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Romano M. DE SANTIS
Département de Génie Électrique

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par : Romano M. De Santis
Département de génie électrique.
École Polytechnique de Montréal.

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Romano, M., De Santis
Ecole Polytechnique de Montréal
Montreal, Canada
DeSantis@auto.polymtl.ca

0. Summary.

A tuning method based on a novel 2 degrees of freedom PID controller with a dual loop form and which can be used in conjunction with and as a completion of currently available tuning procedures is proposed. The idea is to modify the gains provided by these procedures so as to improve process-disturbance response while preserving process-setpoint response procured by the original gains. Application modalities and ensuing benefits are illustrated by applying the method to a number of plants with high order dynamics, significant dead times and non minimum phase behaviour.

Keywords: PID, disturbance, industrial controller, dual loop, inner loop, tuning, 2 degrees of freedom, non minimum phase.

1. Introduction

Structural simplicity and large adaptability of usage, intuitive and continuously improved understanding of operation, and a generally adequate performance make a PID (proportional+integral+derivative) the most popular among currently adopted industrial process controllers (figures 1, 2). These properties, somehow intrinsic to the very nature of the PID concept, are also in part tributary of relentless efforts directed at transferring into PID technology novel ideas and techniques as soon as they have become available. Considerable from the very first inception of the PID (e.g., Minorski 1937, Smith 1936, Ziegler Nichols 1943), a number of recent events reveal these efforts to remain as intense as ever at the present time. It suffices to consider the publication of the Computing and Control Engineering journal special edition on PID tuning methods (Anon 1999), the well attended IFAC workshop on Past Present and Future of PID Controllers (Quevedo and Escobet 2000), and the Control Engineering Practice journal special issue on PID Controllers (Astrom Quevedo and Escobet 2001).

One of the main justifications for this continuing interest is that tuning a PID, still involves costs and start up times that can be further reduced, it may still lead to a process response that can be considerably enhanced, and it may still leave uncertainties about quality of tuning outcome that can be removed. Among a variety of avenues to bring about these improvements, is the replacement of a standard PID with a two degrees of freedom (2DOF) controller structure (figure 3a, Horowitz 1963, Tagushi&alias 1987, Hiroi 1992, Wu Yu Cheng 2001, Astrom and Hagglund 2001). The interest of this structure is that it is made of the serial composition of two PIDs. As a consequence, the tuning objective can be pursued in a de-coupled fashion with gains of a first PID being tuned to optimize response to disturbance, and gains of the second to optimize setpoint response. Recently, a somewhat different approach in this same direction has been proposed in the context of speed drives and position servos (DeSantis 1994). According to this approach, a standard PID is interpreted as (rather than replaced by) a 2DOF controller, and the 2DOF controller under consideration is given by the parallel (rather than serial) composition of two PIDs (figure 3b). This interpretation has led to the emergence of a dual loop PID form for speed drives and position servos that is functionally equivalent to the standard PID and which at the same time enjoys a considerably higher degree of de-coupling between response to disturbance and setpoint response (DeSantis 1996).

The objective of the present paper is to extend application of this alternative 2DOF approach from the context of speed drives and position servos to more general plants characterized by a transport delay (as found, for example, in the temperature and product concentration control of chemical reactors), unstable modes (as in magnetic levitation systems), or by an inverse response (as found, for example, in angular speed control of hydro-electric turbines). For a more specific explanation of intent, the reader is invited to move forward to figures 5-9, where process responses to a stepoint change and to an external disturbance in correspondence to two sets of PID gains, K_O and K_M are given. Observe that while the setpoint responses are very similar for the two sets of gains, responses to disturbance obtained with K_M are considerably better than responses with K_O. Be advised that gains K_O are obtained by applying PID tuning procedures that are among the most popular and the most effective currently available procedures. The objective of this paper is to propose a tuning procedure to systematically modify K_O so as to obtain K_M.

This objective will be pursued by first characterizing similarities and differences between standard and dual loop PID forms (section 2). Then, by unveiling the special de-coupling properties of the dual loop form (section 3) and by developing a technique by which these properties can be advantageously applied in concert with most of the available tuning procedures (section 4). Application of this technique is subsequently demonstrated in conjunction with a number of examples involving from both classical and recent tuning procedures (section 5). Finally, practical issues concerning real time implementation in an industrial environment are discussed (section 6).

2. Standard and dual-loop PID forms

An important role in the present development is played by the PID configuration in figure 4. This configuration is called a Dual-loop PID form (PID_DL) because given by the parallel composition of two PIDs. A first PID, referred to as the "inner loop PID", is identical to a standard PID; a second PID, referred to as the "outer loop PID", is reminiscent of PIDs considered in sliding mode developments (Slotine 1984, DeSantis 1988, 1989, Yeung and alias 1993). In spite of the apparent greater complexity relative to a standard PID, and in contrast to classical 2DOF PID proposed by other authors (including Horowitz 1963, Hiroi 1986, 1992), any standard PID can be given a PID-DL form, and conversely. In particular, any PID-DL form with inner loop gains k_1, k_2, k_3, and k_4, and outer loop gains k_5, a_2, a_1 and a_0, is functionally equivalent to a standard PID form of which the gains are given by: $\underline{k}_1 = k_1 + a_1 k_5$, $\underline{k}_2 = k_2 + a_2 k_5$, $\underline{k}_3 = k_3 + k_5$, $\underline{k}_4 = k_4 + (a - a_1) k_5$.

