Teaching a conscious use of PI/PID tuning rules

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Abstract: This paper presents a didactic activity concerning the use of PI/PID tuning rules, also addressing the issue of how to achieve a knowledgeable selection of the most suited one for the particular problem at hand. The activity aims at making the students aware of the rationale of said rules, and therefore of their suitability for the dynamic (not necessarily physical) characteristics of the controlled process, and the objectives to achieve. The ultimate goal is to induce a conscious use of tuning rules, making the students approach them (also) as conceptual tools and not just recipes.

Keywords: PI/PID control; PI/PID tuning rules.

1. INTRODUCTION

For many years, the PI/PID law has been providing the backbone of most control applications (Åström and Hägglund, 2006). Nowadays, the emergence of more and more articulated control structures has been changing the role of that fundamental law, but by no means has diminished its importance. For example, when presenting the paper (Hägglund, 2012) in his plenary session lecture, the author suggested to view PIDs in modern control systems like "ants in a colony", which we may interpret and rephrase for the purpose of this work as "objects that operate locally, but have their role evidenced – and the quality of their operation judged – at higher system levels". As such, be the considered PID the master of a standalone loop or just an ant, the importance of tuning it in a methodologically sound, structured and reproducible manner, is apparent; and to this end, a fundamental tool are the so called "PI/PID tuning rules".

In fact, somehow backing up the statement just made, the number of such rules available in the literature is impressive (O'Dwyer, 2006). However, the evolving role of the PID sketched above calls for a correspondingly more conscious use of said rules. Instead of perceiving them as mere "recipes" – a term used quite often, and in the authors' opinion significantly, in lieu of "rules" – the control engineer should master not only their operation, but also the underlying *rationale*. Only such a deepened knowledge can allow him/her to choose and correctly apply the most suited rule for the problem at hand, and most important, to use tuning rules in such a way that a plurality of PIDs operate in an effectively coordinated manner.

2. PEDAGOGICAL GOALS AND ACTIVITY OVERVIEW

The peculiar characteristics of the presented activity, thus the contribution of this work, can be summarised in the following two points. First, care is taken right from the beginning to distinguish between a tuning *rule* and a tuning *procedure*, as there is much more to the latter than the former. Anticipating a bit, the same rule can lead to very different tuning result by just changing, e.g., the method used to find the parameters of the same process model structure from the same measured process input/output data. In the authors' opinion the literature too often tends to be a bit silent on this matter, although incorrect ideas on it are primary causes for undesired outcomes, and also for the difficulties encountered by many advanced rules at gaining acceptance. Second, and in more than one sense consequence of the previous point, the students are *first* led to understand the underlying ideas, and *then* see the rules. This is to foster a more conceptual viewpoint, as stated to be a specific objective of the activity, and explained in the following sections.

The following sections present the didactic activity, by reporting in extreme synthesis the messages conveyed to the students. To have sufficient space for that, we have decided to limit technical details and examples to a minimum. This should cause no problem, since the reader can easily complement the presented material with the provided reference, and his/her knowledge of PID tuning.

3. PART I: TUNING RULES AND TUNING PROCEDURES

The aim of this part of the activity is to make the students aware of the role of a tuning *rule* within a tuning *procedure*, so as to clarify that the former cannot be judged (thus chosen) for a given application, if not within the context of the latter.

3.1 Process information

Any tuning procedure starts from some *process description*. This can be a *model* in the strict sense of the term, i.e., most frequently a transfer function $M(s, \theta_M)$. Its structure is very often decided *a priori*, depending on that of the controller and on the type of process dynamics the rule is targeted to manage (more advanced techniques, allowing for variable-structure models, are not considered in the activity described herein). Its parameters (vector θ_M) are obtained based on some measured process response to a conveniently chosen stimulus. In this case we talk about *Model Based Tuning (MBT)*, and $M(s, \theta_M)$ is called the *Nominal Tuning Model (NTM)*. Therefore, from the process description viewpoint, a MBT procedure is qualified by the following entities.

