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Discrete Stochastic Optimal Control

and Direct Digital Control of a Process

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DISCRETE STOCHASTIC OPTIMAL CONTROL AND DIRECT DIGITAL CONTROL OF A PROCESS

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1 INTRODUCTION

In controlling industrial processes, factors that have to be confronted often include random variations in operating parameters and the effects of external disturbances. These issues are compounded when there is a significant pure time delay or dead time in the process. In addition, the inability of a process to adapt to an adjustment plays a part in its effective operation. In this report, we discuss the need to identify the dead time and the effects of the system *dynamics* (inertia) (explained subsequently) while attempting to control the process. A brief description of *direct digital control* (**DDC**) and justification for using it are presented. Some methods to compensate for dead time by means of direct digital control are also discussed as are the effects of dynamics (inertia).

2 Self-tuning (adaptive) Control

Measurement on-line and control problems of system identification (estimation[1]) *a priori* are connected in the formulation (design) of 'self-tuning'

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[1] The terms 'identification' and 'estimation' are synonymously used by some authors. See, in this connection, Marshall [1985].

(*adaptive*) controllers. By modelling, it is possible to apply the principles of prediction to the disturbances in order to improve control. Methods to deal with the problems of identification of systems afflicted by disturbance on-line give estimates recursively for use in adaptive controllers.

Methods which involve parameter estimation (identification) of processes for which the parameters change slowly with time result in adaptive control. Time-delay control systems benefit from improved process modelling. Control systems combining estimation techniques and use of minimum variance controllers are called 'self-tuning' (adaptive) controllers. Self-tuning (adaptive) control schemes favour recursive methods of estimation. Simultaneous estimation of parameters and on-line control may not be possible without digital computation since quick computer solutions are required for adaptive control. Process regulation schemes involving recursive techniques can be programmed using micro-processors. One way to automate modelling and design of self-tuning regulators is by (i) determining suitable models, (ii) estimating model parameters recursively and (iii) using estimates to calculate the control rule. A regulator (controller) with facilities for tuning its own parameters is called a 'self-tuning regulator'. Such regulators can also assist control by suitably altering algorithms to track process parameters which change with time.

3 Background and Development of Discrete Stochastic Optimal Control Theory

Stochastic control theory provides a means to explore the common interface and the area of overlap between on-line quality control methods of SPC and APC (MacGregor [1988]). Any on-line control logic should be based on knowledge about the nature of disturbances and the nature of the process. Process knowledge is necessary in order to best decide how to respond to observed upsets that occur in a process due to unexpected disturbances. Knowledge about the nature of the disturbances is necessary to detect 'out-of-control' situations and to estimate the true levels of the output deviations from the required targets.

In recent times, suggestions made to superimpose statistical process monitoring on closed-loop (feedback) control systems have opened new lines of research in quality improvement. MacGregor [1988] drew attention to the overlap between SPC and APC which occurs when (i) control actions have their full effect on the process outputs in the immediately succeeding periods, (ii) process disturbance is modelled as a first-order *integrated moving average* process (IMA), (iii) a fixed cost is associated with taking any nonzero control action, and (iv) additional costs are assessed in proportion to the *squared deviation* of the outputs from the required target. There are situations in the process industries, when control actions ('adjustments') have little or no effect on the process outputs in the immediately succeeding periods due to dead time and dynamics (inertia).

The performance of an *(optimal) stochastic minimum variance controller* depends upon the stochastic models assumed for the disturbance. A 'sampled-data' (discrete) control system is a continuous system, sampled periodically and followed by a sequence of 'discrete control' actions. Examples of sampled-data systems are found (i) in power electronics and (ii) in signal transmission in biological nervous systems.

In discrete control systems, time delays are integral multiples of the sampling period (known as the 'clock period'). *Univariate stochastic control theory* based on simple discrete time series dynamic (transfer function) models for the process and its disturbances, leads to digital control algorithms which include the classical PID (proportional, integral and derivative) terms containing *dead time compensation* features. Palmor and Shinnar [1979] gave a set of rules to choose the parameters of *discrete controllers* with dead time compensation. For this purpose, they used the structure of the form of stochastic controller proposed by Box and Jenkins [1970,1976] (Harris, MacGregor and Wright [1982]).