The motivation for representing a standard PID with a PID-DL controller is that the double-loop structure of the PID-DL suggests a different way of tuning a PID that is somewhat complementary to what is currently done (De Santis 1994, 1996). To see this difference, observe that the control provided by a standard PID is the sum of contributions proportional to the error and its derivative and integral. By contrast, the control provided by a PID-DL is the sum of a component that is the output of the inner loop PID plus a component that is the output of the outer loop PID. The first component is identical to the control provided by a standard PID; the second component is made to be proportional to the "error residue" and (as it will be demonstrated in the following sections) enjoys the remarkable property not to influence the setpoint response provided by the first component. Because of this property, tuning a PID-DL can be carried out by following a de-coupled two step approach. In a first step inner loop PID gains are tuned for best setpoint response. In a second step, the outer loop PID is introduced and its gains are tuned for best response to disturbance. As it turns out, this latter tuning boils down to simply tuning gain k_5 and can be considerably simplified by exploiting the special monotonic properties that characterize influence of k_5 over response to disturbance.

3. Properties of the PID-DL form

Consider a plant equipped with a dual loop PID of which outer loop PID gains are zero. Assume the inner loop PID to have been tuned so as to procure a satisfactory setpoint response and assume this response to be described by the transfer function

$$F_{10} := \frac{P_v(s)}{P_s(s)} \cong \frac{(1+\alpha_0 s)}{\left(1+\alpha_1 s+\alpha_2 s^2\right)} \tag{3.1}$$

where the symbols P_v and P_s denote, respectively, process variable and setpoint. With reference to figures 1 and 4, it follows from this assumption that the influence of a control-input equivalent disturbance (denoted with the symbol P_t) over the process variable P_v can be described by

$$F_{20} := \frac{P_v(s)}{P_t(s)} \cong \frac{s(1+\alpha_0 s)}{(k_3+k_1 s)\left(1+\alpha_1 s+\alpha_2 s^2\right)}. \tag{3.2}$$

To improve process response to disturbance, we select the outer loop PID gains so as to complement the inner loop PID action with a supplementary action, Δu, proportional to the integral of the error residue. The error residue is defined as the difference between actual value of $\ddot{P}_V$ and the value that $\ddot{P}_V$ would have in the absence of the disturbance. More precisely,

$$residue\ error := \ddot{P}_v - \frac{P_s+\alpha_0\dot{P}-\alpha_1\dot{P}_v-P_v}{\alpha_2} \tag{3.3}$$

and therefore

$$integral\ of\ residue\ error := \dot{P}_v + \frac{\alpha_1 P_v + \int (P_v - P_s)dt - \alpha_0 P_s}{\alpha_2}. \tag{3.4}$$

Taking into account That (from figure 4)

$$\Delta u = k_5\left\{-a_2\dot{P}_v - a_1 P_v + a_0 P_s + \int (P_s - P_v)dt\right\} \tag{3.5}$$

it follows that for Δu to be proportional to the integral of the error residue it is sufficient to select

$$a_2=\alpha_2,\ a_1=\alpha_1,\ a_0=\alpha_0,\ \text{and}\ k_5 \geq 0 \tag{3.6}$$

which gives

$$\Delta u = -Laplace\left\{k_5(\alpha_2 \dot{P}_v + \alpha_1 P_v + \int (P_v - P_s)dt - \alpha_0 P_s\right\}$$
$$= -\frac{k_5}{s}\left\{(\alpha_2 s^2 + \alpha_1 s + 1)P_v - (\alpha_0 s + 1)P_s\right\} \qquad (3.7)$$

Let us now analyze the modifications to transfer functions $\frac{P_v}{P_s}$ and $\frac{P_v}{P_t}$ that have been produced by the introduction of outer loop PID gains as in (3.6). For the transfer function between P_v and P_s observe that the second order hypothesis described by (3.1) implies

$$\frac{P_v(s)}{\Delta u(s)} = \frac{s}{(k_3 + (k_1 + k_4)s)} \frac{(\alpha_0 s + 1)}{(\alpha_2 s^2 + \alpha_1 s + 1)} \qquad (3.8)$$

It follows

$$P_v = \frac{(\alpha_0 s + 1)}{(\alpha_2 s^2 + \alpha_1 s + 1)} P_s + \frac{s}{(k_3 + (k_1 + k_4)s)} \frac{(\alpha_0 s + 1)}{(\alpha_2 s^2 + \alpha_1 s + 1)} \Delta u \qquad (3.9)$$

hence

$$P_v = -\frac{s}{(k_3 + (k_1 + k_4)s)} \frac{(\alpha_0 s + 1)}{(\alpha_2 s^2 + \alpha_1 s + 1)} \left\{\frac{k_5}{s}(\alpha_2 s^2 + \alpha_1 s + 1)P_v - (\alpha_0 s + 1)P_s\right\} + \frac{(\alpha_0 s + 1)}{(\alpha_2 s^2 + \alpha_1 s + 1)} P_s \qquad (3.10)$$

This last equation implies

$$\left(1 + \frac{k_5(\alpha_0 s + 1)}{(k_3 + (k_1 + k_4)s)}\right) P_v = \left(1 + \frac{k_5(\alpha_0 s + 1)}{(k_3 + (k_1 + k_4)s)}\right) \frac{(\alpha_0 s + 1)}{(\alpha_2 s^2 + \alpha_1 s + 1)} P_s \qquad (3.11)$$

and therefore

$$F_{IC} := \frac{P_v(s)}{P_s(s)} \cong \frac{(\alpha_0 s + 1)}{(\alpha_2 s^2 + \alpha_1 s + 1)} \qquad (3.12)$$

F_{IC} being identical to F_{10} means that the introduction of the non-zero gains in the outer loop PID has produced the same setpoint response as when these same gains are equal to zero.