- The structure of the NTM, or equivalently, the meaning of θ_M. For example, the widely used First Order Plus Dead Time (FOPDT) structure corresponds to

$$M(s,\theta_M) = \mu_M \frac{e^{-sD_M}}{1+sT_M}, \quad \theta_M = [\mu_M \; T_M \; D_M]', \qquad (1)$$

  and is the most used in the activity (just a few words are spent on integrating models, unstable ones are left to advanced courses).
- The response used to parametrise the NTM—for example, that of the controlled variable $y(t)$ to a step applied to the control signal $u(t)$ with the system initially at an equilibrium.
- The method used to obtain θ_M from the measured response. For example, (1) can be parametrised from the process step response just mentioned, normalised to be the unit step one,
  - by taking μ_M as the asymptotic value, D_M as the time to reach 10% of that value, and T_M as the time to go from 10% to 90% (many variants exist for such an idea, with different percentages than those just mentioned),
  - with the tangent method,
  - with the method of areas.

Alternatively, the process description may just consist of some characteristic value (e.g., a settling time, an overshoot, and so forth) of the considered process response; in this second case, we talk about *Characteristics Based Tuning (CBT)*, and θ_M can be interpreted as the vector of said characteristics. Thus, from the process description viewpoint, a CBT procedure is characterised by the following entities.

- The nature of the characteristics contained in θ_M—for example, the ultimate frequency ω_π and magnitude M_π of the process frequency response.
- the response on which they are measured—for example, sticking to ω_π and M_π, by a relay test or by applying proportional control and driving the so closed loop to the stability limit.
- The measurement method, which can contain a lot of machinery such as filtering, outlier removal and so on, but is in any case more "direct" (i.e., less dependent on arbitrary design choices) than is any method for parametrising a model used in MBT.

Observe that when talking about MBT, the examples were chosen referring to the time domain, while for CBT, frequency domain information was mentioned. This is somehow consistent with traditional distinctions like that of "time domain" tuning, typically using step responses, and "frequency domain" or "relay-based" tuning; however, on this particular subject much care has to be taken, because although widely used, in the authors' opinion such a distinction can be misleading. First, one may for example parametrise models like (1) "in the frequency domain" as well, for example by some sine input tests. But most important, the real choice is another.

- *MBT process information* attempts to describe the process "globally", i.e., to reproduce its behaviour to the best of the capabilities of the NTM at reproducing the measured response. Depending on how much exciting the stimulus is, and on which parametrisation procedure is used, the same process input/output data can result in very different NTMs, each one approximating the process in a different sense, e.g., as a low-frequency approximation, or one valid in the vicinity of the applied sine input frequencies, and so on. MBT has the powerful feature of providing a NTM to validate the tuned controller upon, but since MBT information is "global but imprecise", there is *a priori* no guarantee that a property assessed on the nominal control system, containing the NTM, carries over to the real one, that conversely contains the process.
- *CBT process information*, on the contrary, is local – e.g., a single point of the process frequency response like the ultimate one – but exact, having just to account for measurement (not model parametrisation) errors. CBT does not provide a NTM, or in other words, the same CBT information could belong to infinite NTMs. Thus, either *a priori* process information is available, or assumptions can be made on the nature of the control problem so as to determine a *set* of NTMs, see e.g. Schlegel and Cech (2005), or the controller tuning too has to be based on just the achievement of local properties. However, in the third case above, said properties are inherently guaranteed (locally, remember) also for the real control system. Furthermore, when operating in the frequency domain, it is possible and natural to prescribe local properties while operating on transfer function models, while this is not true when acting in the time domain—and most likely, this is the main reason for the prevalence of frequency domain information for tuning based on local properties.

Finally, when process information is sought in the time domain, care has to be taken that the measured data do not contain any residual process motion originated before the stimulus is applied, or very erratic results can be obtained. Thus, having the process at rest at the beginning of the procedure is important, albeit not easy to achieve in several industrial contexts. When conversely operating in the frequency domain, only "steady state" periodic regimes are of interest, thus the sensitivity of the experiment to the initial process condition is lower. Choosing the correct stimulus for a specific problem is very important, and one could say that it is, up to a significant extent, a matter of trading the local or global character of the obtainable information versus the higher or lower risk of mistaking residual process motion for effects of the applied *stimuli*. We do not further delve into this matter, also because stimulus design has often to comply with technological constraints impossible to treat herein. However, even with the short considerations just exposed, the students should understand the importance of not assuming a certain stimulus to *reliably* provide some information that in fact it cannot yield. They should also perceive that the choice of MBT or CBT in real-world applications may be relevnt for success, and be prepared to address such advanced topics in subsequent courses.

