TUNING OF PID CONROLLERS: SURVEY OF SISO AND MIMO TECHNIQUES

H. N. Koivo and J. T. Tanttu

Tampere University of Technology, Control Engineering Laboratory, P O Box 527, SF-33101, Tampere, Finland

Abstract.

A survey of different tuning methods of a PID controller is given. The scalar case is limited to most recent developments only. In multivariable case the different approaches for unknown plants are reviewed. The basic results have been extended to time-delay systems and distributed parameter systems. Decentralized control tuning, adaptive and expert system directions are also briefly discussed.

Key words. PID control; Multivariable control systems; Expert systems; Decentralized control; Adaptive control.

INTRODUCTION

The perennial workhorse of industrial controls is a proportional-integral-derivative (PID) controller. Well over ninety percent of all existing control loops are PID controllers. Since their number is so overwhelming, tuning of PID controllers is an important issue both in starting up new plants and in everyday operation. It is therefore surprising that only in the 1980's has automatic tuning of PID controllers received more attention, witnessed by a number of excellent surveys for tuning of SISO (single input - single output) PID-controllers (Åström and Hägglund, 1984, 1988; Clarke, 1986; McMillan, 1983).

Several different design methods for multivariable PI(D) controllers have also been suggested - e.g. Smith and Davison (1972), Solheim (1974), Seraji and Tarokh (1977), Owens (1978) - the tuning in the MIMO (multiple input -multiple output) case has received much less interest, although from the industrial point of view it is equally important. Multivariable PI(D) controllers have been used in a number of applications, among them heat exchanger (Davison, Taylor, Wright, 1980), paper quality variable control (Kunde, Chen, Mathre, 1983), robot control (Koivo and Sorvari, 1985) artificial heart (Wang, Lu, and McInnis, 1987), and paper machine head box (Jussila. Tanttu, Piirto, and Koivo, 1989).

The objective of this paper is to survey the existing results for tuning both scalar and multivariable PID controllers.

In another paper of this conference (Lieslehto, Tanttu) a comparison is made between four different multivariable PI controller tuning methods. Lieslehto, Tanttu, and Koivo (this conference) consider an expert system, which performs the steps from input -output pair selection to controller tuning . So in this paper we concentrate more on the tuning methods proper, although the previous steps of the design process i.e. modelling, dividing the process to be controlled into manageable blocks, selecting the input-output pairs for SISO control, and the interaction analysis to decide whether multivariable control should be used, are very important.

SCALAR PID CONTROLLER TUNING

The ideal SISO PID controller is of the form

$$u(t) = K_P e(t) + K_I \int_0^t e\,dt + K_D \frac{de}{dt}$$

or equivalently

$$u(t) = K\left[e(t) + \frac{1}{T_I}\int_0^t e\,dt + T_D \frac{de}{dt}\right]$$

where u is the control variable, $e = y_{ref} - y$ the error , y the output, , and y_{ref} the reference signal. The gains K_P ,K_I , and K_D are real numbers. The latter form with proportional gain K, integral time T_I , and derivative time T_D is often preferred.

Because of the space limitations the review on the SISO tuning methods will be limited to some recent developments only. The reader is assumed to be familiar with the classical tuning methods.

The emphasis in 1980's has been on automatic tuning of scalar PID controllers. Automatic tuning is not a straightforward exercise in applying e.g. standard optimization techniques, but a rather complicated problem in data analysis, modelling, and control. The steps are roughly as follows: when to start tuning procedure, how long a data window should be used, is process delay significant, what is the model to be used, is the modelling (identification) performed in open loop or closed loop, is tuning a one shot effort or continuous (self tuning).

Some tuning methods rely on examining the process data (Kraus and Myron, 1984) to initiate tuning. Others generate their own excitation e.g. with a relay technique (Åström and Hägglund, 1984, 1988). A separate time delay estimation seems to be required in many industrial problems where the delay is unknown or time varying. Efforts in this direction have been suggested in Hansen (1983) and de Keyser (1986).

Dumont, Martin-Sánchez, and Zervos (1988) make an interesting comparison of auto-tuned regulators and adaptive predictive control system on an industrial bleach plant. Other comparisons have been made by Kaya and Titus (1988) on four self tuning control products and by Minter and Fisher (1988) on academic vs. industrial adaptive controllers.

An interesting development in tuning scalar PID controllers has been the use of expert systems: Åström, Anton, and Årzén (1986), Porter, Jones, and McKeown (1987), Sripada, Fisher, and Morris (1987), Lieslehto, Tanttu, and Koivo (1988), Thompson and McCluskey (1988). Robust control has also influenced PID tuning witnessed by Pohjolainen and Mäkelä (1988) and Rivera and Morari (1990). A fresh look into tuning problem has been taken in Zervos, Bélanger, and Dumont (1988).

A more detailed discussion of scalar PID tuning is provided in Koivo and Tanttu (1990).

