SOME ISSUES IN CONTROL ENGINEERING PRACTICE

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Abstract. In the last years a lot of papers appearing in the control literature introduced elaborated control design algorithms. Most of them contain mathematical approaches that apparently solve control problems. However in many cases the engineering perspective is lost. Some case-dependent conclusions are proposed to be of general use and some properties are considered as universal, even they can fail under some specific situations. In this paper, a critical perspective based on some illustrative results suggests the need of a final review of any control solution according to the control engineering good practice. Delays in the feedback control loop are not always bad, multirate control not always leads to rippled behaviour and feedback of the actual process output is generally better than inferential control.

Key-Words: - Discrete-time systems, multirate systems, sampled-data systems, time delay, inferential control.

1 Introduction

Control engineers must deal with control problems and find solutions in practical applications. That means, they should be able to formulate a control problem, to apply a design methodology, to implement a control strategy and to fine-tune the control system to adapt to changing operating conditions. It is for these reasons that control engineers must be always able to understand the behaviour of the controlled plant, to interpret the effects of changing parameters and to develop a number of options to solve an emergency situation.

Other than knowing the theory behind all these activities, they must have engineering common sense, that is, to have the skill to react in the correct way to an unexpected condition in the controlled system. In the old days, a good control engineer should be capable of understand the time and frequency response of the single-loop continuous time controlled plant.

Nowadays, the use of powerful control design theories and tools leads to control solutions that appear as "magic" solutions, but there is a general lack of knowledge about how to react if minor changes in the process, operating conditions or implementation constraints appear. The obtained control structures, their parameters and their operational properties are derived through mathematical procedures where the physical meaning of the actions is hidden and it is difficult to interpret and change unexpected behaviours.

Two different sources of trouble are going to be considered in this contribution. First, there is the tendency generalise, that is, to admit as a general property what happens in some specific circumstances. But, what is correct in some applications is inapplicable in others leading to rules of thumb that could result in wrong actions. On the other hand, some not well posed problems may lead to erroneous conclusions which can be easily proved to be false. There are many of these circumstances in control engineering practice.

We are going to consider three different general situations. They are related to the influence in the controlled system behaviour of time delays in the control loop, the use of model based inferential control, and the ripple effect in multirate control systems. These characteristics are frequent in modern control systems where the use of computer-based control structures allows for complex control schemes but also results in unavoidable time delays.

To motivate our discussion, a number of contributions available in the control literature will be analysed and some alternatives will be presented. Finally, some general remarks and conclusions are outlined.

In the abstract of the paper by Moore and coauthors, [1], it is said that "*Multirate sampling techniques … lead to a degradation in the intersample behavior of the system*". This drawback has been always around the nature of multirate systems and it can be easily considered as unavoidable. In order to derive this conclusion, the lifting technique [2] to modelling multirate signals and systems is used. As it is well known, in using this technique, the input and output signals are grouped in block vectors, and the system is modelled by a linear time invariant state space representation with enlarged input and output vector dimension. The elements of the block signal vectors are the values the corresponding signal have at different instants of time, those of the sampling/updating of the respective variables. Each block is composed by the corresponding signals taken at the metaperiod, that is, a global period which is the minimum common multiple of all the sampling periods in the system. We will show that this conclusion is wrong, the trouble, in this case, being a miss interpretation of the meaning of these block vectors. Their elements are not independent variables but samples of a few variables taken at different instants of time.

The common use of computer-based control systems allows to easily implement model-based control algorithms and virtual sensors providing that estimated measurements are included in the control loop. In the paper [3], a dual-rate inferential control is analysed and compared with a fast single-rate control and the following result is extracted from the abstract: "*Comparing such an inferential controller with the corresponding fast single-rate controller … the former is advantageous in stability robustness of the closed-loop system*". This may lead to the conclusion that: "if an uncertain system is controlled by using estimated values of the output variable it is more robust than implementing the control using actual output measurements". This clearly is unacceptable as a general rule, although, as we will show later on, it can be true under some very specific operating conditions.