To obtain the transfer function between process variable P_v and disturbance P_t the equation to be considered is

$$P_v = \frac{s}{(k_3+(k_1+k_4)s)}\frac{(\alpha_O s+1)}{(\alpha_2 s^2+\alpha_1 s+1)}P_T + \frac{s}{(k_3+(k_1+k_4)s)}\frac{(\alpha_O s+1)}{(\alpha_2 s^2+\alpha_1 s+1)}\Delta u$$

(3.13)

where,

$$\Delta u = -\frac{k_5}{s}(\alpha_2 s^2+\alpha_1 s+1)P_v. \quad (3.14)$$

It follows

$$\left(1+\frac{k_5(\alpha_O s+1)}{(k_3+(k_1+k_4)s)}\right)P_v = \frac{s}{(k_3+(k_1+k_4)s)}\frac{(\alpha_O s+1)}{(\alpha_2 s^2+\alpha_1 s+1)}P_t \quad (3.15)$$

hence

$$P_v = \frac{k_3+(k_2+k_4)s}{(k_3+k_5+(k_1+k_4+\alpha_0 k_5)s)}\frac{s}{(k_3+(k_1+k_4)s)}\frac{(\alpha_O s+1)}{(\alpha_2 s^2+\alpha_1 s+1)}P_v \quad (3.16)$$

One can therefore conclude that

$$F_{2C} = \frac{P_v}{P_t} = \Gamma(s)F_{20}$$

(3.17)

where $\Gamma(s)$, (in classical studies referred to as the sensitivity reduction operator, Horowitz 1963, Cruz 1973), is given by

$$\Gamma(s) = \frac{k_3+(k_1+k_4)s}{(k_3+k_5+(k_1+k_4+\alpha_0 k_5)s)}. \quad (3.18)$$

4. Tuning a standard PID using a Dual Loop form

The implications of the above development over tuning can be formalized in terms of the following statements.

Statement 1: For the feedback system to remain stable after the introduction of the non-zero outer loop gains it is necessary and sufficient that

$$k_1+k_4+\alpha_0 k_5 > 0. \quad (4.1)$$

This condition is always satisfied for minimum phase plants ($\alpha_0>0$). It is conditionally satisfied for non minimum phase plants ($\alpha_0<0$), in which case one needs $k_5 \le -\frac{k_1+k_4}{\alpha_0}$.

Statement 2: Provided that (3.6) is satisfied and that stability condition (4.1) holds:

i. introduction of the outer loop PID does not influence the response to setpoint obtained in its absence;

ii. introduction of the outer loop PID modifies response to disturbance obtained in its absence. This modification is a function of the spectral components of the disturbance;

iii. response to disturbance improves for those disturbance components of which the frequency satisfies the condition

$$\left|\frac{k_3+(k_1+k_4)j\omega}{(k_3+k_5+(k_1+k_4+\alpha_0 k_5)j\omega)}\right|<1; \tag{4.2}$$

it deteriorates otherwise.

Statement 3: For minimum phase plants:

i. condition (4.2) is satisfied for all spectral components of the disturbance;

ii. feedback system response to disturbance improves monotonically with increasing k_5;

iii. for an assigned value of k_5, disturbance attenuation as a function of disturbance spectral components varies monotonically from $\frac{k_3}{(k_3+k_5)}$ for low frequency to $\frac{(k_1+k_4)}{(k_1+k_4+\alpha_0 k_5)}$ for high frequency.

Statement 4: For non minimum phase plants:

i. condition (4.2) is no longer satisfied for all spectral components of the disturbance;

ii. response to disturbance low frequency spectral components improves monotonically with increasing k_5;

iii. for an assigned value of k_5, response to disturbance improves in correspondence to disturbance spectral components such that

$$\omega^2<\frac{k_5+2k_3}{-\alpha_0(\alpha_0 k_5+2(k_1+k_4))}; \tag{4.3}$$

it deteriorates otherwise.

The above statements make it clear that tuning a PID with the sole objective of optimizing setpoint response presents a level of difficulty that is independent from whether a standard PID or a PID-DL form is considered. At the same time, tuning a PID with the objective of optimizing response to disturbance while preserving established setpoint response, is a considerably simpler task if a dual loop PID rather than a standard PID form is used.

A typical tuning approach commensurate with these observations would evolve along the following three steps.

A. Tuning the inner loop PID

With outer loop gains equal to zero, k_1 k_2 k_3 and k_4 are determined with the intent of optimizing setpoint response. This step would be carried out by adopting whatever tuning procedure may be the most appropriate on the basis of personal choice, current state of the art, or more simply pragmatic convenience, for the specific plant under consideration;

B. Tuning the outer loop PID

i. With inner loop gains k_1 k_2 k_3 and k_4 as determined in step A, submit the feedback system to setpoint step change and determine parameters α_0, α_1 and α_2 that make the transfer function

$$\frac{P_v(s)}{P_s(s)} \cong \frac{(\alpha_0 s + 1)}{(\alpha_2 s^2 + \alpha_1 s + 1)} \tag{4.4}$$

best describe the feedback system setpoint response. Determination of this 2nd order best approximant can be carried out by adopting standard parameter identification techniques (Ljung 1999) ;

ii. With outer loop gains $a_0 = \alpha_0$, $a_1 = \alpha_1$, $a_2 = \alpha_2$, submit the feedback system to a sequence of setpoint step changes; after each test, gradually increase k_5 up to the point where setpoint response starts to no longer be satisfactory;

iii. Submit the feedback system to a disturbance test. Verify that introduction of the outer loop PID has indeed improved response to disturbance; in the negative, reduce k_5 down until this is indeed the case;

