modified DTC is quite flexible. It is possible to design it for partial DT cancellation rather than for full cancellation. In some cases further improvement may be achieved in this fashion. The degree of cancellation may be considered as a

design parameter to be determined either analytically or by simulation according to requirements, as is demonstrated in the paper.

In retrospect, the modification suggested seems to be quite straightforward since almost all the necessary elements are already present. The main difference lies in the need to measure the disturbance, exactly as is done in feedforward control. Although the same process model is realized in both schemes, it has been shown that the realization in the new scheme is in general more restricted, since the point of entrance of the disturbance and the relative distribution of the various dead times must be reflected in the realization.

In summary, the modification described enhances the regulation capabilities of the conventional DTC, in that it eliminates the need for a separate feedforward controller in many circumstances under which one might normally be employed.

INTRODUCTION

The control of processes with significant dead times between inputs and outputs has been a long-standing problem in process control. A way to improve the control under these circumstances is to incorporate the Smith (1957, 1959) dead-time compensator (DTC) in the control scheme. Many simulation and experimental studies (Lupfer and Oglesby, 1962; Buckley, 1960; Nielsen, 1969; Garland and Marshall, 1974; Meyer et al., 1976; Ross, 1977; Alevisakis and Seborg, 1974; Ioannides et al., 1979, for example) have demonstrated the potential improvement of the DTC over conventional controllers. The DTC has been extended to multivariable systems with single dead time (Alevisakis and Seborg, 1973, 1974) and with multiple dead times (Ogunnaike and Ray, 1979). It has also been shown that optimal steady-state stochastic control laws for processes with dead times include the DTC (Palmor and Shinnar, 1979; Palmor 1982).

Despite the remarkable improvements offered by the DTC, there has been some controversy regarding the success of its application, mainly due to the common practice of tuning and designing the dead-time-compensated primary controller for the seemingly equivalent system in which dead time does not exist. This practice has been shown (Palmor, 1980) to be inadequate and misleading since the stability and sensitivity properties of the DTC can neither be detected nor analyzed through the seemingly equivalent system with no dead time. Based upon sensitivity properties, a design and tuning approach for these controllers has been proposed (Palmor and Shinnar, 1978, 1979). The special stability and sensitivity features of systems incorporating DTC controllers have been quantitatively analyzed, and theoretical means by which those properties and allowed modeling errors can be estimated have been derived (Palmor, 1980). One important property shown in that reference is that improper design of the DTC may lead to a practically unstable system (i.e., a system which is asymptotically stable when perfect models are assumed, but which loses stability for infinitesimal modeling errors).

While the servomechanism properties of conventional controllers are significantly enhanced by the addition of the DTC, the improvement in the regulatory properties due to the DTC does not appear to be prominent. This topic is discussed and analyzed in this paper. We show that the DTC has the potential capability to achieve a remarkable improvement in compensating for load or input disturbances, but this capability has never been utilized.

A very minor modification in the DTC scheme is required. In fact, what is needed is to transmit the measured disturbance into the proper places in the DTC. By so doing the DTC, as will be shown, exhibits simultaneous feedforward and feedback actions.

THE CONVENTIONAL DTC CONTROLLER AND ITS REGULATION PROPERTIES

A common scheme of a feedback control system containing a DTC-based controller is shown in Figure 1. $G_p(s)$ is the overall process transfer function which is assumed to consist of a rational part $G_{po}(s)$ and a dead time θ (i.e., $G_p(s) = G_{po}(s)e^{-\theta s}$). $G_p(s)$ is composed from $G_{p1}(s)$ and $G_{p2}(s)$ where each contains a rational transfer-function and a dead time. Thus, $G_{p1}(s)$ and $G_{p2}(s)$ are given by:

$$G_{p1}(s) = G_{p1o}(s)e^{-\theta_1 s} \tag{1a}$$

$$G_{p2}(s) = G_{p2o}(s)e^{-\theta_2 s} \tag{1b}$$

such that

$$G_{p1o}(s)G_{p2o}(s) = G_{po}(s) \tag{2}$$

and

$$\theta_1 + \theta_2 = \theta. \tag{3}$$

$H(s)$ is the overall transfer function of the elements in the feedback path, which typically includes a sensor and in many cases in process control, a lead network. If $H(s)$ contains a dead time it is written as

$$H(s) = H_o(s)e^{-\theta_3 s} \tag{4}$$

The DTC-based controller combines a primary controller $G_{co}(s)$ and a feedback path as shown in Figure 1, where $\hat{G}_{po}(s)$ is a model of $G_{po}(s)$, $\hat{H}_o(s)$ is a model of $H_o(s)$ and $\hat{\bar{\theta}}$ is an estimate of $\bar{\theta} = \theta + \theta_3$. If $H(s)$ is under the designer control, then $\hat{H}(s)$ and $H(s)$ are sensibly identical, and in many cases the same H is shared by both feedback paths.