3.2 Objectives

Any tuning procedure aims at achieving some *objectives*. These may be given by an *Objective Model* (OM), denoted here as $O^\circ(s,\theta_O)$, to which the closed-loop transfer function $O(s,\theta_M,\theta_R)$ of interest (e.g., set point to controlled variable or load disturbance to controlled variable) has to be made either nominally equal or as close as possible; consistently with the introduced notation, vector θ_O – rigorously, once the structure of $O^\circ(s,\theta_O)$ is decided – represents the tuning objectives. Another way to express objectives is by a vector – termed here again θ_O for uniformity – of *Objective Characteristics* (OC). The most frequent ones are the cutoff frequency ω_c and the phase margin φ_m, but many others are found in the literature, like the gain margin, the maximum sensitivity, and so on.

In general, we can notice that OM-based objectives are actually perceived as the attempt to achieve certain closed-loop responses in the time domain, which the OM is a way to express in an MBT-compatible manner. On the contrary, OC-based objectives refer primarily to the frequency domain, thus being more keen to be prescribed based on local information gathered in that context, as is frequently the case with CBT. Again, one can use the concepts just introduced to re-visit the "step versus relay" traditional classification, however with more abstract and conceptual a viewpoint, focusing on the nature of the gathered process description, and consequently on its possible and advisable uses.

3.3 The rationale *of tuning rules*

Any tuning procedure uses a *tuning rule* to attain the objectives based on the process description. The *rationale* of that rule thus significantly contributes to that of the procedure, and to its greater or lesser aptitude for one problem or another. However, as should now be clear, the *rationale* of a rule cannot be fully discussed if not within that of the procedure where it resides.

As noticed, expressing objectives as an OM is intrinsically connected to MBT. In the former of the OM-based cases listed in Section 3.2 – $O(s,\theta_M,\theta_R)$ nominally equal to $O^\circ(s,\theta_O)$ – the controller is substantially parametrised by taking the NTM, expressing the transfer function of interest by using the NTM, and then solving for θ_R; we refer to this case as *Model Based, Model Following Tuning by Nominal Equivalence (MBMFT-NE)*. This *modus operandi* naturally gives rise to the so called "cancellation based" MBT rules, as the controller is ideally computed such that for example

$$\frac{R(s,\theta_R)M(s,\theta_M)}{1+R(s,\theta_R)M(s,\theta_M)} = O^\circ(s,\theta_O) \qquad (2)$$

in the case of a set point to controlled variable objective, which is often called "servo tuning". Numerous variations exist, e.g., when the objective refers to the transfer function from load disturbance to controlled variable ("regulatory tuning"), when properness considerations oblige to augment $R(s,\theta_R)$ with some additional poles, when possible transcendent term in the NTM are approximated with rational ones, and so on.

In the latter case – $O(s,\theta_M,\theta_R)$ as close as possible to $O^\circ(s,\theta_O)$ – one has to specify a norm $||\cdot||_N$ to evaluate the distance of $O(s,\theta_M,\theta_R)$ from $O^\circ(s,\theta_O)$, choose a method $\mathscr{M}$ to minimise it, and then determine θ_R by means of that minimisation; in this case, we talk about *Model Based, Model Following Tuning by Distance Minimisation (MBMFT-DM)*, and when this is relevant, we can specify *in the N norm with method* $\mathscr{M}$. Here too a number of variants are found, depending, e.g., on $\mathscr{M}$ but also on possible frequency weighing to privilege a certain band.

On the other hand, OC-based objectives naturally lend themselves to CBT, a notorious example being "one point relay tuning", where one point $Ae^{j\phi}$ of the process frequency response is obtained, a phase margin is prescribed, the frequency ω_{ox} of the oscillation induced by the relay test becomes the cutoff, and the controller is tuning such that

$$R(j\omega_{ox},\theta_R)Ae^{j\phi} = e^{j(\varphi_m-\pi)}, \qquad (3)$$

here too with a number of variants inessential to discuss at this point. In general we can collectively qualify these *modi operandi* by the fact that OCs are prescribed (again) "exactly but locally", and characterise each of them as *Characteristics Based, Characteristics Following Tuning (CBCFT)*, possibly adding the particular OC(s) enforced, like, e.g., *CBCFT-*φ_m.