A general rule of thumb in applying a designed closed loop control system is that an increment on the loop gain reduces the stability of the system. The same applies with the phase lag. Additional time constants or time delays in the loop deteriorate the stability margin of the controlled system. If they are not considered at the control system design stage, their main effect is a reduction in the controlled system performances: lower damping, higher settling time, reduction of the phase margin and, in the worst case, instability. In particular, there are limitations in the time delay to guarantee the stability of a controlled system. If the delay is included in the plant model, the controller design is more complicated. Since the seminal work of Smith [4], a lot of research to overcome the negative effect of the delay has been reported (see, for instance, [5]). Thus, it is quite common to generalize and use the concept that delays are always bad for the system dynamic behaviour.

But it is well known that there exist systems denoted as conditionally stable, where the stability is only achieved in a range of loop gains. In these cases, a stable system may become unstable if the gain is reduced and vice versa. A similar situation can be foreseen related to the time lag. The presence of delays may have positive effects, either in the design or in the implementation of the control. Recently, it has been reported, [6], that control action delivering delays in digital control systems may have a positive effect on the closed loop stability. And this is in contradiction to the assumed concept that *time delays in the loop are always bad*.

Let us analyse in some detail each one of these common and interesting situations.

2 Intersample Behaviour in Multirate Control

Let us consider a multirate control system composed by a continuous process and a digital controller connected by means of a set of samplers and hold devices acting at different frequencies. Moreover, each input/output variable may be treated at different sampling rate. One of the most common schemes in this environment is the so called MRIC (multirate input control). In this case a slow sampling of the plant output is taken (due to physical or economical restrictions), at period T_1, and a fast updating is used at period T_2 ($<T_1$). This kind of situations leads in a natural way to a dual rate control loop where the global sampling is repeated periodically each minimum common multiple of every sampling period in the digital loop. In the MRIC basic case, with $T_2=T_1/N$, N being a natural number, this metaperiod is $T=T_1$. Actually the global model is T-referred. See [7] for instance.

Basically, there are two approaches to deal with this kind of systems. The first and more generally used is the state space approach. This is called the lifting modelling method. In this case the different signals (input, output, and some times also the states) are lifted taking into account their values at instants relatives to one metaperiod and enlarged vector variables are obtained. For instance, the discrete time signal $y_k = \{y(0), y(1), y(2), \ldots\}$, $y_k \subset R^p$, is transformed into the lifted signal

$$\bar{y}_k = \left\{ \begin{bmatrix} y(0) \\ y(1) \\ \vdots \\ y(N-1) \end{bmatrix}, \begin{bmatrix} y(N) \\ y(N+1) \\ \vdots \\ y(2N-1) \end{bmatrix}, \ldots \right\} \quad (1)$$

But the components of these vectors are connected in time. Thus, they are not independent. There are different options in building up the vectors depending if the sampled signal is considered in its own sampling period over one metaperiod [8,9] or a decomposition by the maximum common divisor sampling period is assumed [10]. A specific algebra is proposed to treat these systems, and interesting properties can be inferred.

A second approach is the input/output modelling. Actually an internal representation is developed and afterwards a decomposition in transfer functions attached to certain subsystems is proposed. Another possibility is the decomposition of the global model assuming every relation (transfer function) between the different inputs and outputs over a global period. For instance, in a SISO MRIC environment, the slow output of the plant P is computed as the sum of the products of *different* fast inputs by their relative subsystems. Following [1], for N=2, the output is:

$$\begin{aligned} Y(z^2) &= Y_1(z^2) + Y_2(z^2) \\ &= G_1(z^2)U_1(z^2) + G_2(z^2)U_2(z^2) \end{aligned} \quad (2)$$

where the variable z^2 denotes the slow sampling rate of the variables (z^{-2} is the T delay operator). The proposed control structure is depicted in fig. 1.