The models in the feedback path of the DTC-based controller are used to predict the effect of the input u on the process during the dead time, and this prediction is deducted from the actual error e. Thus, the signal flowing to the primary controller is the error caused directly by its own actions. In this fashion the overcorrections usually associated with conventional controllers operating on processes with large dead time are eliminated, higher gains are allowed and improved control obtained. The structure of the DTC leads, under ideal circumstances (perfect models), to the elimination of the dead time from the characteristic equation. This led many practitioners, as well as theoreticians, to base the design and tuning of the DTC on the seemingly equivalent system with no dead time. The incorrectness of this approach has been pointed out (Palmor and Shinnar, 1978; Garland and Marshall, 1974), and the special sensitivity and stability properties induced by the structure of the DTC have been analyzed (Palmor, 1980).

Despite these properties, it is generally recognized that DTC-based controllers offer significant improvement in the control of processes having large dead times, but these controllers cannot be designed and tuned using conventional methods.

Considering again the conventional scheme in Figure 1 and assuming no modeling errors, the effect of the disturbance d on the output y is given by:

$$y(s) = \left(1 - \frac{G_{co}(s)G_{po}(s)H_o(s)e^{-\bar{\theta}s}}{1 + G_{co}(s)G_{po}(s)H_o(s)}\right) G_{p2}(s)d(s) \tag{5}$$

From Eq. 5 it is clearly seen that due to the DTC, higher gains may be employed since all dead times were eliminated from the characteristic equation. (Although the disappearance of the dead times from the characteristic equation occurs only in theory, it has been shown—Palmor and Shinnar, 1978—that higher gains may be used despite modeling errors.) On the other hand, it is noticed from Eq. 5 that the control action begins influencing the output $\theta_1 + 2\theta_2 + \theta_3$ units of time after the disturbance occurs. This is because the disturbance d must change the output y before any corrective action by the primary controller is taken. In this respect the DTC-based controller is similar to conventional feedback con-

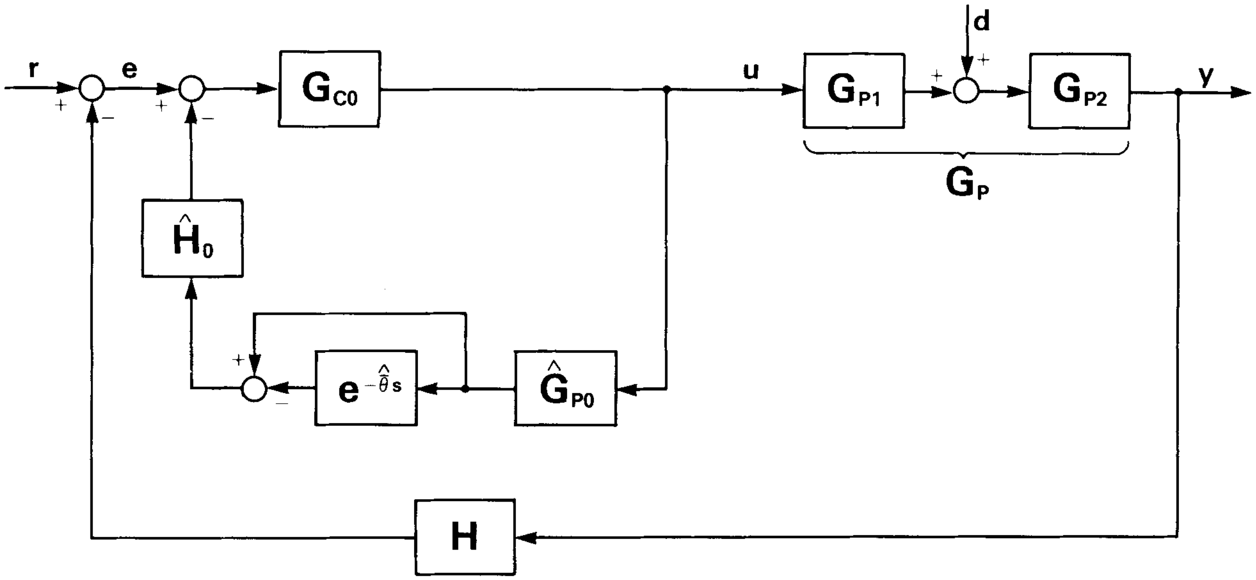

Figure 1. Block diagram of conventional DTC.

trollers. We show in the next section that by exploiting the special properties of DTC controller this situation can be significantly improved.