C. Computation of the standard PID gains

The final gains of the standard PID are computed as follows

$$\underline{k}_1 = k_1 + a_1 k_5,\ \underline{k}_2 = k_2 + a_2 k_5,\ \underline{k}_3 = k_3 + k_5,\ \underline{k}_4 = k_4 + (a_0 - a_1) k_5 \tag{4.5}$$

An alternative and basically equivalent tuning approach is obtained by replacing steps B.ii and B.iii with the following

ii'. With outer loop gains $a_0 = \alpha_0$, $a_1=\alpha_1$, $a_2 = \alpha_2$, submit the feedback system to a sequence of disturbance-step tests; after each test, gradually increase k_5 up to the point where deterioration rather than improvement in response to disturbance is obtained;

iii'. Verify that presence of the outer loop PID has not unduly affected setpoint response; in the negative, reduce k_5 until setpoint response is acceptable.

Remark 4.1. In currently available 2DOF procedures, one first tunes the internal PID to optimize response to disturbance. Subsequently, the external PID is tuned to optimize setpoint response while preserving established response to disturbance (Hiroi 1986, 1992). By contrast, in the proposed procedure, the two tuning objectives can be carried out in an inverse order. One first tunes the inner loop PID to optimize setpoint response, then the outer loop PID to optimize response to disturbance.

5. Simulation Examples

The results in sections 3 and 4, have been obtained under the explicit assumption that closed loop process-setpoint and process-disturbance responses are described by second order transfer functions (equations (3.1) and (3.2)). In what follows it will be investigated the extent within which these results remain meaningful in the context of more general plants where closed loop responses can be only approximately described in terms of second order transfer functions. Such an investigation will be carried out by considering examples of plants that have already been used as test bench in authoritative previous studies on the subject, and which therefore appear particularly suitable to put the present development into perspective relative to the state of the art.

Example 1: Use of the PID-DL form in conjunction with the classical tuning procedures

In Ogunnaike and Ray 1994, methods proposed by Ziegler-Nichols (ZN), Cohen Coon (CC) and the Internal Model Controller (IMC) method are applied to tune a PID in correspondence to a plant described by the transfer function

$$G(s) := \frac{P_v(s)}{U(s)} = \frac{6}{(1+2s)(1+4s)(1+6s)} . \qquad (5.1)$$

In what follows we use the results reported in this reference to illustrate how our novel PID tuning procedure would be carried out in conjunction with these classical methods.

A. Tuning the inner loop PID : By carrying out this step with the Ziegler-Nichols method, as done in Ogunnaike and Ray 1994, p.354, gives the following inner loop PID gains

$$k_1 = 1;\ k_2 = 1.5;\ k_3 = .5;\ k_4 = .166; \qquad (5.2)$$

B. Tuning the outer loop PID

i. submitting the feedback system with above inner loop PID gains to a setpoint step gives the result in figure 5; using standard least square parameter optimisation, we find that the best 2nd order approximant I/O transfer function is described by

$$\frac{P_v(s)}{P_s(s)} \cong \frac{(\alpha_0 s + 1)}{(\alpha_2 s^2 + \alpha_1 s + 1)}$$ with $\alpha_1 = 2$, $\alpha_2 = 10.7$, and $\alpha_0 = 0$ (figure 5);

ii. introducing outer loop PID gains $a_0 = \alpha_0$, $a_1 = \alpha_1$, $a_2 = \alpha_2$, and $k_5 = 1$ and submitting the feedback system to a setpoint step, no deterioration in process variable response is observed; repeating the sequence of increasing k_5 and implementing a setpoint response test until process response is no longer satisfactory, leads to $k_5 = 100$ (figure 5);

iii. by submitting the feedback system to a disturbance test, one finds that the introduction of the outer loop has produced a response to disturbance that is of several order better than the one procured by the original Ziegler-Nichols gains (figure 5).

C. Computation of the PID final gains

The modified Ziegler-Nichols gains for the standard PID are

$\underline{k}_1 = 187, \underline{k}_2 = 10^3, \underline{k}_3 = 100.5, \underline{k}_4 = -55$ (5.3)

Remark 5.1. Application of the proposed procedure reveals that the original Ziegler-Nichols gains can be considerably increased with no deterioration of response to setpoint and with a remarkable improvement in response to disturbance. In particular, the integral square (ISE) produced by a disturbance step is reduced from a value of 4.8 to $2.5*10^{-5}$. In practice, considerations other than optimization of setpoint and disturbance responses (e.g.: robustness to parameter variation), may suggest to settle for some smaller gain values. For example, a two order of magnitude improvement in response to disturbance, without any reduction in robustness to parameter variation, can be obtained by simply setting $k_5 = 3$, (which leads to $\underline{k}_1 = 7, \underline{k}_2 = 33, \underline{k}_3 = 3.5, \underline{k}_4 = -5.8$).

Remark 5.2. Table 1 summarize results that one obtains by tuning the inner loop PID gains with the Cohen Coon or the Internal Model Control method instead of the Ziegler-Nichols'. Similar results have been obtained by applying the procedire to all the other PID examples considered in Ogunnaike and Ray 1994.

