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Industrial Adaptive Controllers Based on Frequency Response Techniques*

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Frequency domain approaches can be used to develop industrial controllers with automatic tuning, gain scheduling, adaptive feedback and adaptive feedforward.

Key Words—Adaptive control; automatic tuning; feedforward control; frequency response; frequency domain; PID control; process control.

Abstract—This paper describes several adaptive techniques based on frequency response analysis, which are used in industrial controllers. Automatic tuning is used to obtain PID controller parameters, to build up gain schedules, and to initialize adaptive algorithms. A simple adaptive feedback algorithm which is based on the idea of tracking a point on the Nyquist curve is presented as well as an adaptive feedforward procedure. The adaptive techniques have been implemented in various industrial products. Industrial experiences from using the controllers are summarized in the paper.

1. INTRODUCTION

RESEARCH ON adaptive control has now progressed to the stage where adaptive technology is starting to be used industrially. Adaptation and automatic tuning of PID controllers is well established among manufacturers and users of industrial controllers. There are also a few general purpose adaptive controllers for industrial use (see e.g. Åström, 1987; Seborg *et al.*, 1986 and Åström and Wittenmark, 1989). The industrial applications have given useful insight into needs and limitations of adaptive control. Ease of use is emerging as one of the key requirements. This is the explanation why the autotuners, where tuning is accomplished simply by pushing a single button, have been so well accepted. Many of the general purpose adaptive controllers require significant insight into the properties of the system as well as a judicious choice of design parameters. For this reason many manufacturers have introduced a pretune feature to assist in finding the initial data required. Tuning is easier to perform than continuous adaptation which requires a substantial safety network to guarantee proper operation in all cases.

Parameterization in terms of a rational transfer function is one of the reasons for the lack of robustness of adaptive controllers. A key difficulty is that it is hard to capture unmodeled dynamics in such a model. This difficulty can be avoided by using a frequency domain approach, to obtain a coherent approach to industrial adaptive control.

This paper summarizes several uses of adaptive techniques based on frequency response. The techniques have been implemented in various industrial controllers and instrument systems since 1984. They are currently used in several thousand systems.

The paper is organized as follows. Different ways to use adaptive techniques for industrial process control are discussed in Section 2. Frequency domain characterization versus parametric models is discussed in Section 3. Section 4 describes relay autotuning which is a key ingredient to provide prior information and safe PID control. Section 5 describes gain scheduling and Section 6 presents an adaptive controller based on tracking a few values of the transfer function. Adaptive feedforward control is presented in Section 7. Section 8 presents some of the industrial experiences obtained with the techniques. Conclusions are given in Section 9.

2. INDUSTRIAL USE OF ADAPTIVE TECHNIQUES

There are many different possibilities to use adaptive techniques for industrial process con-

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trol. Model structures, identification methods and control design techniques can be chosen in many different ways. Operational issues like supervisory techniques, safety networks and user interfaces add to the complexity. In this section we will discuss some of these issues in order to motivate the choices that led to the controllers discussed in this paper.

The first adaptive controllers for process control were annnounced in 1983. In 1991 there have been about 8 years of experience of using such devices. Experience has also shown that PID controllers can handle many of the industrial problems. The main exceptions are systems whose dynamics is deadtime dominated, systems with oscillatory dynamics and systems with significant stochastic disturbances. In such cases controller structures other than the PID may give significant benefits. The PID controller also has the added benefit that many users are familiar with it.

Many adaptive controllers are based on a sampled controller, with a sampling period which is of the same magnitude as the process time constant. These controllers introduce extra dead-time in the control loop because of the sampling. Such a controller is often not suitable for control loops subject to load disturbances, (see McMillan, 1986).

Feedforward control is very useful but it requires reasonably accurate process models. The industrial benefits of using adaptive feedforward control have been demonstrated very clearly, particularly in applications with the Novatune controller (see Bengtsson and Egardt, 1984). It has also been demonstrated that automatic tuning, which makes it possible to keep controllers well tuned, is a very desirable feature. There are many cases where dynamics does not change very much. If it does the changes can often be correlated to measurable signals and thus compensated by gain scheduling. It thus appears that a device capable of realizing PID feedback control and feedforward control could be a useful component for industrial process control. If the controller is provided with facilities for automatic tuning, gain scheduling and adaptation it will also be very easy to use.

The diagram in Fig. 1 gives another view on the use of different adaptive techniques. If the requirements on the control performance are modest, a controller with constant parameters tuned for the "worst case" is often adequate. With larger demands on performance, choice of adaptive techniques is determined primarily by the nature of the process variations. If process dynamics are constant, a controller with constant

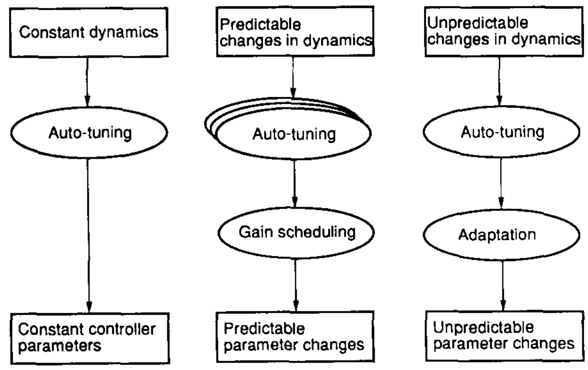

FIG. 1. Determination of structure of feedback controller.