THE MODIFIED DTC

The capability of the DTC to predict the effect of the primary controller actions on the output long before they change it is effectively utilized in the conventional scheme. This leads, as mentioned previously, to the theoretical elimination of the dead time from the characteristic equation, which in turn allows tighter control to be used, resulting in improved servomechanism properties. This is because setpoint changes are transmitted with no delay to the primary controller. On the other hand, a dead time of $\theta_2 + \theta_3$ (see Figure 1) exists between the disturbance d and the primary controller, leading to a retarded control action and to a less significant improvement due to the DTC. However, this long delay may be eliminated if the existing process model in the conventional DTC is further exploited to predict the effect of the disturbance d on the output. To achieve this, the signal carrying the measured disturbance must be transmitted into appropriate points in the DTC. These points in turn depend on the point of entrance of the disturbance into the process and on the relative distribution of the dead times in the system.

The general idea of the proposed modification is shown in Figure 2, where the process and the entering point of the disturbance are as in Figure 1. Since the disturbance enters the process between $G_{p1}(s)$ and $G_{p2}(s)$, the measured disturbance signal must be transmitted in an equivalent fashion into both the process model and the dead-time-free process model, as indicated in Figure 2.

The advantages of the modified DTC can be best seen if the relations between the manipulated variable u and the disturbance d in both the conventional and the modified DTC schemes are

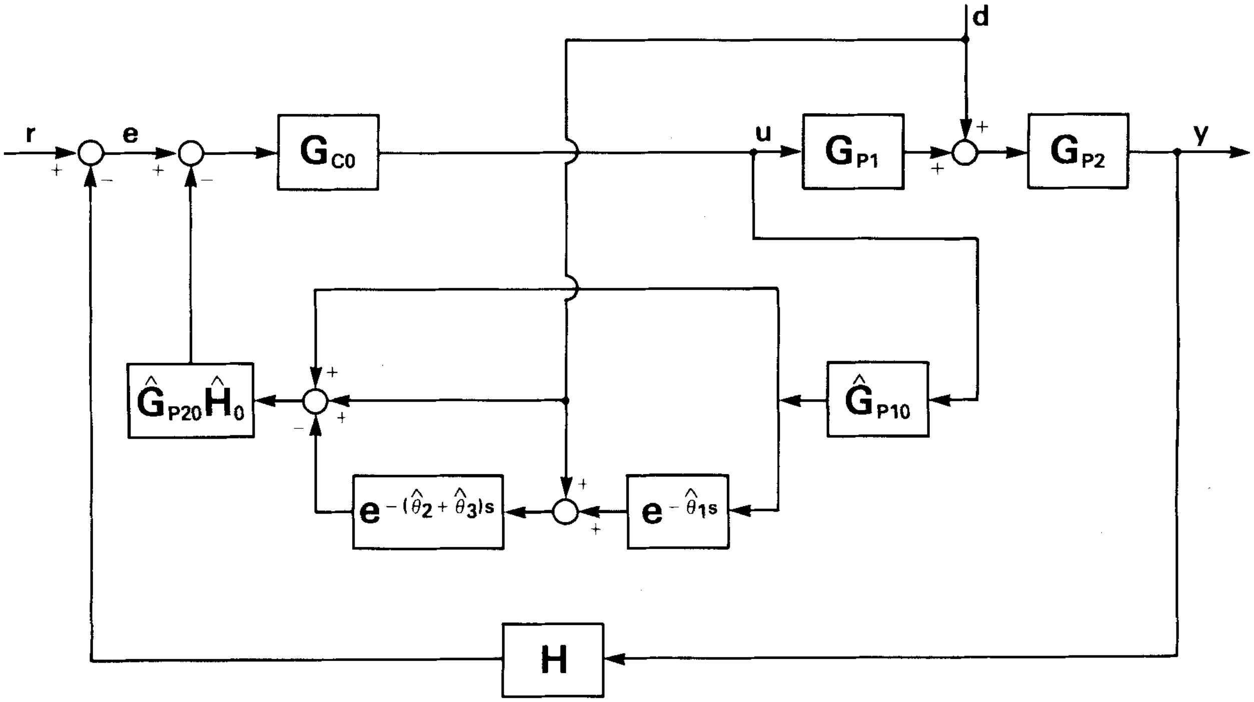

Figure 2. Block diagram of modified DTC.