Quite intuitively, one can also use MBT process information to prescribe one or more OCs, leading to *modi operandi* that can be defined *Model Based, Characteristics Following Tuning (MBCFT)*, again possibly adding the particular OC(s) employed.

4. PART II: DESIGNING A TUNING PROCEDURE

In this part, the students are guided to design a very simple MBCFT procedure for a PI, based on a cancellation *rationale*. This allows them to directly experience the numerous choices to be made, and effect of both the rule and said choices on the operation of the procedure.

The procedure has to tune a PI in the form $R(s) = K(1+1/sT_i)$ for an asymptotically stable process. It is obtained by means of a cooperative work, that however is guided so that the outcome be as follows:

(1) assume that the process is initially at steady state;
(2) apply a step variation to the control signal;
(3) wait for the controlled variable to settle;
(4) attempt to describe the process with a FOPDT model like (1);
(5) attempt to enforce a prescribed cutoff frequency ω_c and phase margin φ_m, privileging the latter if its achievement prevents to attain the former, using a cancellation strategy.

The rule *stricto sensu* resides in the last item of the list, and can easily be devised, e.g., as

$$T_i = T_M, \quad K = \min\left(\frac{\omega_c T_M}{\mu_M}, \frac{T_M}{\mu_M D_M}\left(\frac{\pi}{2}-\varphi_m\right)\right), \qquad (4)$$

which adheres to the cancellation paradigm, thus determining T_i, and chooses K so as to fulfil the objectives in the specified priority order. Of course one could conceive different rules for the same purpose, but since the goal of the presented activity is a conscious use – not the design – of tuning rules, the students are advised to take the rule so designed as a possible one to consider for application, characterised as its *rationale* by the last item of the list just mentioned.

In fact, the most important thing to perceive at this point is that, apart from the rule, in the procedure there are two points where alternatives are possible. One is how to decide that the process is in fact at rest before starting the operations, or – somehow equivalently – to detect when the controlled variable's step response is exhausted; the other is how to parametrise the FOPDT model. The first point would be a serious issue if the procedure had to be automated, but given the scope of the activity, the matter is just mentioned and briefly commented on, mentioning for example the alternative use of a double (up/down) step or rectangle pulse, while the work immediately comes back to concentrate on the second.

To this end, some alternatives are chosen for the model parametrisation method. To better evidence the possible criticalities, said alternatives are structurally identical, and just differ by some parameters. In detail, with reference to (1), D_M and T_M are respectively chosen as the time required to reach a fraction α of the final step response value, and to go from a fraction α to one β of the same value; the used (α,β) couples are $(0.01, 0.6)$, $(0.05, 0.65)$, $(0.1, 0.9)$, and $(0.15, 0.95)$. Then, two processed are chosen, namely

$$P_1(s) = \frac{1+0.8s}{(1+s)(1+1.2s)}, \quad P_2(s) = \frac{1}{1+2\frac{0.8}{1.2}s+\frac{s^2}{1.2^2}}, \qquad (5)$$

and the tuning procedure is applied with all (α, β) couples, $\omega_c = 1$, and $\varphi_m = 60°$. Fig. 1 reports the controlled variable responses of the so obtained control systems to a unit set point step.

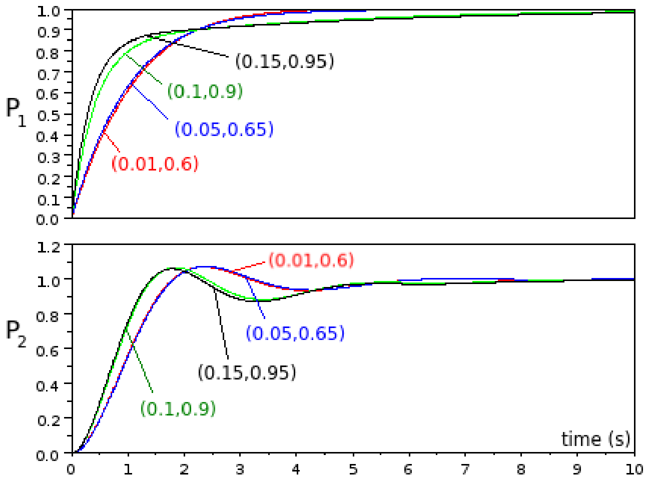

Fig. 1. Closed-loop responses of the controlled variable to a unit set point step with processes $P_1(s)$ and $P_2(s)$ as per (5) and PI controllers tuned with the rule (4) on the model structure (1), parametrised with various (α, β) couples (indicated in the plots).