4 DIRECT DIGITAL CONTROL (DDC)

4.1 Background of the application of Digital Computers to Process Control

Use of automation techniques in industry make it possible to apply digital computer capabilities for solving process control problems. It has been established that it is easier to design and use computer based (adaptive) controllers incorporating tuning tools than designing adaptive controllers by other methods (Astrom and Wittenmark [1984]).

The control of a process with a computer requires (i) that the computer inputs and outputs are compatible with the plant's outputs and inputs with operational flexibility and a degree of control and (ii) the computer has a large storage capacity, high speed, appropriate command and word structure and versatility in handling software (Patranabis [1981]).

4.2 Digital Control history and the concept of Direct Digital Control (DDC)

The application of digital computers in on-line automatic process control (APC) to make quick computations started in the late fifties. In processes monitored by digital computers, the output is measured and the input is changed only at discrete intervals of time. Computer based controllers incorporating tuning tools appeared in the mid-eighties for use in the process industries. The use of digital computers permits and makes possible the solution of complex algorithms in practice.

The development and growth of digital computer capabilities changed the practice of discrete stochastic process control theory in industry by applying these capabilities to increase profitability. Direct digital control (DDC) is the term used for controlling processes directly by computers. DDC offers advantages such as flexibility to change the computer-controlled systems. DDC systems focus on the basic control functions such as problems relating to choice of sampling period, ('The time interval between observations in a periodic sampling control system'), control algorithms and reliability of processors. The development of digital computer technology and the matching of process-control computer requirements with progress in integrated circuit technology resulted in small, fast, reliable and cheap computers. It made possible also design of process-control systems by using minicomputers.

4.3 Direct Digital Control (DDC)

In traditional (conventional) feedback (analogue*) control systems, a measuring system senses the value of the output controlled variable and transmits a message, dependent on it, to its controller. The controller compares this value with the value of the controlled variable desired, or an input variable which sets the desired value of the controlled variable, (called the *set point),* so as to generate a deviation, (called the error). The controller acts on this error to produce a control signal. This signal is then fed to a final control element to reduce the error. (*An analogue system is one in which the data are everywhere known or specified at all instants of time and the (input,output) variables are continuous functions of time).

In sampled-data (discrete) digital control systems, in contrast to conventional analogue control systems, discrete signals represent information by a set of discrete values in accordance with a prescribed law and the (input ,output) variables are sequences of numbers known only at sampling instants.

In a basic sampled-data (discrete) control system, the electrical signal represents the output controlled variable. It is fed to a device called an *analogue-to-digital converter*, where it is sampled, the sampling period, (called the 'clock period' in digital computer terminology), being a constant in process control applications. The value of the discrete signal produced is compared with the discrete form of the set point in the digital computer to produce an error. A computer programme representing the controller called a control algorithm is executed yielding a discrete controller output. This discrete signal is then converted to an electrical signal by another conversion device called a digital-to-analogue converter and is fed to a final control element. The control strategy is repeated so as to achieve closed-loop (feedback) computer control of the process. This is a primary type of sampled-data (discrete) computer-control technique, referred to as *direct-digital computer control.* In a sampled-data (discrete) control system, the analogue controller in a conventional control system is replaced by a digital computer and the control action produced by the controller in the feedback (closed) loop is initiated by the computer programme. The feedback controller is a *special-purpose analogue* computer used in the direct digital discrete (sampled-data) control of production processes. Digital computers collect data about a process and its operating conditions automatically. The information associated with a plant's operation also gives details about the product produced by the plant, its reliability and specifications. By using digital techniques in process control of some time-delay models, it is possible to achieve the objectives for sampled-data (discrete) digital control (DDC).