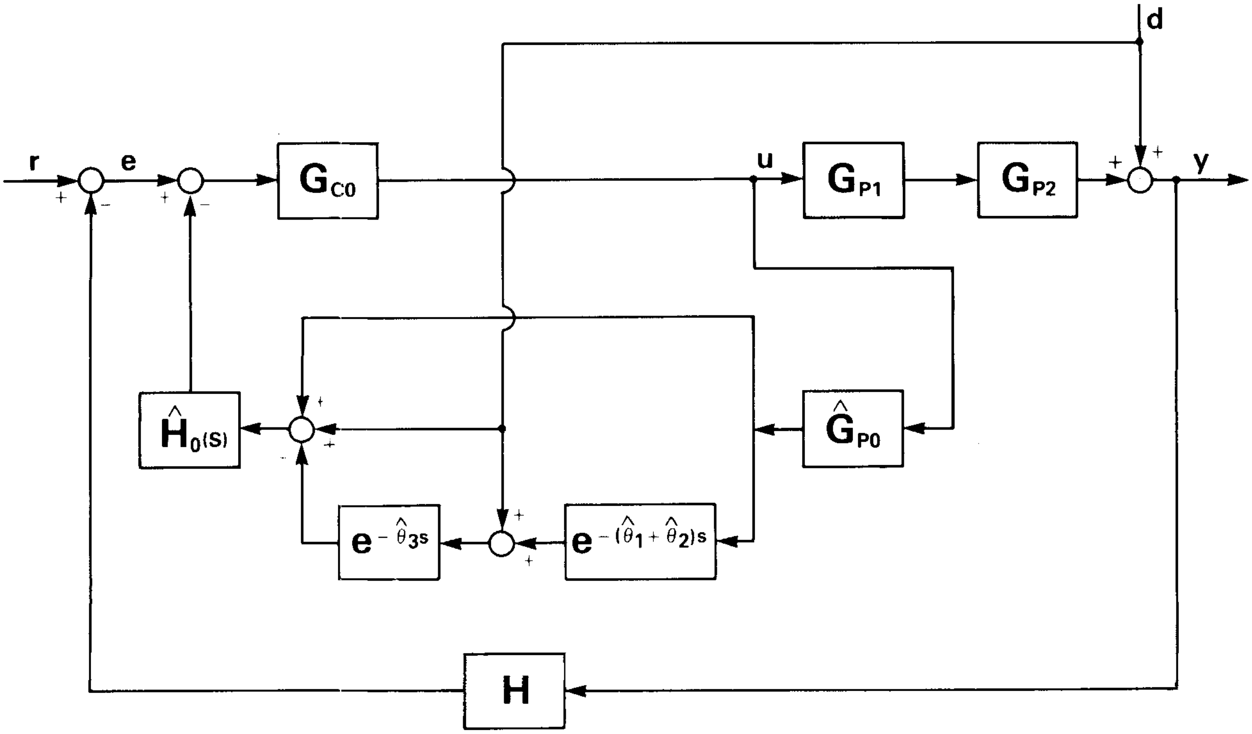

Figure 3. Block diagram of modified DTC with output disturbances.

compared. Denoting the manipulated variables in the conventional and modified schemes by u_c and u_m, respectively, we have:

$$u_c(s) = -\frac{G_{co}(s)G_{p2o}(s)H_o(s)e^{-(\theta_2+\theta_3)s}}{1 + G_{co}(s)G_{po}(s)H_o(s)}d(s) \qquad (6)$$

and

$$u_m(s) = -\frac{G_{co}(s)G_{p2o}(s)H_o(s)}{1 + G_{co}(s)G_{po}(s)H_o(s)}d(s) \qquad (7)$$

and it is evident that the dead time $\theta_2 + \theta_3$ by which the control action is delayed in the conventional scheme is effectively cancelled. By counteracting the effect of the disturbance before it can appreciably change the output, the modified DTC behaves in a manner similar to that of a conventional feedforward controller. Thus, this scheme adds a new dimension to the DTC, namely that of feedforward compensation.

The transfer function relating y to d in the modified scheme is given by:

$$y(s) = \left(1 - \frac{G_{co}(s)G_{po}(s)H_o(s)e^{-\theta_1 s}}{1 + G_{co}(s)G_{po}(s)H_o(s)}\right)G_{p2}(s)d(s) \qquad (8)$$

Thus, the effect of the control on the output is delayed by only $\theta_1 + \theta_2$, which is shorter by $\theta_2 + \theta_3$ than the corresponding dead time in the conventional scheme. Furthermore, the delay between the effects of the disturbance and the control in the modified scheme is only $\theta_1 + \theta_2 + \theta_3$. In cases where $\theta_1 = 0$, the effects of the control and the disturbance appear at the output at the same time. The larger the dead time $\theta_2 + \theta_3$ as compared to θ_1, the better the potential improvement offered by the modified scheme becomes. While these relations, however, are suitable for the configuration in Figure 2, a more general criterion for the potential improvement of the modified DTC can be developed.