parameters should be chosen. An autotuning procedure is useful to set the parameters. If process dynamics are varying, the controller should compensate for these variations by varying the controller parameters. We distinguish between two types of variations; predictable variations and nonpredictable variations. The predictable variations are typically caused by nonlinearities in the control loop. These variations are best handled by using a gain schedule. An autotuning procedure is useful to build the schedule by finding controller parameters for different operating conditions. The second type of process dynamics variations are those which are not predictable. They may be caused by nonmeasurable variations in raw material, wear, fouling, etc. These variations can not be handled by gain scheduling. True adaptive control is the only way to make the controller follow the process variations. As will be seen below, an autotuner is useful even in this case to initialize the adaptive controller. The variations of the process dynamics may of course consist of both predictable and nonpredictable parts. A combination of gain scheduling and adaptive control is then suitable.

A diagram analogous to Fig. 1 could also be drawn for feedforward compensation. It is often difficult to tune the parameters of a feedforward compensator manually, since the operator often can not manipulate the disturbance from which the feedforward is made. In feedback control, the controller performance can be determined by changing the reference signal. In the feedforward case, the operator often has to wait for suitable transients in the disturbance signal before he can decide if the compensator parameters are suitable. An adaptive algorithm is therefore particularly useful in the feedforward case, since such an algorithm continuously waits for transients in the disturbance signal, and adjusts the compensator parameters based on the transient response. Adaptation is therefore useful even if the dynamics between the disturbance and the measurement signal are constant because it simplifies tuning significantly.

Initialization or pre-tuning

Initialization is an important issue for an industrial adaptive controller. Some of the early adaptive controllers were very demanding on the user. It was necessary to know many parameters like sampling rate, deadtime, model order, desired response time etc. This made the controllers difficult to use because it was necessary to have special skills to commission and use the controllers. Many of the early adaptive controllers were therefore provided with a pre-tune feature that was intended to help the operators to derive the required knowledge. The pre-tune feature was often based on an open loop step response measurement or some other transient response experiment. This will, however, also require some prior knowledge like the size of the step and how long we have to wait for steady state. In some cases the pre-tune required a closed loop experiment. To make this it is necessary to know values of the controller parameters that will give a stable response.

If the controller is supposed to be used by personnel not familiar with adaptive control, and perhaps with a limited knowledge about process dynamics and control, it is not possible to force the operator to make decisions which will determine the performance of the adaptive controller. In the system discussed in this paper the initialization is made using relay feedback which has proven very reliable.

3. FREQUENCY DOMAIN APPROACHES TO ADAPTIVE CONTROL

In this section we will discuss advantages and disadvantages of frequency domain models compared to parametric models in adaptive control.

Approaches to adaptive control

Much work on adaptive control has been focused on process models in terms of rational transfer functions. The advantage of such models is that the identification problem is simple and that many control design methods are based on this structure. The approach does, however, also have some severe disadvantages. The estimation is sensitive to unmodeled dynamics which becomes particularly serious when combined with high frequency excitation. The parameters of a rational transfer function can also change significantly without changing its transmission properties if there are poles and zeros that are close. To estimate parameters of a transfer function it is also necessary to have prior information about the time scale and the time delay of the process. For discrete time systems this is necessary in order to choose sampling period and model structure. For continuous systems it is necessary to choose suitable filters. One way to get around the problem of knowing the time scale is to let the user choose it and to provide pre-tuning facilities to help him make the choice.

A particular problem for a rational transfer function model is that the parameters lack orthogonality. Parameters of low order models thus have little relation to parameters of high order models. This is different from expansions in orthogonal functions where an increase in model complexity simply implies that new parameters are added and the old parameters remain.

Laguerre polynomials

One way to avoid the problems with the rational transfer function representation is to use other representations. One possibility is to represent the process by a series expansion of its impulse response in orthogonal polynomials. For stable systems a natural choice is Laguerre polynomials which are orthogonal on $(0, \infty)$. This was suggested by Lampard (1955) and has recently been explored by Zervos and Dumont (1988). The Laguerre polynomials have the Laplace transforms

$$F_i(s) = \sqrt{2a}\,\frac{(s-a)^{i-1}}{(s+a)^i}, \quad i = 1, \ldots, N. \quad (1)$$

A drawback with this approach is that it is necessary to know time scales in order to choose the parameter a. Theoretically any value of a will do. If bad values are chosen it is, however, necessary to use many parameters in the series expansion. Also it is not possible to represent unstable systems by an expansion in Laguerre polynomials.

Transfer function representations

Another alternative is to simply represent the process by its transfer function. Being a nonparametric representation this avoids several of the problems. There are many ways to determine the transfer function of a process. Conventional frequency domain based excitation with sinusoids can be used. By using FFT, any type of input signal can be applied. Parametric methods can also be used to estimate the transfer function (see Ljung, 1985 and Wahlberg, 1987). To determine the transfer function efficiently it is, however, also necessary to have prior information about the time scale.