The rule is apparently conceived for an overdamped process—a category to which $P_1(s)$ belongs albeit exhibiting a near zero-pole couple, and for which $P_2(s)$ is on the contrary quite borderline. Nonetheless, with the latter process, the rule produces comparable results with all couples, while with the former two of the same couples – curiously enough, those producing the fastest response with $P_2(s)$ – result in an evident lack of integral action, whence the slow settling.

Generalising, a tuning rule based on a certain model structure here shows less uniform results with processes more similar to that structure, depending just on how the model is parametrised based on the same data. In fact the example has been a bit deliberately sought, but is not at all unrealistic: zero-pole couples so near in frequency are not rare in thermal problems with multiple energy storages, like, e.g., a fluid and its containment, while moderately underdamped open-loop responses are not so infrequent, e.g., in hydraulic systems. Indeed, at this point the students should be convinced that talking of the aptitude of a *rule* for a given process (or problem) can be sometimes quite misleading, and the overall *procedure* is to be accounted for.

5. PART III: SOME WORDS ON ROBUSTNESS

As a very important by-product, the students should now be aware also that models like (1) are in practice nothing but a useful abstraction. Attempting a very high-level parallel, one may say that also MBT process information has some "locality" character—not in the same sense as in the CBT case, as already discussed, but rather residing in the restriction of the NTM to the sole purpose of tuning the controller.

Limiting the scope of this section to MBT for practical reasons, the statement above poses another relevant problem, since in virtually the totality of industrial cases, the NTM is parametrised so as to reproduce some process response, which is *not* the real purpose that model turns out to actually have. There exist some alternatives to such an attitude, like many works drawn from the identification for control domain, or the recently proposed "contextual" approach (Leva et al., 2010) to reduce the need for *ad hoc* experiment design, but to keep the activity complexity at an adequate level, it was decided to just mention said possibilities as research topics.

Coming back to the main topic, the considerations just made reveal that the NTM will invariantly exhibit some mismatch with the real process, owing to its limited descriptive capabilities. A robustness problem is thus immediately perceived. However, in the world of (PI/PID) tuning rules, such a problem has a very particular flavour. In fact, to state a robustness problem, it is necessary to specify *which property* is robust, with respect to the variation of *which entity* in *which set*. The most relevant properties are closed-loop stability (to which the treatise is here restricted) and/or performance, the varying (or better, uncertain) entity is the dynamics seen by the regulator, which is given by the NTM subjected to the mentioned mismatch.

The problem is however that the set is never available. When using tuning rules, one makes a *single* experiment. Even if some model reliability estimate is obtained, for example in the form of parameter variance, this gives information on the model's inability to explain the data, and in no sense on what the mismatch may look like. Hence, all that can be done with MBT rules is is to quantify robustness *a priori*, i.e., to determine some bound for the acceptable model error for the considered property to be preserved. Considering closed-loop asymptotic stability, that of the nominal closed-loop system carries (the one composed of the tuned controller and the NTM) carries over to all the systems for which

$$\|\mathscr{E}_a(s, \theta_M) C_n(s, \theta_M, \theta_R)\|_\infty < 1 \qquad (6)$$

where $\mathscr{E}_a(s, \theta_M) := P(s) - M(s, \theta_M)$ is the additive model error, $C_n(s, \theta_M, \theta_R)$ is the nominal control sensitivity function, defined as

$$C_n(s, \theta_M, \theta_R) := \frac{R(s, \theta_R)}{1 + R(s, \theta_R) M(s, \theta_M)}. \qquad (7)$$

Thus, the frequency response magnitude $|1/C_n(j\omega, \theta_M, \theta_R^o)|$ yields an overbound for the additive model error that $M(s, \theta_M)$ can commit while preserving closed-loop stability (Leva and Colombo, 2000). As such, another important fact to notice about a tuning rule is its tendency to produce looser or tighter bounds when confronted with some "typical" process dynamics. This will be done later on in the activity, once the students have seen a selected zoo of rules, and of benchmark process dynamics to experiment on with them.