If θ_{d-e} denotes the overall dead time from the point of entrance of the disturbance to the error e, and θ_{u-d} denotes the dead time from u to the point of entrance of d, such that $\theta_{d-e} + \theta_{u-d} = \overline{\theta}$, then it can be stated that the modified scheme effectively reduces the dead time between the control and its effect on the output by θ_{d-e}. Therefore, the larger the ratio $\theta_{d-e}/\theta_{u-d}$, the more significant the improvement becomes.

Except for the measuring element needed in the modified DTC, no additional elements or models are required. The realization of the DTC is however affected, as can be seen by comparing Figures 1 and 2.

This realization depends on the entering point of the disturbance and the distribution of the various dead times. To illustrate this point, another modified scheme is shown in Figure 3. In this case, the disturbance enters at the output, and this is directly reflected in the realization of the process model in the DTC.

It is worthwhile noting that with regard to stability, both the modified and the conventional schemes have the same sensitivity to modeling errors. Therefore, all the stability and sensitivity results derived previously (Palmor, 1980) apply to the new scheme as well.

To demonstrate the advantages of the modified scheme, an illustrative example comparing the performance of the new scheme with the conventional one and with PID control is given.

Example 1. The scheme shown in Figure 2 is considered. The following process transfer functions were taken:

$$G_{p1}(s) = \frac{1}{s + 1} \qquad (9a)$$

$$G_{p2}(s) = \frac{e^{-s}}{s + 1} \qquad (9b)$$

$$H(s) = e^{-0.2s} \qquad (9c)$$

The primary controller in both DTC schemes was taken to be:

$$G_{co}(s) = \frac{k(s + 1)^2}{s} \qquad (10)$$

which is an ideal PID controller. The value of 3 has been chosen for the gain k. This value is quite conservative. The PID controller with no DTC has been tuned by the Ziegler-Nichols tuning method.

The remarkable improvement achieved by the modified DTC is shown in Figures 4 and 5. In Figure 4 the responses to a unit step change in the disturbance d is depicted, and in Figure 5 the responses to simultaneous unit step changes in both the setpoint and the disturbance are shown. From Figure 4 it is clearly seen that while the conventional DTC achieves faster and smoother response

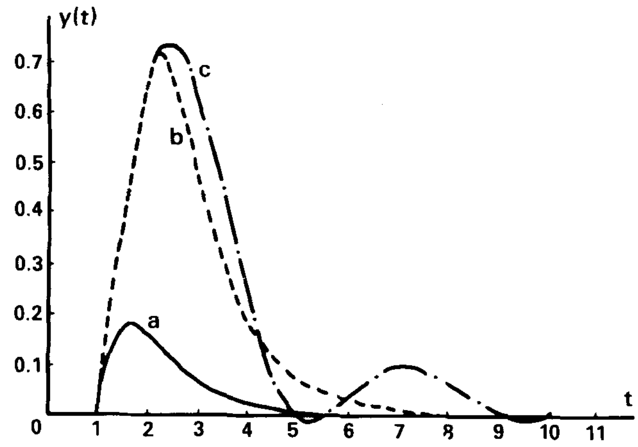

Figure 4. Response to unit step change in *d* of (a) modified DTC, (b) conventional DTC, and (c) ideal PID controller.

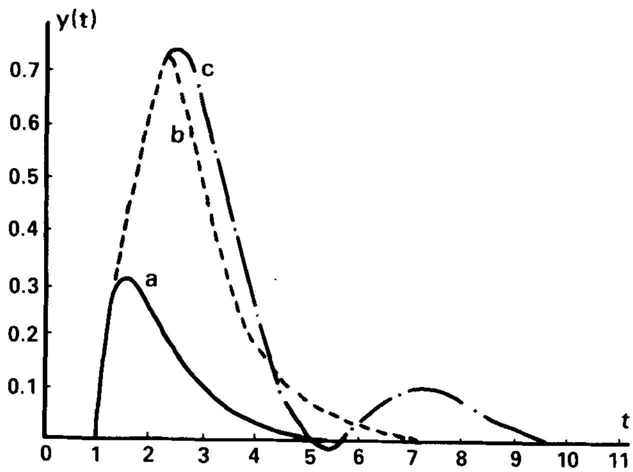

Figure 6. Responses to unit step change in *d* (process as in Figure 4, with $\theta_1 = 0.2$ and $\theta_3 = 0$).

with no overshoot as compared to that of the PID, the improvement gained by the modified scheme is tremendous. With the conventional scheme, the maximum amplitude of the error in this example is 0.73, and the settling time (error of 5% or less) is 5.5 units of time. The corresponding values with the modified DTC are 0.18 and 3.2 respectively. The advantage of the modified scheme is even more prominent, and its capability to provide simultaneous feedback and feedforward actions is evident, when the system undergoes simultaneous setpoint and load changes as shown in Figure 5. Also note that the improvement of the conventional DTC relative to the PID control is considerably better with respect to setpoint changes than for load changes, as previously discussed.