4.4 Justification for the use of DDC

The use of digital controllers offers advantages such as (i) making available a wider selection of process control algorithms than in analogue controllers, (ii) faster calculations, (iii) logic capabilities both at the controller input and the output, (iv) on-line restructuring of (control) loops and (v) adaptive-control features. A factor in justifying computer control for a given application is the number of conventional controllers that are to be replaced by digital computers. A possible justification for computer control may come from better process control performance. The computer needs to be used to automate functions and operations that could not be automatically accomplished earlier. By exploiting the capabilities of the computer and by the use of DDC hardware systems, concepts and techniques such as feedforward control, dead-time compensation and optimal control can be implemented.

Control strategies can be implemented that are otherwise impractical or impossible with conventional analogue hardware. The availability of control computers makes possible a hybrid approach to process control which involves both digital and analogue capabilities. The implementation of control strategies is achieved by leaving those (feedback) loops with conventional analogue control systems where feedback control is envisaged and employing direct digital control (DDC) only for those process loops in which there can be significant improvements in control performance.

5 DEAD TIME OR TIME DELAY

5.1 The need to identify Dead time

For a time series controller, if the best achievable performance is not adequate enough to provide minimum variance control, alternate approaches such as feedforward control and other similar measures may be adopted to achieve a reduction in product variability (control error standard deviation). Identifying and minimising dead time in production processes is one of these measures. *Dead time* is the property of a production system by which the response to a control adjustment is delayed in its effect. It is 'the interval of time between initiation of an input change and the start of the resulting observable response'. This dead time occurs when process materials move from one processing stage to another without any change taking place in the properties or characteristics of the processed materials. Such delays are caused by flow of liquids or gases through pipes.

Dead time causes difficulties in satisfactory control of processes by sluggish response to control actions. A (time) delay makes for less satisfactory control so that every effort must be made to reduce it. Time delays are created by sampling systems. If inevitable delay occurs which is several time periods in duration, it may be necessary to decrease the frequency of taking process samples. When pure delays occur, sampling at periods which are much shorter than the delay period may not serve any useful purpose. An effective manner of improving process control is to reduce or eliminate the (feedback) dead time since a feedback control strategy alone by itself cannot return the process output to its target value until the process dead time or time delay has elapsed.

A feedback controller applies corrective action to the input of a process based on the present observation of its output. In this way, control action is moderated by its effect on a process. A process containing dead time does not produce any immediately observable effect and thereby delays control action. The delay produces a change* in slope of the input-output curve and this property becomes an essential consideration in feedback loops characterised by the behaviour of the critical quality variable (during transition between two steady states). In view of this, feedback control-system design techniques must be capable of identifying and dealing with dead time (*called 'phase shift' or 'span shift' in control theory terminology). A time delay is significant over long distances in remote control systems and in processes which involve complex chemical reactions.

5.2 Sampled-data (Discrete) Control Systems and Dead time

There is a connection between sampled-data (discrete) control systems and delays because sampled-data techniques involve the use of storing or holding and releasing information when required, which is a delay process. Systems involving the use of digital computers in process control rely on the use of stores of memory. Reliable storage or holding of data is the delay between the input or the calculation and the output at some multiple of the clock period later. Sampled-data techniques enable algorithms to be used in numerical analysis (digital computing methods). Formulation of a process control problem by sampled-data enables a solution to be found whereas it is difficult to analyse the corresponding continuous(-time) control problem. The characterisation of disturbance in continuous time is difficult to treat in a rigorous fashion; but this is not the case when viewed from a sampled-data view point, when the requirements of the need to design controllers by digital computing techniques are met based on certain minimum assumptions. Smith [1957] prediction techniques and its extensions are capable of using digital computing (numerical) methods. In complex processes in which there are lags as in chemical engineering plants, an assumption convenient from a modelling point of view is to replace the accumulation effects of these lags by a single time delay.