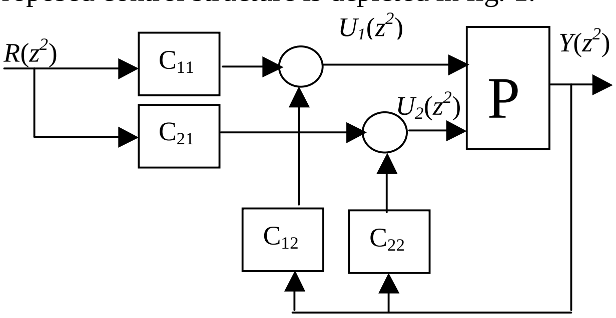

Figure 1. MRIC Control structure (N=2).

In this case it is assumed that each input vector component ($U_i(z)$) is an independent variable, but it is evident that, physically, they are not different inputs. Following [1], the fast control input is computed through its components:

$$U_i(z^N) = C_{i1}R(z^N) - C_{i2}Y(z^N), \; i = 1,2,\ldots N \quad (3)$$

and the controllers are calculated to assign the poles and zeros of the global transfer function.

In both cases the terms of a sequence corresponding to the same signal at different time instants on one metaperiod are assumed like if coming from different signals. So the relation among them is not taken into account. The mechanism –following with the MRIC example- is like if we were controlling the global system by N different controllers each of them designed for a subsystem. Every controller updating is just used once per metaperiod and the new one due to this controller is assumed periodically in the next metaperiod. N independent actions are being chained that led to N switches that obviously produces the continuous output ripple. A conceptual mistake is being done by missing the interdependence among these variables.

An alternative approach, denoted as dual-rate controller, has been proposed by the authors in a previous work, [11]. This is based on a global modelling and consequent design without considering different subsystems. However the hidden oscillations problems could be present in some given cases, but due to other well known causes, [12].

The outline of the approach is as follows. If $M(s)$ represents the desired closed-loop performance for the controlled plant, and $M^T(z) = M(z^N)$, $M^{T/N}(z) = M(z)$ are their discrete time equivalents for T and T/N periods, this non-conventional controller is composed by three elements. A slow part, $G_1(z^N) = \dfrac{1}{1 - M(z^N)}$, that processes the slow rate process output measurement. Then, the slow signal is transformed (by replication) into a fast rate signal by means of a hold device $\dfrac{1 - z^{-N}}{1 - z^{-1}}$. This fast sequence is finally processed by the fast controller subpart $G_2(z) = \dfrac{G_p(z)}{M(z)}$, involving a fast rate plant model, $G_p(z)$. Figure 2 reproduces the proposed scheme.

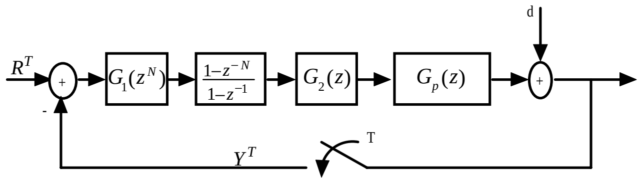

Figure 2. Dual-rate control strategy.

The design does not require any further refinement.

2.1. Illustrative Example

Let us reproduce the example in [1], (section 7). The continuous plant P is a typical DC-motor with transfer function:

$$G(s) = \frac{400}{s(s+50)}$$

the output sampling period being T = 0.05 sec. and N =2. The MRIC model (2) is:

$$G_1(z^2) = \frac{0.1673z^2 + 0.0163}{z^4 - 1.0821z^2 + 0.0821};$$

$$G_2(z^2) = \frac{0.0858z^2 + 0.0977}{z^4 - 1.0821z^2 + 0.0821}$$

The desired behaviour, assuming a *w_n=20 rad/sec*. and a damping coefficient of *0.707*, is expressed by the closed-loop transfer function:

$$M(s) = \frac{400}{s^2 + 28.18s + 400}$$

or, in discrete time:

$$M(z^2) = \frac{0.3047z^2 + 0.1886}{z^4 - 0.7498z^2 + 0.2431}$$

Firstly reproducing the method exposed at [1], in order to be able to achieve full pole and zero assignment, this reference model is slightly modify to:

$$M(z^2) = \frac{(0.3047z^2 + 0.1886)(0.9z^2 + 1)}{z^2(z^4 - 0.7498z^2 + 0.2431)}$$