The advantages of the modified scheme in this case is to be expected since the distribution of the various dead times leads to the ratio $\theta_{d-e}/\theta_{u-d} = (\theta_2 + \theta_3)/0 \rightarrow \infty$. Another case with a finite ratio is considered next. The configuration is again the one given in Figure 2; the process transfer functions are as in Eq. 9, but with $\theta_1 = 0.2$ and $\theta_3 = 0$, and the controllers are as in the previous case. Thus, the ratio $\theta_{d-e}/\theta_{u-e}$ is 5. Therefore, a less prominent improvement is expected. In Figure 6 the responses to unit step change in d are shown. While the maximum error in this case is 0.3, it is still much better than that obtained by the conventional DTC.

In Figure 7, the effect of modeling errors is examined. The system considered is the one investigated in Figures 4 and 5. An error of approximately 17% in θ_2 is assumed. That is, $\hat{\theta}_2$ in the process model is estimated to be 1, while the real θ_2 is 1.2. Although the underestimation of θ_2 has some effect on the response, as is seen in Figure 7, the basic features stay unchanged and the response obtained by the modified DTC is by far better than that of the conventional DTC.

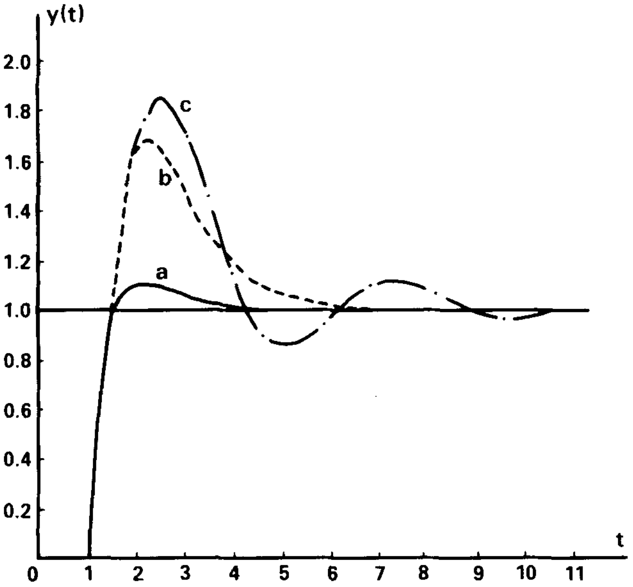

Figure 5. Responses to simultaneous step changes in setpoint and in disturbance (notation in Figure 4).

PARTIAL CANCELLATION OF DEADTIMES

The improved regulatory properties of the modified scheme come primarily from its advanced control actions as reflected in the cancellation of θ_2 and θ_3 in u_m (Eq. 7). The scheme presented so far attempts to eliminate from the control actions all the dead times between the disturbance and the measured output. This might not always be the best strategy. In some cases further improvements may be achieved with partial rather than full cancellation and the modified scheme can be easily extended to cope with such situations. One such case arises, for example, in the presence of a dead time between the points of measurement and entrance of the disturbance. This dead time denoted by δ, as well as the corresponding modified scheme for partial cancellation in such cases, is shown in Figure 8. δ' denotes the uncancelled portion of δ and is considered to be a design parameter. When $\delta' = 0$ a full cancellation takes place. That is, a dead time of $\theta_2 + \theta_3 + \delta$ is eliminated in the corresponding u_m. On the other hand, when $\delta' = \delta$, no cancellation is attempted. A partial cancellation occurs

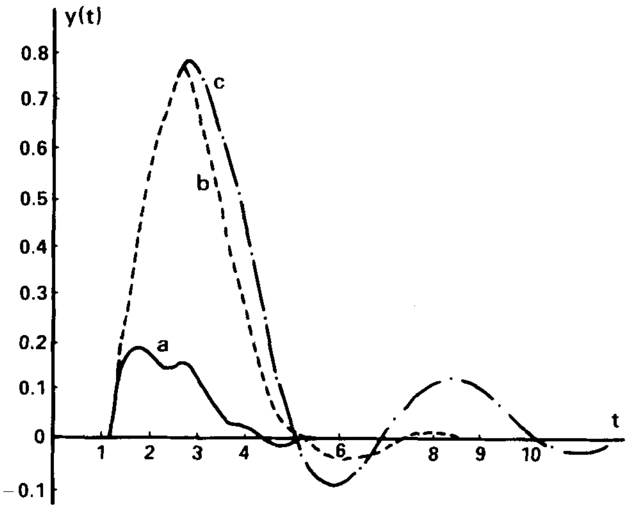

Figure 7. Effect of underestimation of θ_2 on responses shown in Figure 4 ($\theta_2 = 1.2$, $\hat{\theta}_2 = 1$).