If the process is characterized by its transfer function there are several ways to make the control design. Using the Ziegler–Nichols tuning rules, PID parameters can be determined from the value of the transfer function where the phase lag is 180° (see Ziegler and Nichols, 1942). Improved PID parameters can be found if the transfer function is known in the neighborhood of the critical point. Approximate pole placement design can be made if the transfer function is known for a number of frequencies. Knowledge of the gross features of the transfer function can be used to assess the control performance—see Åström (1988).

The adaptive controllers discussed in this paper are based on the idea that there are simple robust methods to determine both the gross features and the fine structure of a transfer function experimentally and also methods for control design that use frequency domain features. In this way we can obtain a system that allows both automatic tuning and adaptation of control systems.

4. AUTOMATIC TUNING

The key idea behind the automatic tuning is to use relay feedback. Processes with the dynamics typically encountered in process control will then exhibit limit cycle oscillations. The autotuner identifies one point on the Nyquist curve of the process from a simple relay experiment. The autotuner principle is shown in Fig. 2. When the operator decides to tune the controller, he simply presses a button. This switches out the PID algorithm and replaces it with a nonlinear function which can be described as a relay with hysteresis. The relay feedback causes the process to oscillate with a small and controlled amplitude. The frequency of the limit cycle is approximately the ultimate frequency where the process has a phase lag of 180°. The ratio of the amplitude of the limit cycle and the relay amplitude is approximately the process gain at that frequency. A relay feedback experiment thus determines a point on the Nyquist curve of the open loop dynamics that is close to the ultimate point. A reasonable PID controller can be designed based on this point.

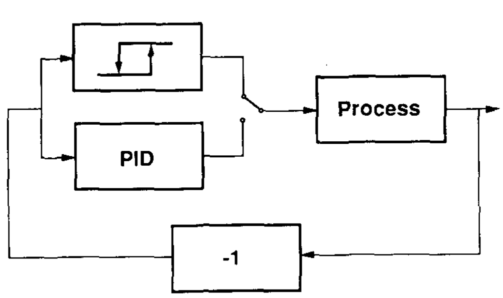

FIG. 2. The autotuner principle.

This autotuning method, which was presented in Åström and Hägglund (1984, 1988a), has been used in commercial autotuners since 1984. It has proven to be a convenient tool for rapid tuning of PID controllers. One of its main advantages is that it admits one-button tuning. This means that tuning is executed simply by pushing the tuning button, and that no prior information has to be given by the operator. Another advantage is that the tuning experiment is executed under tight feedback control and that the experiment generates an input signal that is close to optimal for determining the ultimate point on the Nyquist curve.

The following example illustrates how autotuning can be used.

Example 1. *Autotuning of a flow loop.* Figure 3 shows tuning of a flow loop in a chemical process. The tuning requires about five half periods of the limit cycle oscillation. It takes less than 15 s. Also notice that the amplitude of the perturbation during tuning is modest. The step change made after the tuning shows that the tuning is successful. A comparison of the closed-loop response time with the tuning time indicates that the tuning time is short in comparison with the closed-loop response time. The signals are not smooth because of a sticky valve. □

By using the autotuner, we do not only obtain good PID parameters, but also valuable process information for the initialization of the identification procedure in the adaptive controller. This will be discussed in detail in Sections 6 and 7.

Design methods

Given information about the ultimate point on the Nyquist curve, many design procedures can be used. Unfortunately, there is no design method which is suitable for all processes. By deciding to use a PID controller, we have restricted ourselves to those control problems which can be handled by PID controllers. Even among these problems, it is desirable to have different design procedures for different control problems.

The identification procedure given in the previous section gives information of one point $G(i\omega)$ on the Nyquist curve. By introducing the PID controller $G_{PID}(i\omega)$ in the control loop, it is possible to give the Nyquist curve of the compensated system GG_{PID} a desired location at the frequency ω. For most purposes, we have

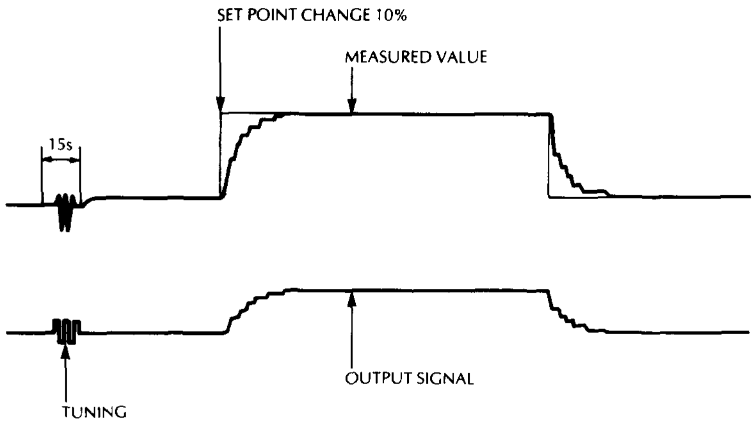

FIG. 3. The autotuner used in a flow control loop.

decided to choose the PID parameters so that $G(i\omega)$ is moved to the point

$$G(i\omega)G_{PID}(i\omega) = 0.5e^{-i135\pi/180}. \quad (2)$$

This design method can be viewed as a combination of phase- and amplitude-margin specification. Since the PID controller has three adjustable parameters, gain K, integral time T_i and derivative time T_d, and the design criterion (2) only gives two conditions, it is furthermore required that

$$T_i = 4T_d. \quad (3)$$

Note that the controllers that we are discussing have an interacting control algorithm; see Åström and Hägglund (1988a). A noninteracting controller would have the relation $T_i = 6.25T_d$. A choice of this type is common in many industrial controllers.