$\frac{6}{(1+2s)(1+4s)(1+6s)}$						
Gains	ZN	Mod ZN	CC	Mod CC	IMC	Mod IMC
k_1	1	187	1.15	168	.55	400.5
k_2	1.5	10^3	1.2	10^3	.7	$2.14*10^3$
k_3	.5	100.5	.17	90.17	.03	200
k_4	.166	-55	.166	-50.2	.166	-400
Overshoot, %	75	36	80	45	40	36
Settling time, sec	49	48	80	55	63	48
ISE due to a disturbance step	4.8	$2.5*10^{-5}$	4.82	$3.3*10^{-5}$	27.6	$2.5*10^{-5}$

Table 1: PID gains via classical and modified-classical methods for plant in example 1.

Example 2: Use of the PID-DL form in conjunction with the tuning procedure proposed by Qing-Guo Wang &alias 1999

In what follows we show how the properties of the dual loop PID form would be used in conjunction with the tuning method recently proposed by Qing-Guo Wang &alias 1999. We start by considering a plant described by the transfer function (example 1 in the cited reference)

$$G(s) := \frac{P_v(s)}{U(s)} = \frac{e^{-2s}}{(s+3)^5} \quad . \tag{5.4}$$

A. Tuning the inner loop PID : Adopting as inner loop PID gains the values proposed by Qing-Guo Wang&alias 1999 gives

$k_1 = 58.6; k_2 = 22; k_3 = 49.7; k_4 = 0$. (5.5)

B. Tuning the outer loop PID

i. submitting the ensuing feedback system to a setpoint step gives the result in figure 6; using second order parameter optimisation, w e describe this response with $\frac{P_v(s)}{P_s(s)} \cong \frac{(\alpha_0 s+1)}{(\alpha_2 s^2+\alpha_1 s+1)}$ where $\alpha_1 = 3.37$, $\alpha_2 = 5.75$, and $\alpha_0 = -1.55$;

ii. introducing outer loop PID gains $a_0 = \alpha_0$, $a_1 = \alpha_1$, $a_2 = \alpha_2$, and a small positive k_5, and submitting the feedback system to a setpoint step, no deterioration in the process response is observed; repeating the sequence of increasing k_5 and implementing setpoint step test until the response begins to deteriorate, leads to $k_5 = 12.5$ (figure 6);

iii. submitting the feedback system to a disturbance step, reveals that the introduction of the outer loop has led to a response to disturbance that is considerably better than the one procured by the original Qing-Guo Wang &alias 1999 method (figure 6); response to setpoint is practically the same as before.

C. Computation of the PID final gains

The final gains for the conventional PID are

$\underline{k}_1 = 100.72$, $\underline{k}_2 = 93.87$, $\underline{k}_3 = 62.25$, $\underline{k}_4 = -61.5$. (5.6)

	$\frac{e^{-.5s}}{(s+1)(s+5)^2}$		$\frac{e^{-.3s}}{(s^2+2s+3)(s+3)}$		$\frac{e^{-.1s}}{(s^2+s+1)^3(s+2)^2}$	
Gains	QGW	Mod QGW	QGW	Mod QGW	QGW	Mod QGW
K_1	2.7	52.5	3.88	11.5	1.5	5.36
K_2	6.4	22.9	2.15	5.9	1.7	5.6
K_3	21	51	5.34	11.3	1.366	3.066
K_4	0	-35.7	0	-10.3	0	-4.3
Overshoot, %	12	11	3	3	3	4
Settling time, sec	5	5.6	5.3	5.8	9	10
ISE due to a disturbance step	$18*10^{-2}$	$7*10^{-3}$	1.1	.4	2.6	.84

Table 2: PID gains via Qing-Guo Wang and modified-Qing-Guo Wang methods (example 2)

Remark 5.3. Results better than or basically equivalent to the above are obtained in the context of all the other examples considered in Qing-Guo Wang &alias 1999. In particular, Figure 7 illustrates results obtained in conjunction with the plant described by the transfer function $G(s) := \frac{P_v(s)}{U(s)} = \frac{.5e^{-.1s}}{(s^2+s+1)(.5s+1)}$. Table 2 resumes results obtained in correspondence to all the other plants considered in the cited reference. Identical conclusions would have been obtained had we worked out all these examples using the tuning procedure proposed by Ho Hang and Cao 1994 (which is considered as second term of comparison in Qing-Guo Wang &alias 1999).

Example 3: Use of the PID-DL form to enhance Ya-Gang Wang and Wen-Jian Cai 2001 tuning procedure

In what follows we show how our PID tuning procedure would be used in conjunction with the method proposed by Ya-Gang Wang and Wen-Jian Cai 2001. We start by considering a plant described by the transfer function (the main example in the cited reference)

$$G(s) := \frac{P_v(s)}{U(s)} = \frac{e^{-0.2s}}{s(s+1)} \tag{5.7}$$

B. Tuning the inner loop PID : Adopting as inner loop PID gains the values proposed by Ya-Gang Wang and Wen-Jian Cai 2001 gives

$$k_1 = 3.03;\ k_2 = 2.6;\ k_3 = 2.53;\ k_4 = 1 \tag{5.8}$$

B. Tuning the outer loop PID

iv. submitting the feedback system with these inner loop PID gains to a setpoint step gives the result in figure 7; we find that the best 2nd order approximant I/O transfer function is described by $\frac{P_v(s)}{P_s(s)} \cong \frac{(\alpha_0 s + 1)}{(\alpha_2 s^2 + \alpha_1 s + 1)}$ with $\alpha_1 = .56$, $\alpha_2 = 1.3$, and $\alpha_0 = 1.1$;

v. introducing outer loop PID gains $a_0 = \alpha_0$, $a_1 = \alpha_1$, $a_2 = \alpha_2$, and a small $k_5 > 0$ and submitting the feedback system to a setpoint step test, no deterioration in the process variable response is observed; repeating the sequence of increasing k_5 and implementing setpoint step test until process response is no longer satisfactory, leads to $k_5 = 5$ (figure 8);

vi. submitting the feedback system to a disturbance step, it is found that the response is now considerably better than the one procured by the original Ya-Gang Wang and Wen-Jian Cai 2001 gains (figure 8); once again, response to setpoint is practically the same.