The procedure to achieve numerator and denominator matching in $M(z^2)$ assumes the classical rules in selecting the polynomials in the controllers $C_{ij}(z^2)$ in (3). In this example, it results:

$$C_1(z^2) = \begin{bmatrix} c_{11}(z^2) \\ c_{21}(z^2) \end{bmatrix} = \begin{bmatrix} -7.28 \\ 1.86 \end{bmatrix}$$

$$C_2(z^2) = \begin{bmatrix} c_{12}(z^2) \\ c_{22}(z^2) \end{bmatrix} = \frac{1}{z^2 - 1} \begin{bmatrix} -16.4 \\ 15.52z^2 + 3.57 \end{bmatrix}$$

As it is shown in that paper the continuous plant output is highly oscillatory (see figure 2 where we reproduce the simulation at [1]). This is normal because there are, as it has been told, two different control actions independent between them.

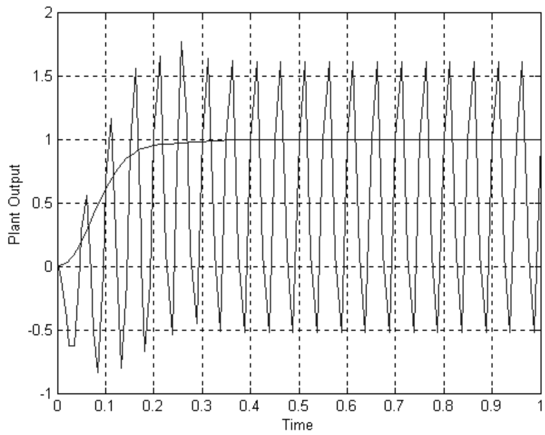

Figure 3. Ripple in the step response.

In the same figure the plant output response with the dual rate controller assuming the same environment (MRIC with N=2) has been added. In this case the results are:

$$G_1^T(z^2) = \frac{z^4 - 0.75z^2 + 0.244}{z^4 - 1.055z^2 + 0.055}$$

$$G_2^{T/N}(z) = \frac{0.0982z^3 - 0.0487z^2 - 0.0716z + 0.022}{0.0858z^3 - 0.0563z^2 - 0.0325z + 0.028}$$

assuming again *T=0.05* and *N=2*.

2.2. Comments

As it is clear if the design takes into account the global input sequence a proper result without ripple can be obtained. The initial requirements are fulfilled without ripple using the dual rate controller. Perhaps the additional constraint of pole-zero assignment is leading to the bad result presented in [1].

3 Inferential control

Model-based control is a popular and powerful control design technique. In one way or another, the controller includes the model of the plant. Virtual sensors [13] are also becoming common “devices” to get inaccessible variables. But, in many cases, the information process takes places in open loop, there is no feedback, and modelling errors or process disturbances cannot be counteracted.

This is the case when the output of the process is measured at low rate (as in the previous case) and the control action is able to be updated more frequently. The MRIC control is one option but another alternative is to predict or estimate the not available output, based on the process model, and implement an inferential control. This schema is depicted in figure 4.

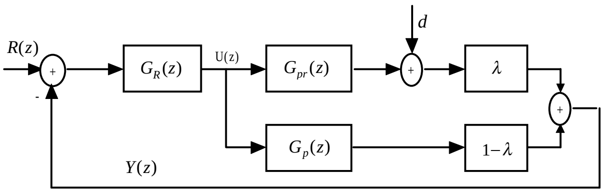

Figure 4. A schema of inferential control.