MULTIVARIABLE PID CONTROLLER

Analogously to scalar PID controller the multivariable controller takes the form

$$u(t) = K_P e(t) + K_I \int_0^t e\,dt + K_D \frac{de}{dt}$$

or the corresponding transfer function

$$G_{PID}(s) = K_P + K_I \frac{1}{s} + K_D s$$

where u is the control vector, $e = y_{ref} - y$ the error vector, y the output vector, and y_{ref} the reference signal. The gains K_P, K_I, and K_D are matrices of appropriate dimensions. The multivariable PID structure has been suggested by many authors among them Davison and Smith (1971 and 1972), Fond and Foulard (1971), Johnson (1968), Porter (1970), and Rosenbrock (1971). The design of multivariable PID controller for linear plants has further been considered from a number of different viewpoints.

The idea of controlling unknown multivariable plants with a PID controller and determining the gain matrices based on a number of measurements is not so well established. What make this significantly harder than the scalar case are interactions between different variables. Can simple tuning rules for multivariable PID controller tuning be established? And further, can these be automated? Although scalar controllers are used in the majority of industrial applications, there are 5-10% control loops which cannot be controlled by SISO PID controllers. These require multivariable controllers.

From the scalar case one can deduce that it is important how the unknown system is modelled. Stability of the plant is essential. One of the first contributions to the tuning is by Davison (1976). He considers an unknown linear time-invariant plant, which is open-loop stable. Limiting his more general results to the multivariable PID tuning the system considered is

$$\dot{x} = A x + B u$$

$$y = C x$$

$$e = y_{ref} - y$$

where x is the state vector, u is the control vector, y is the output vector, and y_{ref} the reference signal. The assumptions made are:

1. Matrix A is asymptotically stable.
2. The control input u can be excited and the output y, which is to be regulated, can be measured. This implies that the number of inputs and outputs are known.
3. The order of the plant and the matrices A, B, and C are unknown.

Problem. It is desired to find a multivariable PID controller for the system so that asymptotic regulation occurs for all constant reference signals and that the response is as "good" as possible.

The problem definition is vague mathematically regarding the goodness of the response. Of course, an optimal control problem could be formulated to determine the "best" gain parameters. In tuning a practical engineering approach is used, as is also the case e.g. in multivariable frequency domain techniques by Rosenbrock (1974) and MacFarlane and Belletrutti (1973). Tuning controllers is based on experiments, e.g. step responses, and the human judgement is used to evaluate the performance of the controller.

Multivariable feedback design in frequency domain (Rosenbrock, 1974; MacFarlane and Belletrutti, 1972) is based on the idea of constructing a controller which approximately decouples the closed-loop plant both at zero frequency and at high frequencies. Consider the open-loop transfer function

$$G(s) = C(sI - A)^{-1} B$$

It is easy to see that at zero frequency, s = 0, $G(0) = C(-A)^{-1}B$. Since the integral controller takes care of the control at steady-state, or zero frequency, the appropriate choice for the integral gain should be inverse of the plant at steady state:

$$K_I = \varepsilon G^{-1}(0) = \varepsilon [C(-A)^{-1} B]^{-1}$$

where ε is a fine tuning parameter. This has been suggested e.g. by Rosenbrock (1971) and Davison (1976).

Proportional controller should be effective at high frequencies. If the transfer function is developed into Taylor series, when s is large then

$$G(s) = \frac{CB}{s} + \frac{CAB}{s^2} + \frac{CA^2B}{s^3} + \ldots$$

Taking only the first term into account, the proportional gain K_P is proposed to be (Penttinen and Koivo, 1979, 1980)

$$K_P = \delta\,(CB)^{-1}$$

where δ is the fine tuning constant. A similar suggestion has also been made by Mayne (1979).

The derivative gain matrix is harder to pick. If it is kept small ($\|K_D\|$ small), a reasonable choice for K_D is to use the same matrix as in proportional gain (Koivo, 1980):

$$K_D = \gamma\,(CB)^{-1}$$

where γ is the fine tuning constant.

Davison, Taylor, and Wright (1980) use as the proportional gain matrix the same as in the integral gain matrix

$$K_P = \delta\, G^{-1}(0) = \delta\left[C\,(-A)^{-1}\,B\right]^{-1}$$

Thompson's (1982) proportional gain matrix is based on arguing that CB is not easy to determine accurately or it might be nonsingular. Therefore let

$$K_P = \delta\left[C\ A^{-1}\,(e^{A\tau}-1)\,B\right]^{-1}$$

Here τ is the so-called average *e*-folding time of the system. It is likely that this matrix will decouple the plant in over its midrange frequency. Koivo and Pohjolainen (1981) give a similar gain matrix to avoid rank deficiency

$$K_P = \delta\left[C\,e^{At_0}\,B\right]^{-1}$$

For derivative gain Thompson (1982) proposes the matrix

$$K_D = \gamma\, I$$

He argues that the effect of D-part is minor compared with the integral and proportional gains at high frequencies. So although it is unlikely that this matrix gain will decouple the plant at high frequencies, both proportional and integral gains will take care of decoupling.