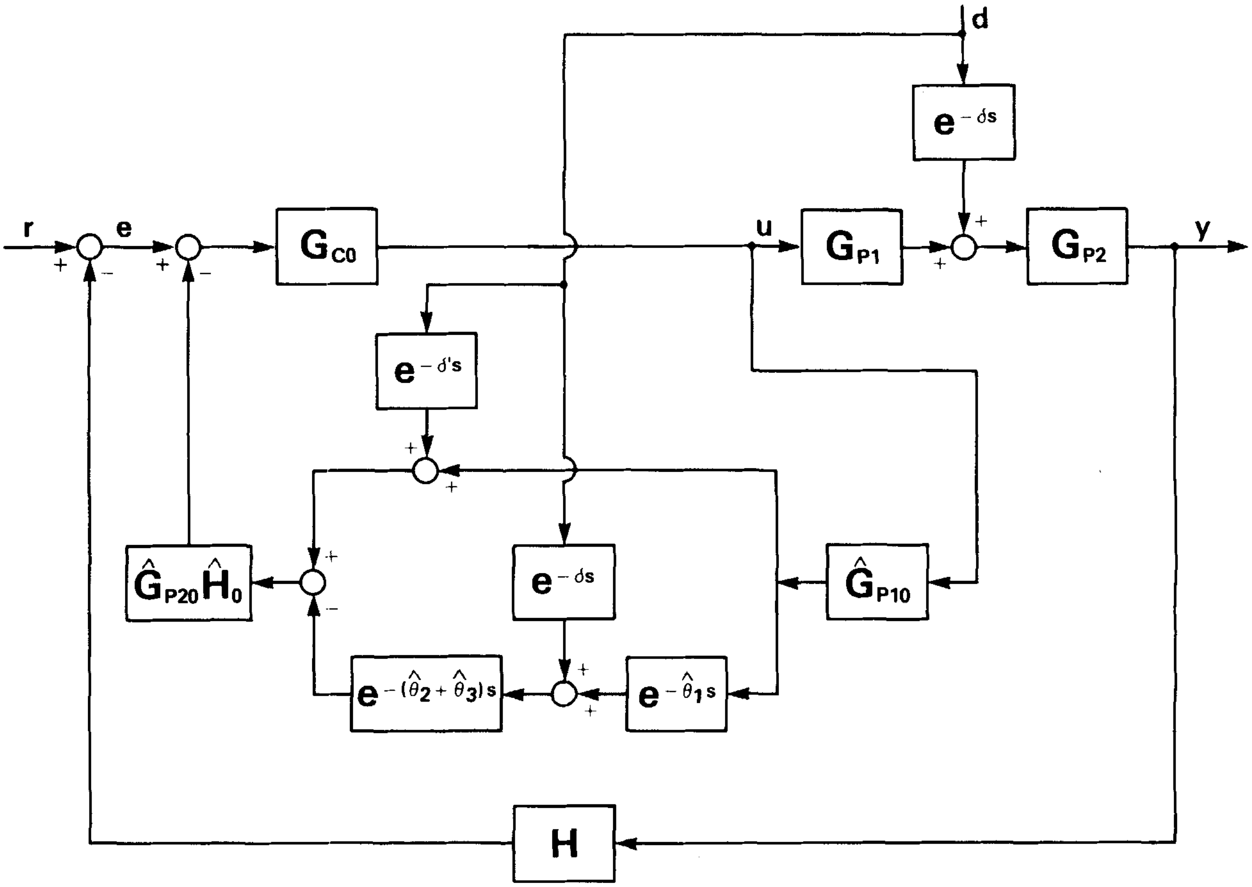

Figure 8. Modified DTC for partial cancellation of DT.

when δ' takes on any value in the range: $0 < \delta' < \delta$. The closed-loop transfer function from d to y for the scheme in Figure 8 is given by:

$$y(s) = \left[e^{-\delta s} - \frac{G_{co}(s)G_{po}(s)H_o(s)e^{-(\theta_1+\delta')s}}{1 + G_{co}(s)G_{po}(s)H_o(s)}\right] G_{p2}(s)d(s) \tag{11}$$

Equation 11 reveals that the disturbance and the corresponding control start affecting the output $\delta + \theta_2$ and $\theta_1 + \theta_2 + \delta'$ units of time, respectively, after the disturbance has occurred. Thus, when $\theta_1 + \delta' < \delta$, the compensating action of the modified scheme reaches the output before the disturbance does. If δ' is too short, the control may react too early and degrade the response. The larger the difference between δ and $\theta_1 + \delta'$, the longer the time by which the control precedes the disturbance. Depending upon the values of δ and θ, a proper choice of δ' may lead to further improvements in the regulatory properties of the modified scheme. This is demonstrated in the following example.