D. Computation of the PID final gains

The final gains for the conventional PID are

$$\underline{k}_1 = 5.8;\ \underline{k}_2 = 9;\ \underline{k}_3 = 7.5;\ \underline{k}_4 = 3.7. \tag{5.9}$$

Remark 5.4. Results basically equivalent to the above are obtained in the context of the plant $\frac{e^{-2s}}{s(s+1)}$ which is also considered in Ya-Gang Wang and Wen-Jian Cai 2001. An identical conclusion would hold if we had developed our example by considering the Poulin and Pomerlau 1996 or the Tan and Tam 1998 method instead of the method by Ya-Gang Wang and Wen-Jian Cai 2001 (application of these three methods to the plant described by eqn (5.7) are compared in the latter reference).

Remark 5.5. It is illustrated in Ya-Gang Wang and Wen-Jian Cai 2001 that gains (5.8) computed in correspondence to plant (5.7) also work satisfactorily for a parameter-perturbed plant described by $G_p(s) = \dfrac{e^{-0.2s}}{s(.1s+1)(s+1.2)}$. Figure 9 shows this robustness property to also hold for PID gains (5.9).

Concluding Considerations

In analogy to traditional 2 degrees of freedom (2DOF) PID forms, the dual loop PID (figure 3, PID-DL) provides a 2DOF PID of which the gains can be tuned in a de-coupled manner. More specifically, the inner loop PID is tuned to establish a desired response to setpoint, the outer loop PID to optimize response to disturbance. Contrary to traditional 2DOF PIDs, any industrial controller capable of fulfilling a function equal or equivalent to a standard PID can benefit 'as is' from this PID-DL property. Besides theoretical justification and simulation results reported in the previous sections, experimental validation of the effectiveness of this technique is supported by results obtained in conjunction with temperature and level control of an industrial water reservoir and which are fully documented elsewhere (Cornieles&alias 1997a, 1997b, 1997c). While further work in a real time industrial process environment is needed before full potential of the proposed approach may be more decisively assessed, it is expected that industrial implementation of the method can be carried out along identical lines as illustrated in our simulated examples. This implementation can be carried out without physically modifying the industrial controller, by taking advantage of whatever tuning capabilities it may already come equipped with, and by requiring no additional provision in relation to such aspects as anti-windup, bump-less transfer or commissioning protocol. Application of the method can be envisioned as taking place in a manual cut-and-try mode, an operator implemented-computer assisted mode or in a completely automated mode. Under most circumstances the benefit is attainment of refined gain settings that considerably improve feedback response to external disturbance without deteriorating the response to setpoint otherwise obtainable by means of the original gain setting.