Since the initial assumption is that the plant is stable, the controlled plant must remain stable. This has been proved by Davison (1976) for I controller and by Penttinen and Koivo (1980) for PI controller.

The previous controller gain matrices can be classified as "low" gains. Owens and Chotai (1982) approach the tuning problem from a different angle using "high" controller gain. The plant assumptions are that the plant may be unstable but minimum phase.

Tuning of multivariable discrete time PI controllers for unknown systems has been discussed by Peltomaa and Koivo(1983).

EXPERIMENTAL DETERMINATION OF THE GAIN MATRICES

Since the plant is unknown, the matrices CB and $-CA^{-1}B$ have to be determined experimentally. Algorithms 1 and 2 outline the procedure:

Algorithm 1. (determining CB)

Step 1. Let $u(t) = 0$. When the steady-state ($y(\infty) = 0$) is achieved, choose a constant input $u(t) = u_1$ ($\neq 0$) and apply it to the plant. Then .

$$\dot{y}(0) = \dot{y}_1 = CB\,u_1$$

From the corresponding step response $\dot{y}_1$ can be computed, e.g., graphically.

Step 2. Repeat step 1 with a constant control u_2, which is linearly independent of u_1. Then

$$\dot{y}(0) = \dot{y}_2 = CB\,u_2$$

Compute $\dot{y}_2$ from the corresponding step response.

Step m. Repeat step 1 with a constant control u_m, which is linearly independent of $u_1, u_2, \ldots, u_{m-1}$. Then .

$$\dot{y}(0) = \dot{y}_m = CB\,u_m$$

Compute $\dot{y}_m$ from the corresponding step response. As a result

$$CB = [\,\dot{y}_1, \dot{y}_2, \ldots, \dot{y}_m\,]\,[\,u_1, u_2, \ldots, u_{m-1}\,]^{-1}$$

Algorithm 2. (determining $G(0) = -CA^{-1}B$)

Step 1. Apply a constant input $u(t) = u_1$ ($\neq 0$) to the open-loop plant. The system is stable, so a steady-state solution $y(\infty) = y_1$ exists. Measure y_1.

Step 2. Repeat step 1 with a constant control u_2, which is linearly independent of u_1. Measure y_2.

Step m. Repeat step 1 with a constant control u_m, which is linearly independent of $u_1, u_2, \ldots, u_{m-1}$. Measure y_m.

As a result

$$G(0) = [\,y_1, y_2, \ldots, y_m\,]\,[\,u_1, u_2, \ldots, u_{m-1}\,]^{-1}$$

EXTENSIONS TO OTHER PLANTS

Many processes have time delays. In SISO cases PID controllers are frequently used to control plants with time delays. Some of the tuning procedures discussed above have been extended for such plants. Koivo and Pohjolainen (1981, 1985) consider systems, which have time delays in control variable. Jussila and Koivo (1985, 1987) treat the case where the delays may also occur in the state variables.

Distributed parameter systems have first been treated in Pohjolainen and Koivo (1979), where tuning of I controller is discussed. Pohjolainen (1982) discusses PI controller for infinite dimensional systems. Kobayashi (1986) considers tuning of a discrete I controller for parabolic systems and a digital PI controller for exponentially stable distributed parameter systems. Logemann and Owens (1987) using frequency domain theory treat the low-gain PI control for a wide class of infinite-dimensional systems.

DECENTRALIZED AND EXPERT TUNING

Davison (1978) first addressed a very important issue of tuning decentralized controllers. He later applied these ideas to load and frequency control of a power system with Tripathi (1978, 1980). Some issues related to this have been treated by Lunze (1989). Adaptive and expert systems in multivariable PID control tuning have been developed by number of authors: Bristol and Hansen (1988), Jones (1988), Jones and Porter (1985), Koivo and Sorvari (1985), Lieslehto, Tanttu, and Koivo (this symposium), Porter and Khaki-Sedigh (1987), Tanttu (1984, 1987), Wang and Owens (1988). Piirto and Koivo (1989) demonstrate in an advanced portable control station how a multivariable PI(D) controller can be implemented and used in real time control of processes.

Multiloop applications are discussed e.g. by Gawthrop and Nomikos (1989).

CONCLUSIONS

Although tuning of MIMO PID controllers has not progressed to the stage of SISO PID control, strong inroads have been made into this very important practical issue. The PID control structure seems to be a good candidate for robust control also in multivariable case. Its simplicity and demonstrated usefulness make the tuning problem an interesting challenge. Different approaches to this problem are surveyed. Decentralized, adaptive and expert system viewpoints to MIMO PID tuning have also been reviewed in the paper.

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