The upper part of the figure represents the actual process $\mathbf{G_{pr}(z)}$ and its control, $\mathbf{G_R(z)}$, being designed by any suitable direct or indirect method. λ is an availability parameter: $\lambda = 1$ if the output is measured and $\lambda = 0$ if it is not. **R** and **d** denote the external inputs corresponding to reference and output disturbance, respectively. In order to implement a faster controller, the missing output is computed based on the plant model, $\mathbf{G_p(z)}$, although the external disturbance is not taken into account, and any modelling uncertainty will affect the value of the estimated output. The output/reference transfer function, from figure 4, is:

$$\frac{Y}{R} = \frac{G_p G_R}{1 + G_p G_R (1-\lambda) + G_{pr} G_R \lambda} \qquad (4)$$

The situation is equivalent to the MRIC if the availability parameter λ is one every N periods and zero in between. Thus, for the sake of comparison with the multirate schemes, the sampling period is assumed to be T and the control updating period T/N.

The main goal is to try to reproduce the behaviour of a fast sampled control system, as depicted in figure 5, where the output is available at the same rate than the input is updated.

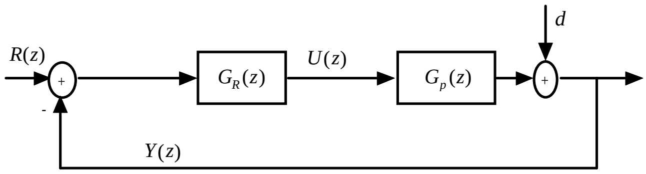

Figure 5. Fast single-rate control.

It is evident that this schema is more comprehensive from the control point of view than the inferential control. Moreover, increasing the value of N, in the limit, an open-loop model based control will be obtained, and model uncertainties or, in the worst case, plant instability could not be counteracted. The comparison may be established at different point:

- Noise rejection. The inferential is feeding back less noise.
- Disturbance rejection. The inferential has less information about the non measurable disturbances.
- Robustness. The model uncertainty is not available in the model.
- Acquisition system. The fast control requires the frequent output accessibility.

Also based on the process model, the dual rate controller previously introduced [11], is an alternative to the inferential control. In this approach, as already said, instead of an explicit model of the plant the controller is split into two parts working at different sampling rates, both involving the discretized model of the plant also at different sampling rates.

Of course, one of the problems we have observed using this approach is the sensitivity of the controlled plant behaviour to model mismatching, also obvious with an inferential control. However if we suppose that both the actual plant and the uncertainty are known, it is possible to deduce an interesting set of conclusions.

3.1. Design example

As an example, consider the process:

$$G_p(s) = \frac{1.5}{(s+0.5)(s+1.5)}$$

An acceptable continuous time **PID** controller is given by

$$u(t) = K_P \left[e(t) + T_D \dot{e}(t) + \frac{1}{T_I} \int_0^t e(\tau) d\tau \right]$$

with: $K_p = 8, T_D = 0.2, T_I = 3.2$. A discrete time **PID** controller approximation for T, is given by

$$G_R^T(z) = \frac{q_0 + q_1 z^{-1} + q_2 z^{-2}}{1 - z^{-1}};$$

$$q_0 = K_P\left(1 + \frac{T_D}{T}\right); q_1 = -K_P\left(1 + -\frac{T}{T_I} + 2\frac{T_D}{T}\right); q_2 = K_P\left(\frac{T_D}{T}\right)$$

An output sampling period $T = 0.2$ sec and a fast control updating of $T/N = 0.1$ have been selected for the dual rate strategies, whereas a unique fast sampling rate of $T/N = 0.1$ is used for the single rate fast control. Usually it is considered that $G_p = G_{pr}$ and some erroneous conclusions about another magnitude relations, like control w.r.t. disturbance, *u/d*, are reached.

Let us assume a multiplicative uncertainty, the actual process transfer function being:

$$G_{pr}(s) = \frac{1.5}{(s + 0.5)(s + 1.5)} \frac{(10s + 1)}{(100s + 1)}$$

Some experimental results could be easily obtained by means of a sampled-data frequency response analysis tool proposed by the authors. The magnitude Bode diagrams are shown in fig. 6

In this figure, the following notation, about the legend of the different curves, is assumed:

a) discrete fast control loop (as in fig. 5) applied to the fast plant model
b) discrete fast control loop applied to the real process.