5.3 IDENTIFICATION OF DEAD TIME

For satisfactory operation of a process which contains an element of pure time delay, it is necessary to ensure that the process should not be affected by parametric variations or extraneous noise (disturbance). Suitable (feedback) 'control strategies' may be employed to minimise the effects of external disturbance and variations in the process parameters. An appropriate (feedback) control strategy for a process containing an element of time delay, is to assume a dynamic model which adequately represents the process that it is required to control. As the system operates, this model should be capable of tracking any variations in the parameters of the process. Thus a process must be identified continually and the parameters of the model adapted accordingly. Identification of a process consists of deriving a suitable form for the model and fitting it with the required parameters. The form of the model and the initial values for it are determined beforehand and as the process operates, it is usual, in practice, to determine the changes in parameters. For this purpose, it is often found suitable to fit an ARIMA (0,1,1) time series model for the process.

Despite advances made in techniques for controlling systems which contain an element of dead time, the best solution is to eliminate it, if at all possible (Buckley [1961]). This remark is made in view of the attendant problems dead time creates. Having discussed the dead time and its characteristics, focus is now turned to other dynamic parameters of the process, namely, the dynamics (inertia) and r, the rate of drift.

6 THE ROLE AND CHARACTERISTICS OF INERTIA IN A PROCESS

The inertia is an important determinant of an optimal process control system. A control action applied to a process at time zero may not be fully effective until an elapse of some significant time due to the system dynamics (inertia). This is true in the process industries, where attempts to compensate for the disturbances, ignoring the dynamics, may lead to inappropriate control actions.

Consider the inertial properties of the feedback control equation

$$(1-\delta B)Y_t = \omega_0 X_{t-b} = g(1-\delta)X_{t-b} = g(1-\delta)B^b X_t \qquad 0 \leq \delta < 1 \qquad (1)$$

where there are both step and impulse changes to the input variable, X_t. After a finite incremental step response (or change) is made in the input X_t, the output variable, Y_t is affected immediately and asymptotically approaches the value of the gain of the system. The dynamic parameter δ governs the rate at which the asymptote is reached, being quick for values of δ near zero and slow when the value of δ approaches unity. Whereas for an impulse change in the input, the impulse response *tails off* exponentially from the initial value, $\omega_0 = g(1-\delta)$. This means that the gain is reduced from its initial value due to the inertia (dynamics) in the system. Refer to figure 10.6, page 349, Box and Jenkins [1970, 1976] for examples of impulse and step response functions.

A minimum variance feedback control scheme, when applied to a monitored process, may require excessive changes in the input variable. This may be due to (i) the parameter, δ, governing the dynamics (inertia) of the system being large in relation to the monitoring interval and (ii) there may not be any penalty associated with large adjustments. Kramer [1990] showed a method to evaluate the expected variance of the control actions (adjustment variance) by using the fact that minimum variance control generates deviations from target that are equivalent to the uncorrelated random shocks. The adjustment variance becomes larger as δ becomes closer to the value one. Since the dynamic parameter δ is a function of the monitoring (sampling) interval, it may be possible to reduce its inertial effects by lengthening the (monitoring) interval. However, as δ gets larger, the adjustment variance, can also be reduced by suitably lengthening the monitoring interval. This fact was substantiated by Kramer [1990] with arguments which led to the conclusion that altering the monitoring interval also changes the variance. Abraham and Box [1979] showed that the changes in IMA parameter Θ have small effects on the optimal control adjustment while it is considerably affected by changes in δ. A characteristic of the dynamic parameter δ is that it plays a minor role in the determination of the monitoring interval corresponding to an (allowable) increase in the mean square error deviation for minimum variance control, whereas the rate of drift of the process, r plays a dominant role. This is especially true when the value of δ is not near one as a result of the small bias resulting from the dynamic nature of the input-output relationship (Baxley

[1991]). In view of this, we discuss the role of the parameter r in making changes in the variance.