Some very simple control problems, e.g. where the process is approximately a first order system, can be solved effectively with a PI controller with high gain. Derivative action is of little use for these problems. Furthermore, the noise will be amplified by the derivative term. Therefore, it is desirable to use only a PI controller in these cases. In our controller, we can automatically detect this kind of processes and thereby switch off the derivative gain in these cases. The parameters of the PI controller are chosen as

$$\begin{aligned} K &= 0.5/\alpha \\ T_i &= 4/\omega \end{aligned} \quad (4)$$

where $\alpha = |G(i\omega)|$ and ω is the frequency of the relay oscillation.

There is also another case where it is desirable not to use derivative action, namely when the processes has a long deadtime. A PI controller for processes with long deadtime is given by

$$\begin{aligned} K &= 0.25/\alpha \\ T_i &= 1.6/\omega \end{aligned} \quad (5)$$

This controller gives much better control than the PID design (2) for processes with long deadtime. The design methods (4) and (5) are obtained empirically from numerous simulations and field tests.

It is possible to extract more information from an experiment with relay feedback. In Åström and Hägglund (1988b) it is shown that low order process models can be determined. These models also give the relative deadtime. They can then be used to compute the transfer function of the process. It is also possible to obtain a transfer function by applying an FFT to the curves from a relay experiment. The precision of the transfer functions obtained in this way is limited by the excitation obtained from the relay experiment.

A significant advantage of the relay autotuning experiment is that it gives sufficient quantitative information about the process dynamics to determine simple controllers. More information about the process can be extracted by modifications of the experiment. By introducing hysteresis in the relay it is possible to obtain local information about the transfer function in the neighborhood of the ultimate frequency. By introducing an integrator in the feedback we obtain information about the frequency ω_{90} where the phase lag of the process is 90°. Similarly we can obtain the transfer function at the frequency ω_{270} by introducing a differentiator in the loop. Knowledge about the plant transfer function at ω_{90}, ω_{180} and ω_{270} allow us to make an assessment of the achievable control performance and to improve controller design (see Åström, 1988).

5. GAIN SCHEDULING

Gain scheduling is an effective method for processes with predictable variations in dynamics. A gain schedule is a table with several sets of controller parameters, one for each operating point. (Parameter schedule would be a more adequate notation than gain schedule!) A reference signal which is related to the nonlinearity determines when to switch from one set of controller parameters to another. For example if the nonlinearity is caused by a nonlinear valve, the control signal should be used to select controller parameters. If the nonlinearity is caused by a nonlinear sensor, the measurement signal should be used to select controller parameters.

Most process control plants contain several nonlinear control loops. In spite of this, gain scheduling is seldom used in process control. One reason for this is that it is time consuming to build gain schedules. Autotuning greatly simplifies the construction of gain schedules. Using the autotuner once at each operating point automatically gives the schedule.

When the process dynamics are predictable, it is better to use a gain schedule than an adaptive controller. The gain schedule will instantaneously provide suitable controller parameters as the operating conditions change. The adaptive controller needs some time before it has adapted itself to the new conditions.

Gain scheduling can also be used to solve other control problems than nonlinear processes control. One example is level control of surge tanks. The primary goal is not to keep the level at a certain set point, but to keep the control signal as smooth as possible. The level must however be kept within certain limits. This problem can be solved by having different control strategies at different operating ranges. Tight control should be used when the level is close to the limits. A much looser control can be used when the level is far away from the limits.

6. ADAPTIVE FEEDBACK CONTROL

Recursive estimation of the transfer function is a key ingredient of an adaptive controller based on frequency domain concepts. Since many parameters can be estimated only finitely, it is essential to have a methodology to determine appropriate frequencies. If an experiment with relay feedback has been carried out, the frequency ω_{180} is known. For many control designs it is not appropriate to have bandwidths much higher than ω_{180}. From classical control theory we know that a good controller can indeed be designed based on a few values of the transfer function in the range $0 \leq \omega \leq \omega_{180}$. The estimation problem is then simply to track the transfer function at a few frequencies in this range. Determination of the transfer function was an essential part of classical feedback control (see Åström, 1975). Different parametric methods of estimating transfer functions are discussed in Ljung (1985) and Wahlberg (1987). They have shown that a good method is to estimate parameters of dynamic models and evaluate the corresponding transfer functions. The results are reliable provided that there is proper excitation. Filtering can be used to allow for low order models.

In this section we will present an adaptive controller which is based on determination of the transfer function at a selected frequency.

Tracking a point on the Nyquist curve

The identification scheme is shown in Fig. 4. The control signal u and the measurement signal y are filtered through narrow band-pass filters centered at the frequency ω, i.e. the frequency obtained from the autotuner experiment. The two signals are inputs to a least-squares estimator which gives an estimate of $G(i\omega)$.