In both cases, **a** and **b**, the controller has been designed for the plant model.

c) dual rate inferential control (as in fig. 4) with ideal conditions. That is, $G_{pr}(z)$ is identical to the process model (of course is the same curve than **a**)
d) dual rate inferential control applied to the real process.

For **c** and **d** cases, the controller is the same that the one used for **a** and **b**.

e) dual-rate with non conventional controller (as in fig. 2) with ideal conditions.
f) dual-rate with non conventional controller including the actual plant transfer function which has not been used to design the dual rate controller.

It is clear that if the real process is assumed, the frequency responses must be studied deeply. If only the process model is considered, that is, under ideal conditions, the conclusion is clear: taking into account that the **a** and **c** curves are the same, the inference control is preferable. However if the model mismatch happens at the low frequency range, as assumed in this case, the curves of magnitude **b** and **d** lead to the opposite conclusion.

Moreover, if the non-conventional dual rate control structure is used, the performance degrading is attenuated, as it is clearly seen comparing the responses **b**, **d** and **f**.

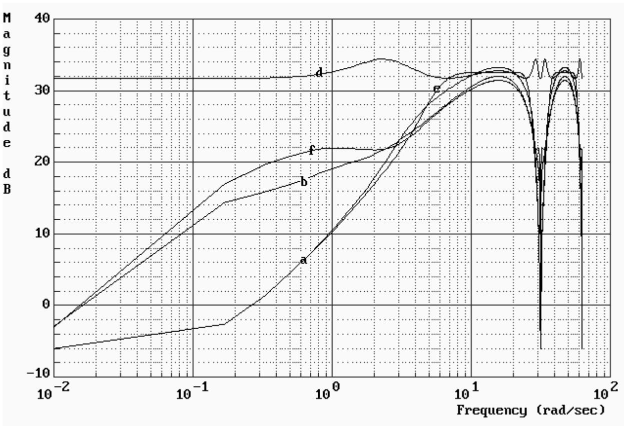

Figure 6. ***u/d*** Bode magnitude plot.

The frequency and time closed loop performances (output versus reference) for these cases are shown in figures 7 and 8, respectively.

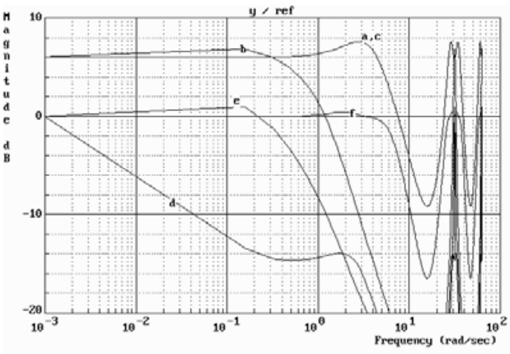

Figure 7. ***y/ref*** Bode magnitude plot, in similar conditions as in fig.6 (see the text).

In [3], it is claimed that the control structure in fig. 4, the inferential control, is better than the fast control in fig. 5. In particular, in the conclusion section is said: “… *the dual-rate inferential control scheme is advantageous in stability robustness over the fast single-rate control scheme.”*

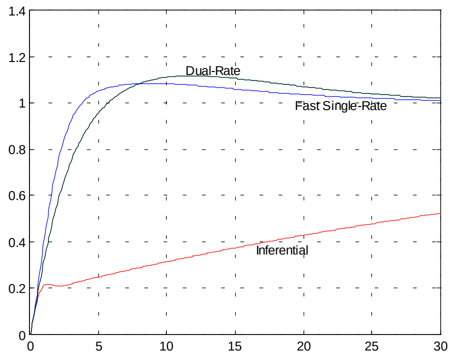

Figure 8. Step responses

This conclusion is “proved” using a very special system and it cannot be generalised. The design is based on a free delay model such as:

$$G_p(z) = \frac{0.15}{z - 0.9}$$

while the real process transfer function is:

$$G_{pr}(z) = \frac{0.13}{z^3(z - 0.92)}$$

Thus, the multiplicative uncertainty is:

$$\Delta(z) = \frac{0.8667}{z^3}\frac{z - 0.92}{z - 0.9}$$

which is dominated by a three time delay units. It is well known that delays in the loop usually degrade the control performance (see the next section). So, if the control is based on the signal without delay, that of the model, the response should be better.