6. PART IV: PLAYING WITH THE RULES

In this section, some well established tuning rules are presented. The presentation is made by describing the *rationale* of each rule as closely as possible to the way it is typically introduced and explained in the literature, also encouraging the interested students to deepen this part of the activity by going through the proposed references. The presented rules are

- the IMC-PID one (Garcia and Morari, 1982; Leva and Colombo, 2004), that is MBT and operates by cancellation, with the MF objective of having a closed-loop set point to controlled variable dynamics as close as possible to a first-order one with unity gain and prescribed time constant;

- the rule by Smith and Corripio (1985), also of the MBT type, aimed however at the CF objective of optimising either set point tracking ("servo" version), or disturbance rejection ("regulatory" version);
- the one-point relay-based rule by (Åström and Hägglund, 1991), that is CBT using ultimate data, and CF aiming at a prescribed phase margin.

Of course many different ones can be used, but time limits are apparent. Note that all rules share the PID structure, and the MBT ones also the model structure, for a meaningful comparison. The required FOPDT models are parametrised based on an open-loop step response with the procedures listed in Section 4, while the critical point is found either by relay feedback or by bringing the closed loop to the stability limit with proportional feedback. The two processes (5) are considered, and all the combination of process, rule, and process information retrieval procedure are examined. Care is taken to the meaning of the PID parameters as provided by the rules, converting all the encountered forms into the ISA one for uniformity. When an ideal PID is produced, this is turned into a real one by putting the derivative part's pole one decade after the cutoff frequency as estimated with the model, or from the ultimate point data. Finally, when the tuning objective is expressed by a phase margin, the "average" value of 60° is chosen, while if the desire is a closed-loop time constant, the selected value is 75% of the observed rise time in the open-loop step response. This more or less asks similar performance to all the rules, again for the sake of uniformity.

The students first classify the rules, the expected result being more or less the list above, and then they experiment using Scilab/Xcos, in an attempt to re-visit the rules' *rationale* with respect to the available process information. More specifically, by observing the obtained performance and *a priori* robustness quantifications as per Section 5, they try to guess (a) for which problem each of the considered rule is best suited, (b) if there are some *caveats* on how to obtain the process information as required by each rule when confronted with various types of process dynamics. There is not the space here to describe this activity, but the outcome is normally a greatly improved insight on the matter, and a firm understanding that the envisaged "rule revisiting" is far from trivial unless a systematic approach is adopted. As a final step, interested students are encouraged to widen the experiment campaign, e.g., by resorting to benchmark sets of processes like that proposed in the work by Åström and Hägglund (2000).

7. PART V: PROCEDURES FOR PROBLEM CLASSES

The systematic approach just mentioned may be re-formulated as the necessity of mapping classes of *models* and *requirements*, i.e., of system-theoretical problem characterisations expressed as a certain available process information to attain certain objectives, onto classes of *industrial problems* – i.e., substantially the same items, however declined into a particular application domain – whenever this is possible. Apart from understanding this point *in abstracto*, the students are confronted with an example aimed at evidencing the importance of conveniently exploited system-level modelling and simulation campaigns, to tailor the use of tuning rules so as to write (industrial) domain-specific procedures. Time limits oblige to have the students just follow the treatise of an example instead of carrying out the entire work on their own, but nonetheless the discussion following the activity is normally quite informative for them.

The addressed example refers to a temperature control problem. The goal is to write a tuning procedure for operators running a plant composed of a heated reactor containing a fluid. Denoting by C_f and C_c [J/K] the thermal capacities of the fluid and the containment, by G_{fc}, G_{fe} and G_{ce} [W/K] the thermal conductance from fluid to containment, from fluid to external environment and from containment to external environment, and with T_f and T_c [K] the fluid and containment temperatures, assuming a first-order actuator dynamics with time constant T_a, P_h [W] being the heating power released to the fluid, and finally taking as exogenous inputs the heating power request u_h [W] and the external temperature T_e [K], the simplest model of such a plant can take the form

$$\begin{cases} T_a \dfrac{dP_h}{\mathrm{d}t} = -P_h + u_h \\ C_f \dfrac{dT_f}{\mathrm{d}t} = P_h - G_{fc}(T_f - T_c) - G_{fe}(T_f - T_e) \\ C_c \dfrac{dT_c}{\mathrm{d}t} = G_{fc}(T_f - T_c) - G_{ce}(T_c - T_e) \end{cases} \tag{8}$$

whence the transfer function from the control signal u_h to the controlled variable T_f