The band-pass filters. These have the form

$$G_{BP}(s) = \frac{s}{s^2 + 2\zeta\omega s + \omega^2}. \tag{6}$$

This filter will give a relatively high gain at the frequency ω, and suppress the signals at other frequencies.

It is known from practical use of adaptive controllers, that filtering is useful. Low frequencies must be attenuated to avoid interactions from load disturbances. High frequencies must be attenuated to avoid high frequency noise from disturbing the parameter estimates. When fitting low order models to complex dynamics, it is also important to filter the signals to admit determination of the relevant dynamics.

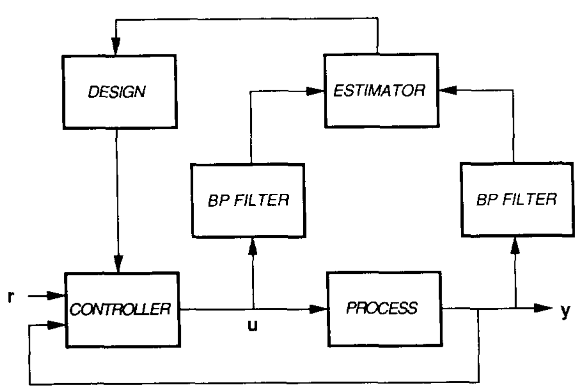

FIG. 4. Block diagram describing the identification procedure.

By using narrow band-pass filters, it is possible to track $G(i\omega)$ at the frequency ω. The traditional filtering problem is also solved very effectively.

The least-squares estimator. The band-pass filters produce two signals which can be approximated with two sine-waves having different amplitudes and phases. The quotient α between the amplitudes and the phase shift φ between the two signals give $G(i\omega)$.

$$G(i\omega) = \alpha e^{-i\varphi}. \tag{7}$$

A least-squares estimator is used to determine $G(i\omega)$. This is done by estimating parameters of the second-order model

$$y(t) = b_1 u(t-h) + b_2 u(t-2h). \tag{8}$$

The sampling period h is determined from the frequency ω. The choice

$$h = \frac{2\pi}{8\omega} \tag{9}$$

i.e. eight samples per period, gives good identifiability properties. The amplitude α and the phase shift φ of the transfer function $G(i\omega)$ are given by

$$\begin{aligned}\varphi &= \arctan\left(\frac{b_1 \sin(\omega h)}{b_1 \cos(\omega h) + b_2}\right) - 2\omega h \\ \alpha &= \frac{b_1 \sin(\omega h)}{\sin(2\omega h + \varphi)}.\end{aligned} \tag{10}$$

The least-squares algorithm is of the constant-trace type. The algorithm can be simplified since the signals $u(t-h)$ and $u(t-2h)$ entering the LS-estimator are approximately sine-waves with a constant phase-shift. Instead of identifying the parameters b_1 and b_2 directly, the following scaling is performed:

$$\begin{aligned}y(t) &= b_1 u(t-h) + b_2 u(t-2h) \\ &= \frac{b_1+b_2}{2}\{u(t-h) + u(t-2h)\} \\ &\quad + \frac{b_1-b_2}{2} n\{u(t-h) - u(t-2h)\}/n \\ n &= \sqrt{\frac{1-\cos(\omega h)}{1+\cos(\omega h)}}.\end{aligned} \tag{11}$$

By estimating the parameters

$$\theta_1 = \frac{b_1+b_2}{2} \quad \theta_2 = \frac{b_1-b_2}{2} n \tag{12}$$

the expected value of the covariance matrix P becomes diagonal with equal diagonal elements. This simplifies the algorithm significantly.

To track the transfer function at several frequencies we simply use parallel filters and parallel estimators. This has proven more efficient than to use one model of higher order. Another way to track a frequency response is given in Balchen and Lie (1986).

Supervision

The adaptive controller cannot run continuously without any supervision. It is necessary to have logic for avoiding updating the estimates when no information is available. Supervision is at least as important as the basic estimation algorithm. However, there are no systematic techniques for the supervision. Different manufacturers of adaptive controllers have their own tricks. We will now shortly describe the supervisory level of our algorithm.

First of all, it must be ensured that the adaptation mechanism is only active when the signals contain useful information. No identification should be made under periods of good control, when both the control signal and the measurement signal are constant. We have a procedure that high-pass filters the control signal and the measurement signal. Adaptation is only allowed when both these signals have had a transient.

Load disturbances are not included in the process description (7). Implicitly it is assumed that changes in the measurement signal are caused by the control actions. The signals are band-pass filtered to avoid disinformation from high frequency noise and load disturbances. Since this is not sufficient, a procedure to detect load disturbances is also included. Adaptation is inhibited during the first part of a load disturbance transient.

There is a very simple relation between the estimated parameters and the physical parameters α and φ. Therefore, it is possible to check if the estimates have reasonable values. The parameter estimates are bounded in such a way that φ is always inside a sector in the third quadrant and that α may not vary more than a specified factor from the initial value given by the autotuner.