3.2. Comments

The first conclusion is that feedback is always an advantage in practical control, due to system uncertainties and disturbances.

Second and most important one is that properties shown by very particular designs cannot be extrapolated and considered as general design rules.

4 Additional Time Lag in the Loop

In an industrial controlled system it is possible to have some sources of unavoidable delays, either in the plant or in the actuators, mainly due to transportation lags, the existence of commutation devices or neglected dynamics. In general, these additional delays are considered in a negative way because they degrade the controlled system behaviour and efforts are taken to cancel or diminish their effect. But this is not always the case. It is well known that the feedback of the measurement noise can excite the system in a non-desired way, amplifying the noise and disturbing more the plant. If a delay is introduced, the noise and its effect on the plant can be decoupled and better behavior could be achieved. In [14], the idea of using an additional delay for decoupling the dominant dynamics of a plant and the possible internal resonance or drifting, has been reported. In multivariable systems, it has been also studied by Morari and co-workers, [15], the positive effect of additional delays in decoupling the decentralized control loops.

Let us first clarify the concept on phase-conditionally stable systems, similar to the concept of gain-conditionally stable systems [16]. This characteristic implies that the system is stable for a given range of phase lag in the loop transfer function. This situation can be find in resonant systems, where the resonant frequency is out of the required bandwidth of the controlled system. In the figure 9, the polar plot of a gain conditional (continuous line, Gain-C) and a phase conditional (dotted line, phase-C) stable system are sketched.

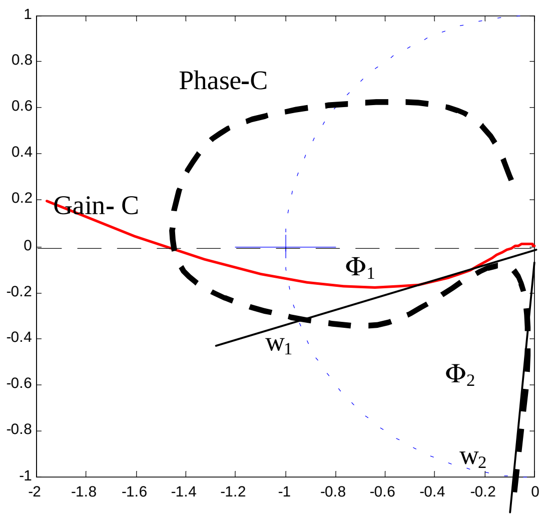

Figure 9**:** Polar plot of gain (Gain-C) and phase (Phase-C) conditionally stable systems

A continuous time system, $G(s)$, in order to present the phase-conditional stability property should be:

- the frequency response gain at the resonant frequency greater than one
- the frequency response gain lower than one for a range of lower frequencies.

In this case, the introduction of either dead time or additional lags may stabilize an unstable system.

For instance, referring to the same figure 9, the system **Phase-C** is unstable but, if a dead time is added in the loop, the system can be stabilized. A greater dead time will turn it again unstable. This system is stable for

$$\frac{\Phi_1}{w_1} < T < \frac{\Phi_2}{w_2}$$

where Φ_1 and Φ_2 are the loop frequency response phases at frequencies w_1 and w_2, respectively of the initial system, the gain being unitary.