Example 2. The scheme shown in Figure 8 is considered. The transfer functions of the process, measuring device, and primary controller are as in example 1, Eqs. 9 and 10. Let δ be 0.5. Four responses to a unit step change in d, each corresponding to a different value of δ', are compared in Figure 9. When the scheme is designed for a full cancellation (i.e., $\delta' = 0$), the control starts affecting the output δ units of time before the disturbance reaches the output. In the other extreme, when $\delta' = \delta = 0.5$ (no cancellation of δ), both the control action and the disturbance reach the output at the same time. The response in this case is therefore identical to the one in Figure 4, but is delayed by the additional dead time, δ. A significant improvement in the case considered is achieved when δ' is set for partial cancellation as is seen in Figure 9. While the modified scheme with $\delta' = 0.25$ leads to much smaller amplitudes in both directions, the one with $\delta' = 0.19$ minimizes the integral square error (ISE), as will be shown next.

Example 2 demonstrates that by considering δ' as a design parameter, the designer gains control over the shape of the response through the time by which the compensating action precedes the corresponding effect of the disturbance. The problem of choosing an appropriate value of δ' can be resolved in various ways. It can be based on simulations. Performing several simulations of the type done in example 2 usually suffices. Or, it can be found analytically. One may define a suitable performance index, for example the ISE, and minimize it with respect to δ' as is done in the next example.

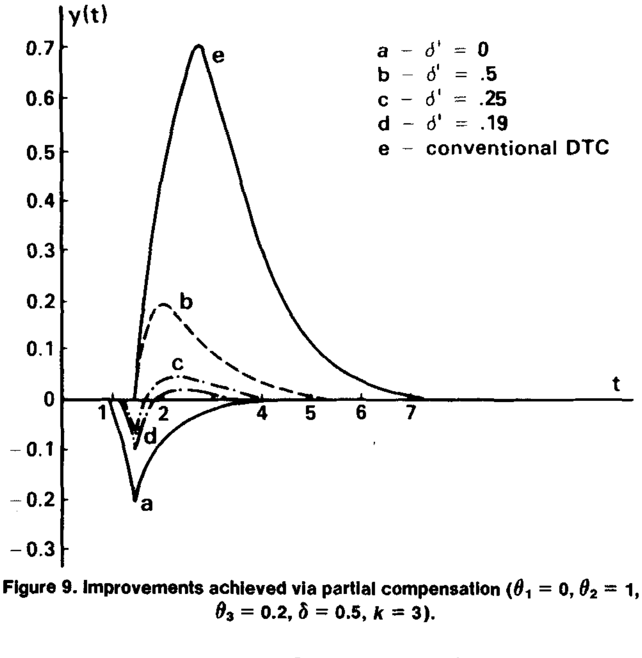

Figure 9. Improvements achieved via partial compensation ($\theta_1 = 0, \theta_2 = 1, \theta_3 = 0.2, \delta = 0.5, k = 3$).

Example 3. The system and the modified DTC are as in example 2. We wish to find the value of δ' which minimizes the following criterion:

$$I = \int_{t_0}^{\infty} y^2(t)dt \tag{12}$$

where the disturbance $d(t)$ is a unit step change occurring at t_0. By Parseval's theorem, Eq. 12 becomes

$$I = \frac{1}{2\pi j}\int_{-j\infty}^{j\infty} y(s)y(-s)ds \tag{13}$$

Substituting $y(s)$ from Eq. 11 into Eq. 13 and performing the integration by the residue theorem we obtain

$$I = \frac{25}{24} + (1-\delta') + \frac{3}{2}e^{-(1-\delta')} + \frac{1}{12}e^{-3(1-\delta')} \tag{14}$$

The value of δ' (in the range $0 < \delta' < 0.5$) which minimizes I in Eq. 12 is easily found and is approximately $\delta' = 0.19$. The response corresponding to this value of δ' is shown in Figure 9 (curve d) and is much better than the responses in curves a and b.

NOTATION

d = disturbance
e = error signal
G_{co} = main controller transfer function
G_p = process transfer function
G_{po} = invertible part of G_p
H = feedback transfer function
I = performance index
r = setpoint
s = Laplace variable
u_c = manipulated variable in the conventional scheme
u_m = manipulated variable in the modified scheme
y = output

Greek Letters

δ = dead time between measurement and entrance of disturbances
δ' = uncanceled portion of δ
θ = dead time
$\bar{\theta}$ = overall loop dead time

Superscript

$\hat{A}$ = model or estimated value of A

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