7. ADAPTIVE FEEDFORWARD CONTROL

Feedforward control is a powerful method to compensate for measurable disturbances. It can often give drastic improvements in control quality. In the context of this paper it is natural to use a frequency domain approach to feedforward control. If G_{yv} is the transfer function from disturbance v to process output y and G_{yu} is the transfer function from control signal u to process output y the ideal feedforward compensator is

$$G_{ff} = -\frac{G_{yv}}{G_{yu}}. \tag{13}$$

This transfer function is not always realizable, neither is it always reasonable to implement feedforward using this transfer function. Low frequency components of the disturbance signal are easily handled by feedback control. Hence, there is no need for a feedforward of these components. High frequency components of the disturbance signal are normally filtered out by the process. In any case, the controller is not able to compensate for very fast variations, so there is no use to feed these components forward either. It can thus be concluded that feedforward control is useful in a limited frequency range. To implement a feedforward controller the appropriate frequency range is determined and an approximation to G_{ff} in (13) in that frequency range is calculated. Feedback becomes less effective around the crossover frequency and may actually amplify disturbances at these frequencies. Estimates of the crossover frequency can be obtained from a relay experiment for the open loop system. Another method is to determine the frequency where the closed loop system has 90° phase lag. This frequency can also be determined by relay feedback on the closed loop system with an integrator after the relay.

We have implemented a simple special case of (13), namely a proportional feedforward control where the compensator has the structure:

$$\Delta u_{ff}(t) = k_{ff}(t)\Delta v(t) \tag{14}$$

where u_{ff} is the feedforward component of the control signal, k_{ff} is the feedforward gain, and v is the disturbance signal. This simple adaptive feedforward compensator has shown to be very useful. In most cases, it is sufficient to use proportional feedforward. Sometimes, it is desirable to delay the signal v, as will be discussed below.

The gain k_{ff} is determined from the model

$$y(t+d) = au(t) + bv(t) \tag{15}$$

where y is the measurement signal. Parameters a and b are determined using ordinary least-squares esitmation. The signals are both high- and low-pass filtered to get rid of noise and bias.

The choice of the time delay d in the model (15) is crucial. If d is not chosen appropriately, the model will not capture the relations between u and y and between v and y. Let the deadtime plus the dominating time constant of the process be T_{uy} and the deadtime plus the dominating time constant of the transfer function between v and y be T_{vy}. The following cases can then be distinguished.

- $T_{vy} \gg T_{uy}$ — In this case it is desirable to delay the disturbance signal v. Otherwise, the feedforward compensation will influence the signal y before the disturbance. The disturbance signal should ideally be delayed with the time $T_{vy} - T_{uy}$.
- $T_{vy} \approx T_{uy}$ — Feedforward is often very efficient in this case.
- $T_{vy} \ll T_{uy}$ — In this case it is not worthwhile to use feedforward. The disturbance can not be compensated before it effects y. The feedback controller can equally well do the job.

From these considerations, it can be concluded that d should be chosen close to T_{uy}, i.e. equal to the deadtime plus the dominating time constant of the process.

In a relay autotuning experiment, the maximum time delay between u and y is half the oscillation period, i.e. $T_u/2$. (If the process consists of only a time delay, the oscillation period is twice the time delay!) The parameter d is chosen as $d = T_u/2$. This choice guarantees therefore that the time delay is not underestimated. The sampling interval of the least-squares estimator is chosen as $h = T_u/8$ which is the same as in the feedback case. This gives the following model equation:

$$y(t) = au(t-4h) + bv(t-4h). \tag{16}$$

The gain of the feedforward compensation is chosen as

$$k_{ff}(t) = -0.8\frac{\hat{b}(t)}{\hat{a}(t)} \tag{17}$$

where $\hat{a}$ and $\hat{b}$ are the estimates of a and b. The adaptive algorithm is provided with a security net similar to the one used in the feedback controller.

8. INDUSTRIAL EXPERIENCES

The adaptive techniques discussed have been implemented in several industrial products. The autotuner and the gain scheduling have been implemented in single loop controllers and instrument systems manufactured by SattControl Instruments AB in Sweden and Fisher Controls in the U.S.A. since 1984 (see Table 1). A single loop controller that combines relay autotuning and gain scheduling with adaptive feedback and adaptive feedforward has been in operation since 1988. Experiences of this controller called ECA400 are reported in the following.

TABLE 1. EXAMPLES OF INDUSTRIAL ADAPTIVE CONTROLLERS

Controller	Type	Manufacturer	Year	Technique	Processor
SDM-20	DCS	NAF Controls	1984	AT, GS	Intel 8086, 8087
ECA40	SLC	SattControl	1986	AT, GS	Intel 8031
ECA04	SLC	SattControl	1988	AT	Intel 80535
Alert 50	DCS	Alfa Laval	1988	AT, GS	Intel 8088, 8087
SattCon 31	PLC	SattControl	1988	AT, GS	Motorola 6809
DPR900	SLC	Fisher Controls	1988	AT, GS	Intel 8031
ECA400	2LC	SattControl	1988	AT, GS, AFB, AFF	Intel 80C188
SattLine	DCS	SattControl	1989	AT, GS	

DCS = distributed control system, PLC = programmable logic controller, SLC = single loop controller, 2LC = two loop controller, AT = autotuning, GS = gain scheduling, AFB = adaptive feedback and AFF = adaptive feedforward.