4.1. Example

Let us consider the closed loop control of the system

$$G(s) = \frac{0.2}{s(s^2 + 0.01s + 1)}$$

This system exhibits a resonance peak around the $\omega_p = \omega_n \sqrt{1-\xi^2} \approx 1[rad/s]$. If a unitary negative feedback is applied, the full output is fed back and the system reaction tries to counteract the overshoot, leading to an unstable closed-loop response.

The Bode diagram for unity feedback is shown in fig. 10.

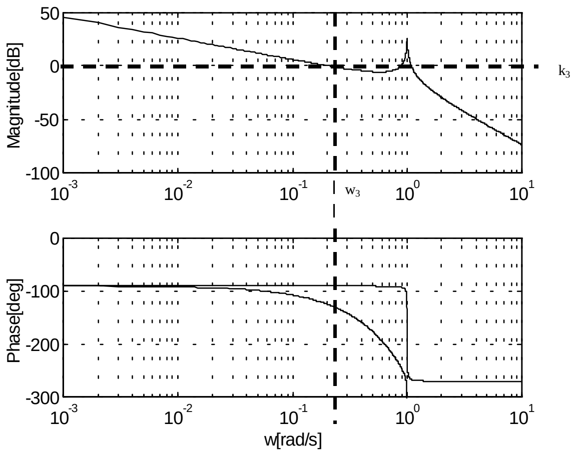

Figure 10: Bode diagram. Process with dead time (lower phase graph).

The magnitude curve crosses the 0 dB line three times, at frequencies {0.2, 0.85, 1.15}. At the point where the phase reaches -π rad (upper line), the magnitude is greater than one. Thus, the system is unstable. It is clear that if the gain is reduced the system becomes stable but very slow. Starting from a stabilizing low gain, if the gain is increased to get a faster response the cut-off frequency jumps almost to the resonant frequency and the system becomes unstable.

If the gain is further increased , the system becomes phase-conditionally stable, as shown in figure 10.

If a dead time in the feedback path is assumed, it does not change the magnitude plot and introduces an additional lag, as shown in fig.10 (lower curve in the phase graph) for T_d=3 s.

In this way, the cut-off frequency is enlarged to ω=0.24 rad/s keeping stable the system with a phase margin of 65º. The closed-loop step response is plotted in figure 11.

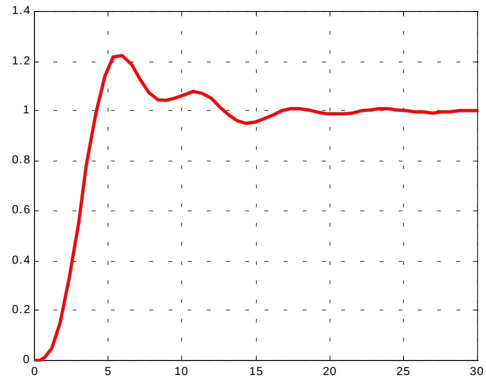

Figure 11: Step response with T_d=*3 sec.*

4.2. Comments

In this case, the general rule about the degrading effect in the controlled system response due to delays in the loop is true, but, in some specific conditions, as those considered in the above example, the delay may improve the stability.

5 Conclusions

The use of powerful control design software packages as well as the development of intricate design procedures lead to "magic" solutions. And the assumptions originally taken to prove the properties of these designs could fail in a new application.

In this contribution, three rather common situations have been analysed. First, the multirate control. There are a bunch of design techniques applicable to these systems. Ripple in the intersampling time response is not an inherent characteristic to this control strategy. A controller design to meet some requirements has been developed following two different approaches. The so-called dual-rate controller allows a fast and smooth response. Thus, the ripple, if it appears, could be due to the used control design approach.

Second, the properties of the so-called inferential control should be properly treated. The suitability of this control strategy strongly depends on the control problem conditions: measurement noise, kind of uncertainty, disturbances, …

Finally, when teaching basic concepts to control students, the effect of time delays in the loop should be also analysed. In very specific conditions, additional delays in the loop may improve the controlled plant performances.

Thus, based on the review of some concepts and design methodologies, the need of a final overview of any control solution according to the control engineering good practice has been suggested.

6 References

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