FEATURE SERIES: PRACTICAL PROCESS CONTROL

4: Tuning a PID Controller

Myke King continues his detailed series on process control, seeking to inspire chemical engineers to exploit untapped opportunities for improvement

IF THERE was an award for the engineering subject that has prompted the largest number of research papers, then tuning the PID controller must be one of the contenders for the top spot. *The Handbook of PI and PID Controller Tuning Rules*, written by Aidan O'Dwyer, includes most of the techniques published between 1935 and 2008. These number several hundred and many more have been developed since. The advent of computer simulation removed the need to use costly instrumentation and allowed research to fit into limited budgets. It provided the means for many students to gain their Master's degree or PhD. Further, chemical engineering is not the only subject in which process control is taught. The pool of potential researchers includes engineers from the mechanical, electrical and systems engineering departments.

Figure 1 shows the results of a survey carried out in 2019. Given the availability of so many tuning methods, it might be surprising that only 19% of engineers are using them. Tuning by trial and error is still the method of choice for many. This is time-consuming. The time to steady state, following a process disturbance, can be calculated from the process dynamics (as $\theta + 5\tau$). For our example fired heater (*Issue 981*), this would be around 30 minutes. Given the number of trials necessary to optimise tuning, such a controller would take several days to tune. In practice, the engineer is unlikely to spend the time necessary and will stop when the tuning is acceptable – almost certainly leaving scope for improvement. Further, given the shortage of expertise within the process industry, the time spent could have been put to better use in implementing new controllers.

Figure 2: Quarter decay ratio

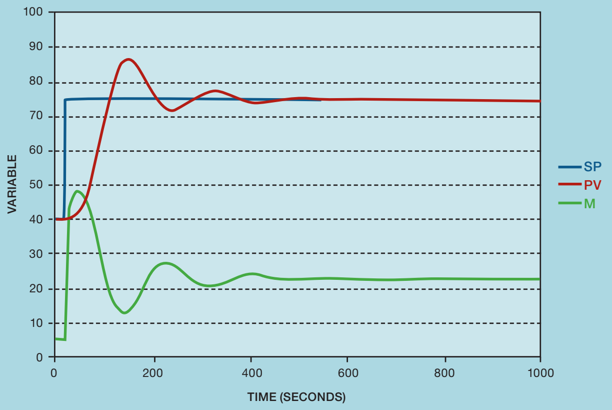
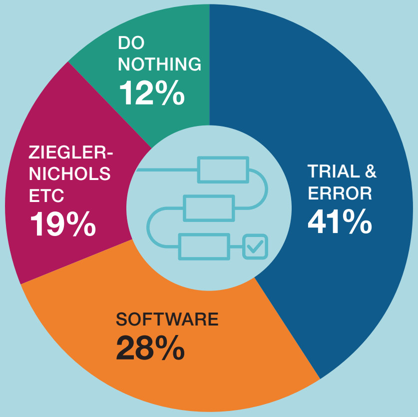


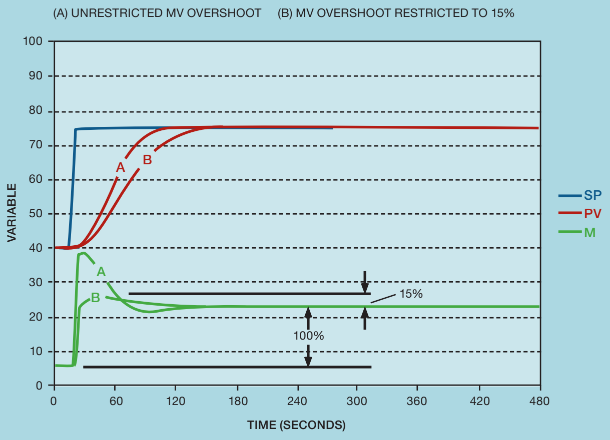
Figure 1: Industrial survey of tuning methods



TUNING CRITERIA

Before deciding on a tuning method, we first need to define what is meant by a well-tuned controller. What criteria do we use to assess this? The earliest published is the *quarter decay ratio*. As Figure 2 shows, following a disturbance, the process has a marginally oscillatory response with the height of each peak being a quarter of the height of the previous. This criterion was used by Ziegler and Nichols in developing their tuning method. Published in 1942, the method appears in almost every textbook and is included in many process control lectures. The method is now around 50 years beyond its use-by date. The instrumentation used at the time of the research would have been pneumatic. This is only an approximation to its modern digital equivalent. The method was developed by making process disturbances (known now as *load changes*) rather than set-point (SP) changes. This gives tuning that is far too aggressive for set-point changes. But perhaps the most significant

Figure 3: MV overshoot limit



change is that we would not today consider quarter decay a well-tuned controller.