$$P(s) = \frac{\mu(1+sT_z)}{(1+sT_a)(1+sT_{p1})(1+sT_{p2})} \tag{9}$$

where the expressions of μ, T_z, T_{p1} and T_{p2} are omitted for brevity. Suppose now that T_a, C_c, G_{fc}, G_{fe} and G_{ce} are constant parameters, while the thermal capacity C_f of the contained fluid can vary, for example from one batch operation to another. Depending on the constant parameters, the varying fluid capacity can have very different effects on the variation of the dynamics seen by the temperature controller. For example, with $T_a = 3$, $C_c = 500$, $G_{fc} = 50$, $G_{fe} = 20$ and $G_{ce} = 10$, a variation of C_f from 50 to 500 makes the time constants change as shown in Fig. 2.

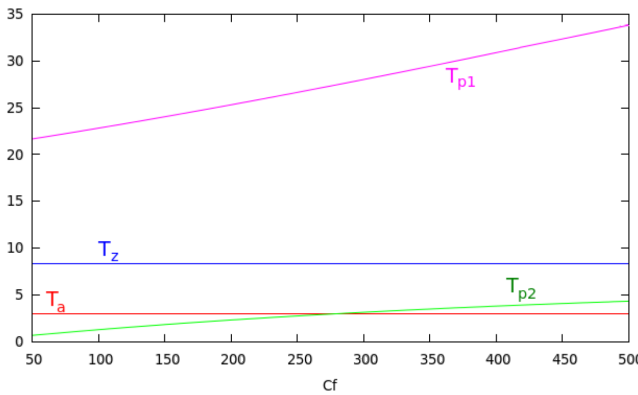

Fig. 2. Time constant variations for $C_f \in [50, 500]$ with $T_a = 3$, $C_c = 500$, $G_{fc} = 10$, $G_{fe} = 20$ and $G_{ce} = 50$.

From Fig. 2, one can expect that the system almost invariantly behaves pretty much like a dominantly first-order one with a hardly sensible delay, so that a cancellation-based rule for a PI structure coupled to a parametrisation method aimed at capturing the dominant (low-frequency) process dynamics can be safely used on the field for any batch. Also, no matter what

C_f is, a tight control requirement (e.g., a small desired closed-loop dominant time constant in the IMC-PI case, where the PI rule is obtained by the students taking the occasion for a deeper explanation of the IMC tuning principle) can be used with virtually no risk of causing oscillatory closed-loop set point step responses. If however the values of G_{fc} and G_{ce} are swapped – i.e., the external containment insulation is made more efficient than the internal one, things are quite different, as in this case the same variation of C_f as above, makes the time constants vary as depicted in Fig. 3.

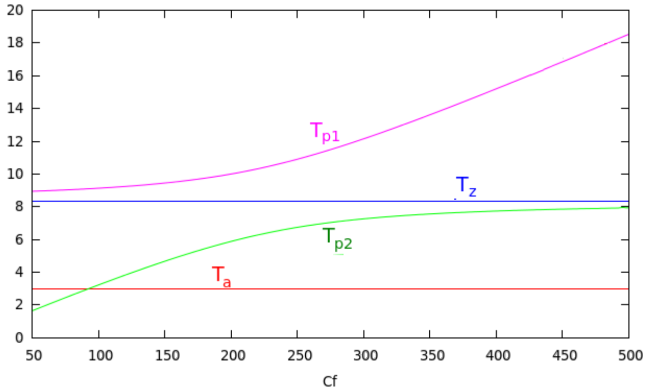

Fig. 3. Time constant variations for $C_f \in [50, 500]$ with $T_a = 3$, $C_c = 500$, $G_{fc} = 50$, $G_{fe} = 20$ and $G_{ce} = 10$.

This time, the process may exhibit a dominantly first-order and significantly delay-free behaviour, for high values of C_f, but also an evident zero-pole dynamics like the one that made the parametrisation procedure critical as in the example of Fig. 1, upper plot. The same cancellation-based rule thus requires the parametrisation procedure to capture essentially the rise time, without overestimating the (actually absent) delay, and may also require rules that prevent the integral time from getting stuck to excessively high values; an interesting discussion, involving not only the rule but the overall procedure, can then be stimulated, e.g., by starting from the SIMC tuning technique (Skogestad, 2003).