7 THE RATE OF DRIFT OF THE PROCESS 'r'

Consider the ARIMA disturbance process, z_t

$$z_t = \hat{z}_t + a_t \tag{2}$$

where $\hat{z}_t$ is an estimate of 'z_t ', which is independent of a_t and is an EWMA of the past data defined by

$$\hat{z}_t = r(z_{t-1} + \Theta z_{t-2} + \Theta^2 z_{t-3} + ...), \qquad 0 \leq \Theta < 1 \tag{3}$$

The coefficients $r, r\Theta, r\Theta^2$, ... in Equation (3) form a *convergent sequence* that sums to unity.

$$z_t = \hat{z}_t + a_t + r \sum_{i=1}^{t-1} a_i , \; 0 < r \leq 1 \tag{4}$$

In particular, if the process mean is set on target at time t = 1 by adjusting its level so that $\hat{z}_t = 0$. Then, the subsequent course of the deviations from the target is represented by

$$z_t = a_t + r \sum_{i=1}^{t-1} a_i , \; 0 < r \leq 1 \tag{5}$$

which is an interpolation between the sequence of uncorrelated random shocks, NID $(0,\sigma_a^2)$, of the stationary disturbance equation, $z_t = a_t$ for a process in a perfect state of statistical control with no drift obtained as r approaches the value 0 and the highly nonstationary *random-walk* model

$$z_t = \sum_{i=1}^{t} a_i , \tag{6}$$

obtained when r = 1.

Statistical process control charts can be considered an appropriate engineering control strategy under certain specific conditions. One of these is specifying a loss function that quantifies the cost of being away from the desired or target value and the cost of making an adjustment to a process. In light of optimal control theory and by using the quadratic criterion function, it is possible to derive minimum variance controllers. The principle employed in the quadratic loss function is that the penalty or loss associated with being off target and large adjustments depends only on the squared magnitude of the mean square error. The quadratic loss function so derived depends only on the absolute value of the standard deviation from target. The control adjustment equation of the MMSE (minimum mean square error) controller is the discrete equivalent of a properly *tuned integral* controller. This form of the minimum variance controller would minimise the mean overall adjustment cost when it is possible to neglect other variable costs. Apart from the process adjustment costs, if there are other costs in monitoring and controlling a process and in taking observations, then the resulting minimum-cost feedback adjustment schemes have to be formulated on the basis of different configurations.

8 SAMPLING INTERVAL AND DEAD TIME

8.1 SAMPLED-DATA (DISCRETE) CONTROL AND DEAD TIME

Process control schemes need to incorporate information regarding the process into the controller, that is, to have a process model (pure delay) built into the controller mechanism. This may be difficult to achieve since there may be some inaccuracies in process modelling and parameter estimation and besides, the process dynamics (inertia) itself changes, for example, the dead time (time delay) changes with transport velocity. Moreover, the pure dead-time element required for building the controller mechanism is not physically realisable; it has to be approximated and such approximations may result in high expenditure, special construction and inaccuracies in modelling (Chandra Prasad and Krishnaswamy [1975]).

So, in discrete (sampled-data) control systems, the value of the pure time delay of the process is assumed *a priori* information (which may change during the operation) of the process. The sampled-data (discrete) control is used to provide the plant operator with information about control actions (changes or adjustments) that should be taken to account for the plant dynamics (inertia) and the nature of the stochastic (random) disturbances.

8.2 SAMPLING AND FEEDBACK CONTROL LOOP PERFORMANCE

Sampling at periods which are much shorter than the time delay (dead time) is likely to result in poor control. A rational choice of sampling rate in sampled-data control must be based on its influence on the closed-loop (feedback) behaviour and also on the recommendations for the selection of the sampling rate. Sampling is economically advantageous where high production rates combine with relatively expensive or time-consuming measurements of individual items. Output-sampling is a practical necessity in the control of a large variety of continuous processes such as paper and sheet plastic and is essential where testing is destructive. In general, for most feedback control loops, as the sampling interval is decreased, the feedback control loop performance will improve, but at the same time, the effort necessary to accomplish this will increase (MacGregor [1976]). Since the control error variance often increases drastically for a decreasing sampling period, (relative to the time response of the process), MacGregor [1976] also introduced a variance constraint on the input manipulated variable. The effect of lengthening the sampling interval would be (i) to increase somewhat the mean square error and (ii) to reduce the cost of the feedback control scheme (Abraham and Box [1979]). Too large sampling periods mean deteriorated control performance and long time delays tend to reduce the controller gain (CG). So, there is a need for careful choice of the sampling interval.