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Figures

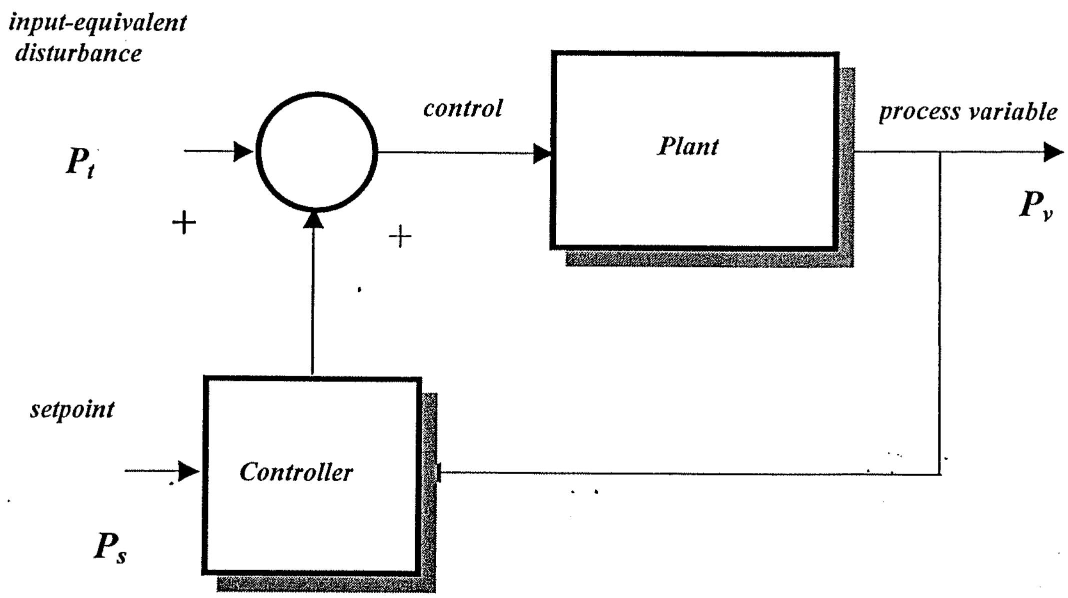

Figure 1: Feedback system under study

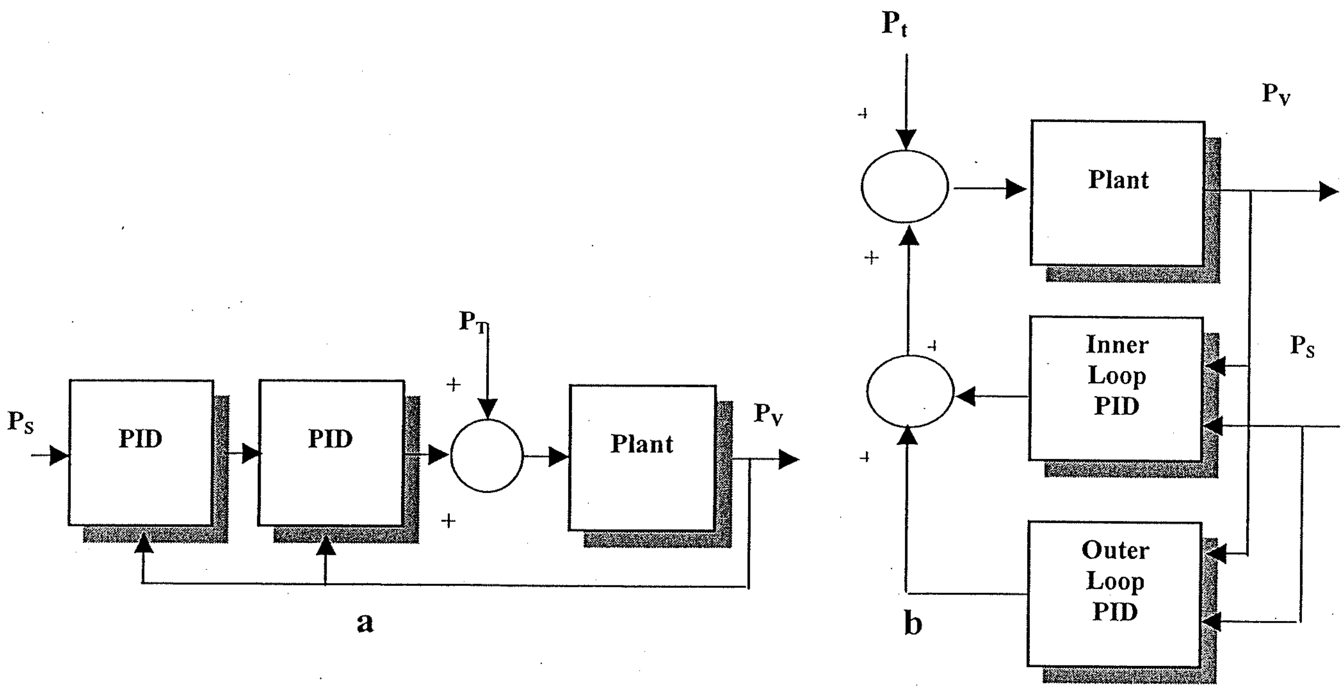

Figure 2: a) A classical 2 degrees of freedom PID; b) A dual loop 2DOF PID