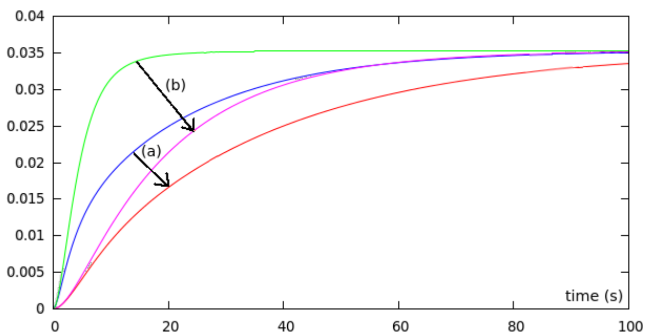

Fig. 4. Variations of the open-loop unit step response of T_f to u_h for $C_f \in [50, 500]$ with the other parameters set as in Fig. 2 (a) and in Fig. 3 (b).

Note that the different encountered dynamic variabilities (thus challenges for the tuning rule) in different operating conditions can also be appreciated by simulation, for example by examining the effect of C_f on the open-loop response of T_f to u_h. For example, Fig. 4 shows in the time domain the effect of C_f already seen parametrically in Fig. 2 and Fig. 3. It is important to observe the system also in this domain, as on the field parameters are typically unknown – consistently with the necessity of using a tuning procedure – but a thorough examination of responses, having in mind the tuning objectives and the set of candidate rules and procedures, can be very helpful. At the end of this final activity section, the students should then perceive how complex it may be to set up a tuning procedure, and how differently a rule can behave if not properly utilised. Also, the importance of analysis (and also simulation, although the matter was just mentioned here for space reasons) to tailor a procedure to a certain class of problems, should be apparent.

8. CONCLUSIONS

An activity was presented to teach a conscious use of PI(D) tuning rules, and above all to stress that such a competence cannot be successfully induced if not by viewing said rules within the context of a tuning procedure. The activity makes the students aware of the potential and pitfalls of such rules and procedures, and with some additional experience, capable of tailoring – or even designing – domain-specific ones. The ultimate goal is to foster a better use of tuning rules, and more in perspective, to favour the students' approach to such a fascinating research area. Of course, many aspects of PI(D) tuning are not treated. The author's hope is that even so introductory a treatise can encounter the students' interest, and encourage them to deepen their knowledge on the subject.

REFERENCES

Åström, K. and Hägglund, T. (1991). Industrial adaptive controllers based on frequency response techniques. *Automatica*, 27(4), 599–609.

Åström, K. and Hägglund, T. (2000). Benchmark systems for PID control. In *Proc. IFAC Workshop on Digital Control – Past, present, and future of PID Control*. Terrassa, Spain.

Åström, K. and Hägglund, T. (2006). *Advanced PID Control*. The Instrumentation, Systems, and Automation Society, Research Triangle Park, NY.

Garcia, C.E. and Morari, M. (1982). Internal model control. a unifying review and some new results. *Industrial & Engineering Chemistry Process Design and Development*, 21(2), 308–323. doi:10.1021/i200017a016.

Hägglund, T. (2012). Signal filtering in PID control. In *Proc. IFAC Conference on Advances in PID Control*. Brescia, Italy.

Leva, A. and Colombo, A. (2000). Estimating model mismatch overbounds for the robust autotuning of industrial regulators. *Automatica*, 36(12), 1855–1861.

Leva, A. and Colombo, A. (2004). On the IMC-based synthesis of the feedback block of ISA-PID regulators. *Transactions of the Institute of Measurement and Control*, 26(5), 417–440.

Leva, A., Negro, S., and Papadopoulos, A.V. (2010). PI/PID autotuning with contextual model parametrisation. *Journal of Process Control*, 20(4), 452–463. doi:10.1016/j.jprocont.2010.01.005.

O'Dwyer, A. (2006). *Handbook of PI and PID controller tuning rules – 2nd edition*. Imperial College Press, London.

Schlegel, M. and Cech, M. (2005). Computing value sets from one of the frequency response with applications. In *Proc. 16th IFAC World Congress*. Prague, Czech Republic.

Skogestad, S. (2003). Simple analytic rules for model reduction and PID controller tuning. *Journal of Process Control*, 13, 291–309.

Smith, C. and Corripio, A. (1985). *Principles and practice of automatic process control*. John Wiley & Sons, New York, NY.