Even when the sampling interval is larger than the time delay, the control achieved using a certain sampling interval may be unnecessarily 'tight' so that a less-frequent sampling interval is called for and there may be little economic incentive for such tighter control. Tighter control can reduce the stable operation of processes. However, there is a broad class of processes which require tighter control. These include quality variables in polymerization, sheet forming and fiber and other 'no blend' type processes (Harris and MacGregor [1987]) in which efforts are constantly made to control these variables as tightly as possible by minimising the variance of the output deviation about their given set-points (Kelly and MacGregor [1987]). A controller can have different levels of performance on a given process depending upon how tightly it is tuned. In other instances, there can be economic incentives for moving process set-points closer to the process or quality constraints. To achieve this, it is usual to minimise the product variability (control error sigma) for a given adjustment interval (Harris and MacGregor [1987]). This can be achieved by simulating the feedback control algorithm for values of the IMA parameter Θ ranging from 0 to 1.0.

9 THE NEED FOR A DEAD-TIME COMPENSATOR

A time lag (time delay or dead time) reduces the ability to control the process as it limits the permissible process gain (PG). So, there is a need for a controller mechanism which attempts to reduce this limitation. This mechanism is called a 'dead-time compensator', explained below.

Assume that a small adjustment in the input variable is made at the 'n'th sample. If the sampling interval is smaller than the dead time (made up of the process delay and the measurement delay), then the adjustment made will have no effect whatsoever on the next sample. If there is no appreciable effect of the adjustment in the process, the same control error deviation from the desired target will be measured at the output. If another adjustment is made, the tendency is to overcorrect the control error deviation. In this scenario, one can opt (i) to reduce the controller gain (CG) and to apportion a part of the dead time (time delay); or (ii) reduce the control action by accounting for all the control actions already taken during the time delay, the effects of which are not yet perceived. The first option is achieved if the CG is chosen by a proper stability analysis. Long time delays reduce the CG (Palmor and Shinnar [1979]). Baxley [1991] actually found different values for the CG in his simulation study by the 'Central Composite Design' method and the corresponding standard deviation of the control error along with the mean adjustment interval. Since, the maximum value of the controller gain for the stable operation of a pure time-delay process is 1.0 (Chandra Prasad and Krishnaswamy [1975]), the first option may be preferred by setting the value of the time series controller gain to be 1.0.

The second option results in deriving an equation for the dead time compensator from optimal control algorithms. An advantage of this type of compensator is that the danger of over-correction is considerably reduced during the time delay and it may be possible to choose the value of the controller gain larger than, for the case without the aid of the dead-time compensator. In real systems, though the dead-time compensator may not be able to eliminate (completely) the dead time, it does have a stabilising effect on the process. Another advantage of the dead-time compensator is that, despite infrequent sampling, its response is faster and smoother than an analogue (continuous) conventional controller.

10 THE SMITH PREDICTOR AND THE DAHLIN'S CONTROLLER

Smith's [1957] principle provides a suitable criterion for selecting an appropriate control strategy for time delay processes. This is perhaps the best known of the dead-time compensation techniques currently in use and is also known as the Smith predictor. This principle states that the response of a process with a time delay should be the same as that for the same process without the delay, but delayed by a time equal to that of the delay. Based on this principle, Smith [1957] proposed a discrete version of a dead-time compensator. This (linear) predictor consists of a conventional PID controller in combination with a process model, which is effectively used as a predictor of the output over the interval of the dead time, in a feedback loop around it. Figure 1 gives a block diagram of the Smith predictor for dead-time compensation.