The functions gain scheduling, adaptive feedback and adaptive feedforward are independent, and may thus be used separately or together. The autotuner is used to initialize the adaptive feedback and feedforward controllers. In this way, the operator does not have to provide the controller with any information about process dynamics. The parameters of the gain schedule are automatically obtained by using the autotuner once at each operating point. The gain schedule may be combined with the adaptive controller. Adaptation is then only performed on the set of controller parameters that are presently used. The result is the same as if several different and independent adaptive controllers are available.

Example 2. *Adaptive temperature control.* The process diagram of a heat exchanger is shown in Fig. 5. Water is heated by steam. The water temperature is measured and the signal is used to control steam flow. The process dynamics change with changes in the steam pressure and water flow.

Experimental results are shown in Fig. 6. The ECA400 controller was used in the experiment. The temperature setpoint was moved up and down in the experiment. The figure shows the measured variable and the control signal. The autotuner gave a PI controller with gain 3.2 and integral time 13 s at the start of the experiment. The controller was in the adaptive mode during the experiment. After 6 min the water flow was suddenly decreased. The process gain then increases and the control loop becomes oscillatory. Because of the low pass character of the process dynamics, the oscillation is most noticeable in the control signal. The adaptation mechanism gradually decreases the controller gain to 2.6 at time 9 min and 2.1 at time 15 min. At time 16 min the controller parameters are $K = 1.5$, $T_i = 8.2$ and $T_d = 2.0$. These controller parameters were not significantly changed until the next water flow alteration.

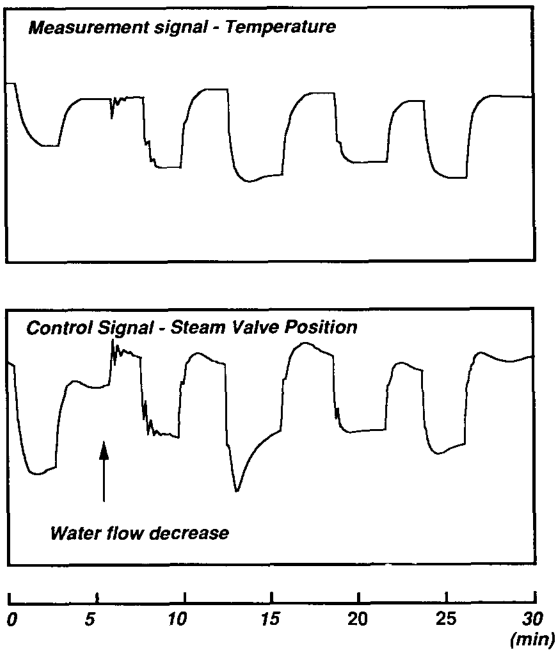

FIG. 6. Adaptive control of a temperature control loop.

The experiment demonstrates the tracking capability of the adaptive controller. The rate of adaptation is quite high in this case, since the increased process gain provides a high loop gain and therefore a good excitation. □

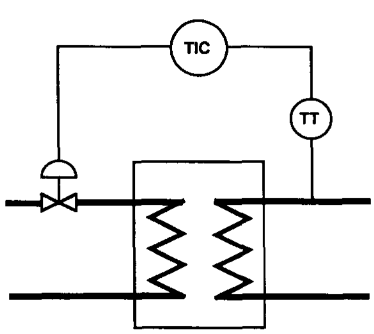

FIG. 5. A steam water heat exchanger.

Example 3. *Adaptive control of pulp density.* This example is a control loop in a paper mill. Pulp density is controlled by diluting the pulp with water. A schematic diagram of the

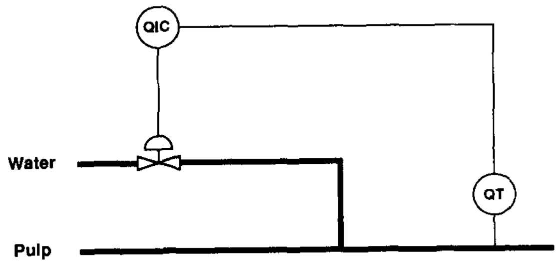

FIG. 7. Pulp density control.

process is shown in Fig. 7. This process has time-varying dynamics, since a change in the pulp flow will cause a change in the process gain and time constant. Parts of an experiment are shown in Fig. 8. The setpoint of the pulp density was changed stepwise to activate the adaptation. Figure 8 shows a case where the pulp flow was increased, resulting in a decreased process gain. Before the flow change, the PID controller had a gain of 0.10. As seen in the figure, this low gain gave a very sluggish control response. After five setpoint changes, the controller gain had increased to 0.30, resulting in a much faster control. □

Example 4. *Adaptive feedforward level control.* This example illustrates the benefits of adaptive feedforward control. A pilot plant consisting of two cascaded tanks was used: see Fig. 9. The level in the lower tank was controlled by the valve on the water inlet tube. The disturbance was a flow to the upper tank. This flow was measured and fed into the controller. Figure 10 shows the results of the experiment. The experiment starts with a relay autotuning experiment to obtain the PID parameters. The autotuner experiment is followed by two setpoint changes to show the behavior of the closed loop control. Adaptive feedforward was then initialized and load disturbances were introduced by making step changes in the disturbance flow.