First appearing in the 1970s, a number of criteria, based on penalty functions, were used to develop tuning methods. The most enduring of these is the *integral over time of absolute error* (ITAE). In its analog and digital forms, it is defined as

$$\int_{t=0}^{\infty} |E|t.\,dt \qquad \sum_{n=1}^{n\to\infty} |E|n.ts$$

The time since the disturbance (t or $n.ts$) acts as a weighting coefficient. It discourages a tuning solution that gives a rapid initial response at the expense of long-term minor oscillation. Empirically it works well. Curve A in Figure 3 shows the result of tuning that minimises this penalty.

COMPROMISE

However, when considering how well a controller is tuned, we need to look beyond a fast return to SP. As Figure 3 shows, in order to achieve this, rapid changes are made to the controller output (M). In our example, this is the set-point of the fuel flow controller. Provided the control valve isn't limiting, the manipulated variable (MV) – the fuel flow - will follow M. The initial kick in M is around double that necessary to reach the new temperature SP. This may cause problems such as violation of burner pressure limits, flame impingement and sub-stoichiometric combustion. We therefore restrict the rate of change of the MV by imposing a limit on its overshoot. Figure 3 shows how this defined. Curve B is the result of re-tuning the controller to work within this constraint. We have compromised between a fast approach to SP and excessive MV movement.

The 15% limit proves to be a reliable rule of thumb for most controllers. Figure 4 shows the circumstances under which it applies – when the θ/τ ratio is less than 1.8. Almost all processes will fall into this range. Knowing that the potential for a large MV overshoot increases as θ approaches zero gives us a method of checking whether a tuning method accounts for MV movement. The Cohen-Coon tuning method, again often taught, gives the following for the full PID controller.

$$K_c = \frac{1}{K_p}\frac{\tau}{\theta}\left[1.35 + 0.25\frac{\theta}{\tau}\right] \qquad T_i = \theta\left[\frac{1.35 + 0.25\frac{\theta}{\tau}}{0.54 + 0.33\frac{\theta}{\tau}}\right] \qquad T_d = \theta\left[\frac{0.5}{1.35 + 0.25\frac{\theta}{\tau}}\right]$$

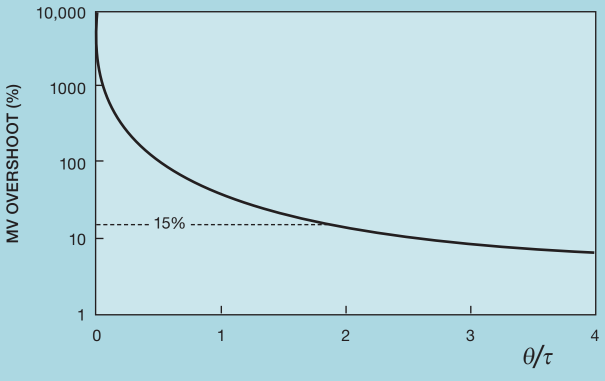
If we set θ to zero, we see that K_c becomes infinite. T_i becomes zero but, remembering that is the denominator of the integral term, again results in infinite action. Only the zero result for T_d seems reasonable; if there is no delay then there is little need to anticipate behaviour. There's no error in the tuning method. If the process truly has zero deadtime, and the control is analog (no sampling delay), then setting the controller gain to maximum is theoretically feasible. It will, of course, cause an MV overshoot that is likely to trip the process. It gives us reason to reject Cohen-Coon as a tuning method.

In the 1990s, another approach gained momentum. It is derived by applying a techniques known as *direct synthesis*. This develops a controller that will respond to a SP change by following a user-defined trajectory. It results in a method described as *lambda* or *IMC* tuning. The result is usually not an exact match to the PID algorithm and so approximations have to be made. Different developers have made different approximations, so the formulae below are only an example.

$$K_c = \frac{1}{K_p}\frac{\tau + \frac{\theta}{2}}{\lambda + \frac{\theta}{2}} \qquad T_i = \tau + \frac{\theta}{2} \qquad T_d = \frac{\tau\theta}{2\tau + \theta}$$

The term λ is chosen by the engineer. It is the lag of the trajectory of the approach to SP. If set equal to the process lag (τ), the closed loop response will follow the same curve as the open loop

Figure 4: Unrestricted MV overshoot



response. Its presence avoids the problem of infinite proportional action and so can be used to restrict MV movement. The problem lies in that the relationship between MV overshoot and λ varies, depending on the process dynamics. The engineer must again use trial and error to choose its value.