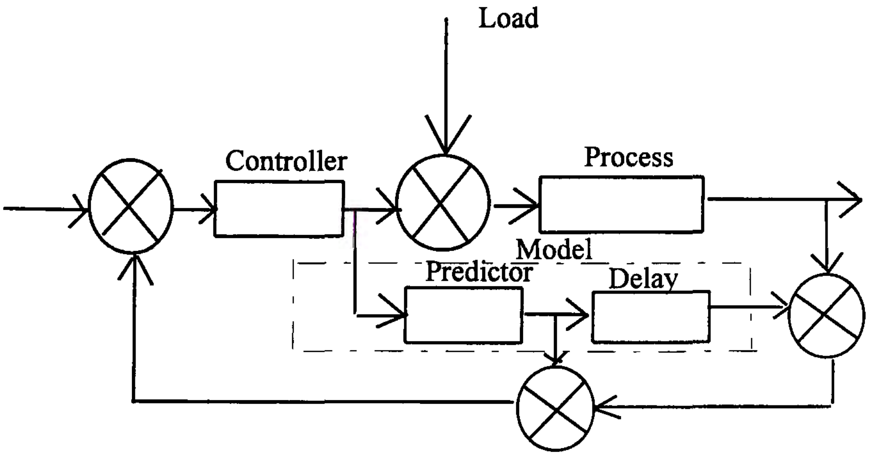

Figure1 Dead time compensation with Smith predictor

The Smith predictor contains two feedback loops; a positive loop containing the dead time and a negative loop without it. The positive feedback loop is intended to cancel the effect of the negative feedback loop through the process, leaving the negative feedback loop in the predictor with only the lag and gain of the model in it. This arrangement makes the predictor input identical to that which would exist if there were no dead time in the process, and hence results in better control. The compensation technique involves the prediction of the process output through the use of a process model which does not contain the dead time. The output of this predictor element is also delayed with a time-delay element which constitutes a separate model of the process dead time. With model dead time, lag and the controller gain matched to a first-order process, the Smith predictor reproduces a step change exactly one dead time later. For first-order processes, some form of derivative action is required, which a Smith Predictor achieves in its feedback path. If the lag in the Smith Predictor is matched to the lag (inertia) in a pure dead time process, the input manipulated variable will follow the process lag exactly but delayed by the dead time. The delayed predictor output is compared to the measured process output and the resulting model error quantity is added to the current predictor output to correct for predictor deficiencies, provided that the model is a true representation of the process and if no further disturbances enter during the dead-time period. In general, the optimal predictor part of the controller algorithm will also change with the time delay. The Smith predictor is an optimal dead-time compensator for only those systems having disturbances for which the optimal prediction is a constant over the period of the dead time.

In brief, the Dahlin's controller works on the principle proposed by Dahlin [1968] that digital controllers be designed to yield a desired first order plus dead-time response to a set-point or load change. Dahlin's algorithm specifies that the sampled-data (discrete) closed-loop (feedback) control system behaves as though it were a continuous first-order process with dead time. For designing sampled-data controllers, Dahlin [1968] considered a tuning parameter ranging from 0 to 1 whereas in the original formulation, the parameter could take values from -1 to 1. This dead time compensator allows the use of a large process gain. To select a suitable value for the Dahlin's tuning parameter, that is, the time constant of the closed-loop response, a (trial or) initial value is assumed and the control system is simulated on a computer. A proper selection of this parameter can be made by repeatedly varying this parameter and examining the closed-loop response. The Dahlin computer-control algorithm is designed for a specific input, for example, a step change in set point. If a load change occurs in a process for which the control algorithm is based on a change in set point, the response may not be equally good. The usual procedure, therefore, is to design for the worst possible change in either set point or load that is likely to occur.

The dead time compensators are usually complex to deal with in real systems. Nevertheless, they have a stabilising effect in the process in a manner which is similar to that of a controller working on an unconstrained optimal control algorithm. The precaution we have to take against instability for large gains in the real systems by having a dead time compensator is by ensuring that there is no deviation between the assumed dynamic (transfer function) model and the real system (Palmor and Shinnar [1979]).

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