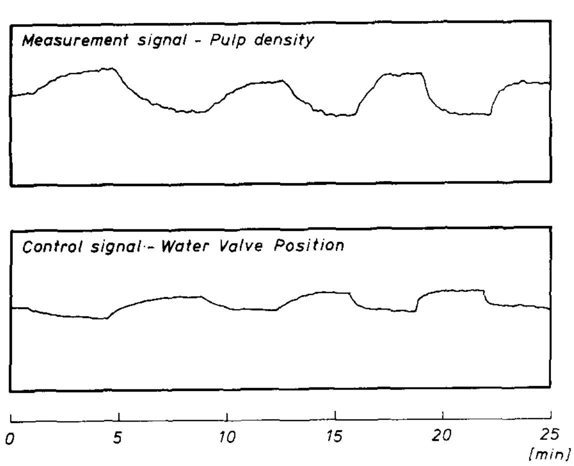

FIG. 8. Adaptive control of a pulp density control loop.

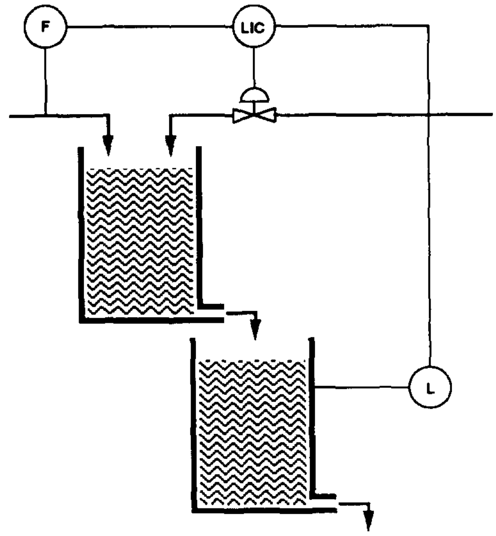

FIG. 9. Pilot plant used for adaptive feedforward compensation.

Figure 10 illustrates clearly how the effect of the disturbance is reduced when the adaptation mechanism finds the appropriate feedforward gain. With step changes in the flow it takes two changes to find the parameters. The rejection of the disturbances is almost perfect at the last two changes. □

9. CONCLUSIONS

Some problems encountered in adaptive control are due to the fact that the process is modeled as a rational transfer function. One possibility to avoid these problems is to use a frequency domain approach, and represent the process dynamics by values of its transfer function at a number of points.

Other problems are due to the operational complexity of adaptive controllers. An adaptive controller requires a fair amount of *a priori*

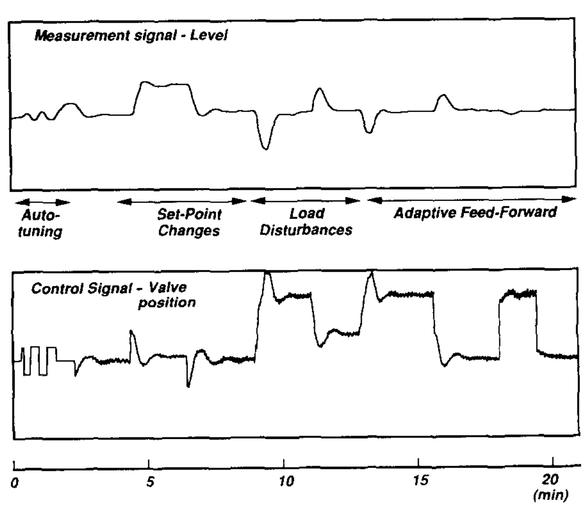

FIG. 10. Adaptive feedforward compensation.

knowledge. This knowledge may either be given by a skilled engineer or may be acquired automatically by some kind of experimentation. The latter alternative is preferable, not only to simplify the task of the operator, but also for the sake of robustness.

In this paper, we have described adaptive techniques based on frequency response analysis. The key element is automatic tuning based on relay feedback. This is a simple experiment that easily can be automated to the "push-button level". Autotuning gives information about the point where the Nyquist curve of the open loop process dynamics crosses the negative real axis. With this information it is possible to find PID parameters. With autotuning as a base it is also possible to add automatic generation of gain schedules, adaptive feedback and adaptive feedforward.

Industrial controllers based on simple versions of these methods have been developed. These controllers use relay autotuning to tune PID controllers and to initialize adaptive feedback control (PID) and adaptive feedforward control (P). Gain scheduling is obtained by using the autotuner at different operating conditions. Good results from industrial use of the controllers are reported.

The adaptive techniques can also be used for more sophisticated controller structures than the PID. Ways to obtain several points on the Nyquist curve using relay autotuning have been reported, as well as adaptive control strategies which are based on tracking the frequency response at several frequencies.

The fact that frequency response methods have been used in the applications described in this paper does not imply that we believe that this is the preferred adaptive technique in all situations. There are other adaptive problems where the traditional methods based on estimation of parameters of a rational transfer function are more appropriate.

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