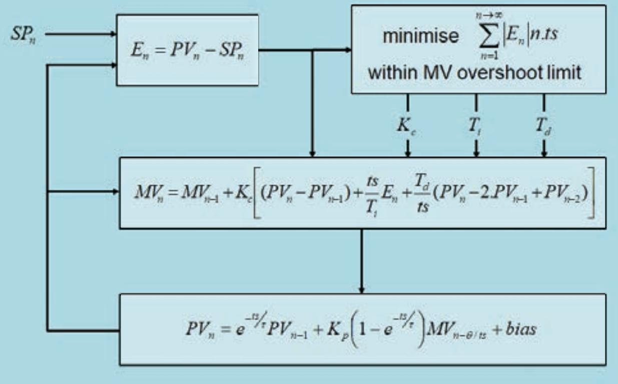
Virtually all published tuning methods assume analog control. This does not present a problem provided the controller scan interval is small compared to the process dynamics. In the process industry this is usually the case. However schemes installed on compressors, such as load control and surge protection, will have dynamics measured in seconds. This is often used by compressor manufacturers as the justification to locate the controllers in a programmable logic controller (PLC), which has a much shorter scan interval than a distributed control system (DCS), or even use analog control. The DCS scan interval is typically 1 to 2 seconds. Taking this into account when tuning should permit effective compressor controls to be located in the DCS, avoiding the need to support an additional control system. To test whether a tuning method is suitable for digital control we need only check whether the scan interval (*ts*) is used in the calculations.

The last, and most important, check that should be made of a candidate tuning method is that it is designed for the chosen PID algorithm. All the controllers presented in the previous article can be tuned to give the same performance but the tuning parameters will be very different. For example, the interactive version closely matches the controller used by Ziegler and Nichols, but it is the ideal version that is commonly used today. In theory we can convert from one set of tuning to another.

$$(K_c)_{ideal} = K_c \frac{T_i + T_d}{T_i} \qquad (T_i)_{ideal} = T_i + T_d \qquad (T_d)_{ideal} = \frac{T_i T_d}{T_i + T_d}$$

However such conversion formulae make assumptions. This method, for example, should strictly be applied only to analog control. Further it takes no account of modifications commonly made to the control algorithms by the system vendors.

Figure 5: Computerised PID tuning



WHY WE NEED TUNING SOFTWARE

What the research has shown us is that a formulaic method of tuning is likely to be impractical. In the previous article we described three control algorithms – PID, PI-D and I-PD. Each can be either ideal or interactive, giving us a total of six. So far we have considered only *self-regulating* processes. Our heater is an example of these. If we change the fuel flow, the temperature will reach a new steady state. The most common non-self-regulating, or *integrating*, process is liquid level. If we change the flow of liquid into (or out of) the vessel, the liquid level will change as a ramp and not reach a new steady state. Since all six of our algorithms can be applied to either type of process, we now need 12 sets of tuning calculations. In later articles we will cover the modifications made to the algorithms by the control system vendors, each of which must be reflected in a modification to the tuning calculation. And we have not yet considered the changes made by the engineer who, for example, might set a different MV overshoot limit.

To develop a more general purpose method of tuning we adopt the trial and error approach that engineers have been using for years. But, instead of the time-consuming work on the real process, we use a computer simulation that runs much faster than real time. Figure 5 shows how this works. We include the equation governing the process dynamics that we derive from step-testing. We connect it to our control algorithm of choice – in this case the ideal I-PD. And we specify our tuning criteria – in this case minimising ITAE subject to a limit on MV overshoot. Such a problem can be readily set up with Excel, using its Solver to derive the tuning. Or, more effectively, the reader may download, at no cost, our tuning software from www.whitehouse-consulting.com/tune.htm. The reader is encouraged to experiment with this, covering many of the points raised in these articles. ■

NEXT ISSUE

The next article is dedicated to just of one the control algorithms, I-PD. Often the best choice, its use is frequently misunderstood. Switching from a more traditional version can make substantial improvements to process stability.

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