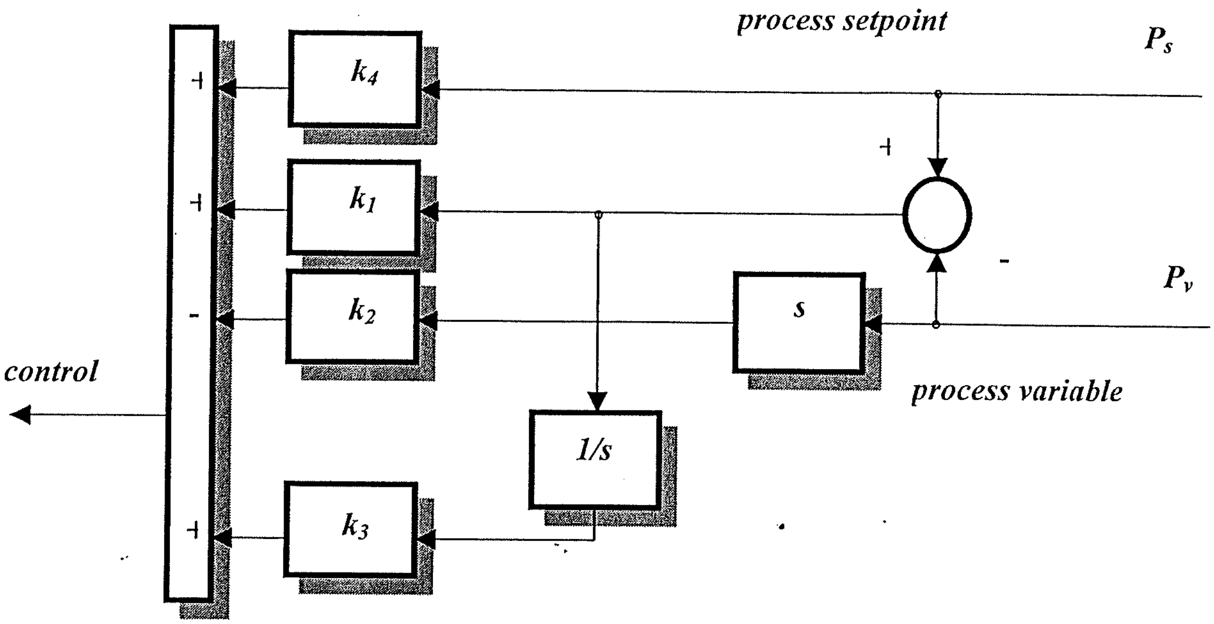

Figure 3: Standard mechanization of an industrial PID

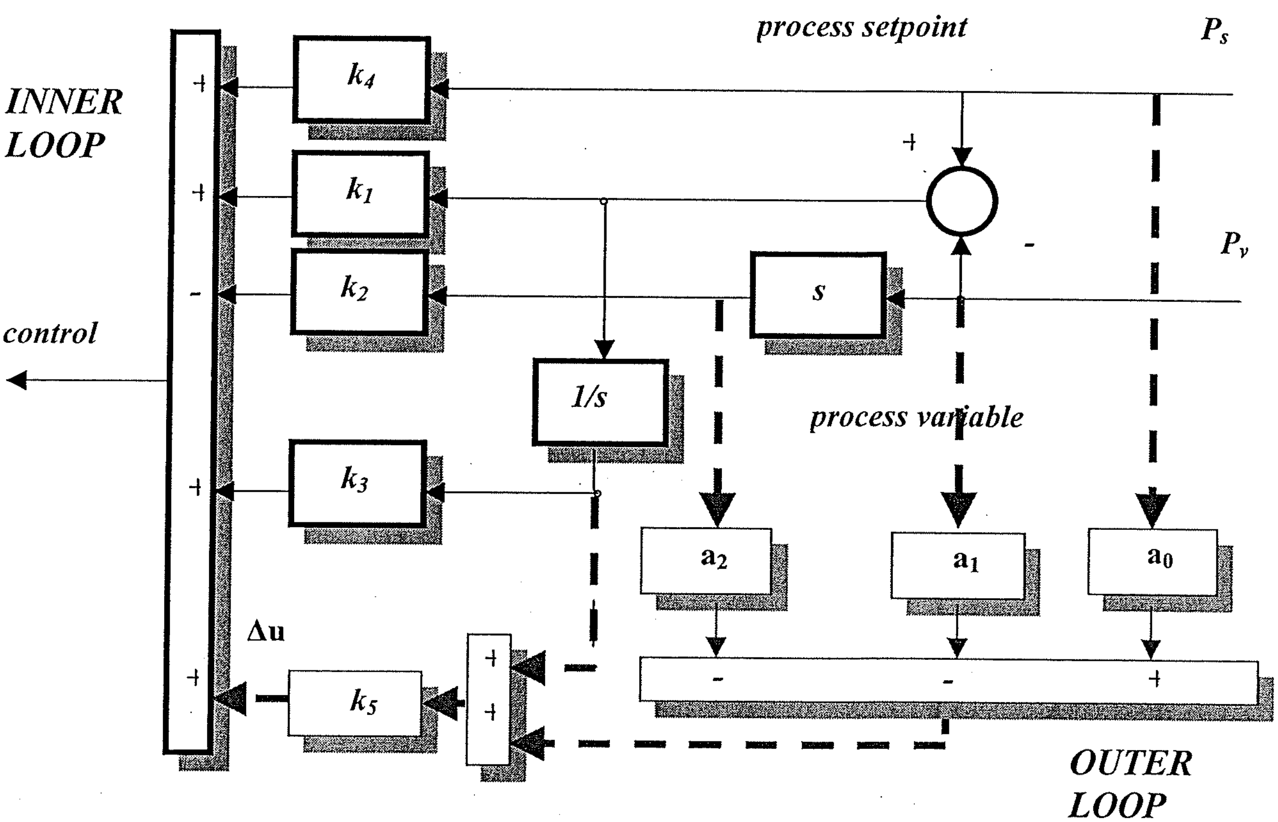

Figure 4: Dual Loop PID controller

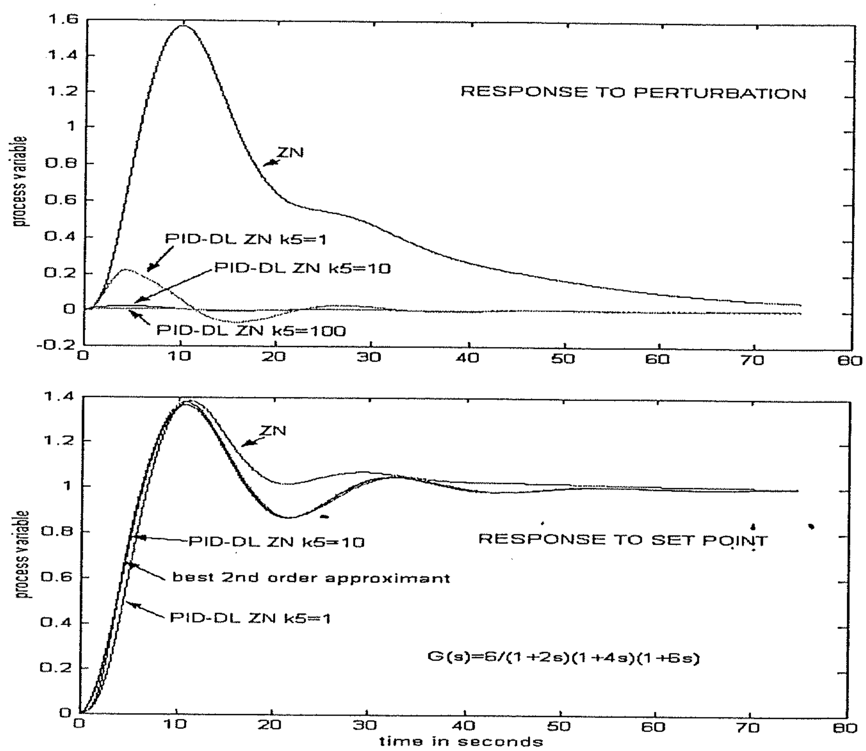

Figure 5: Plant response as a function of outer loop PID gain k_5 (example 1)

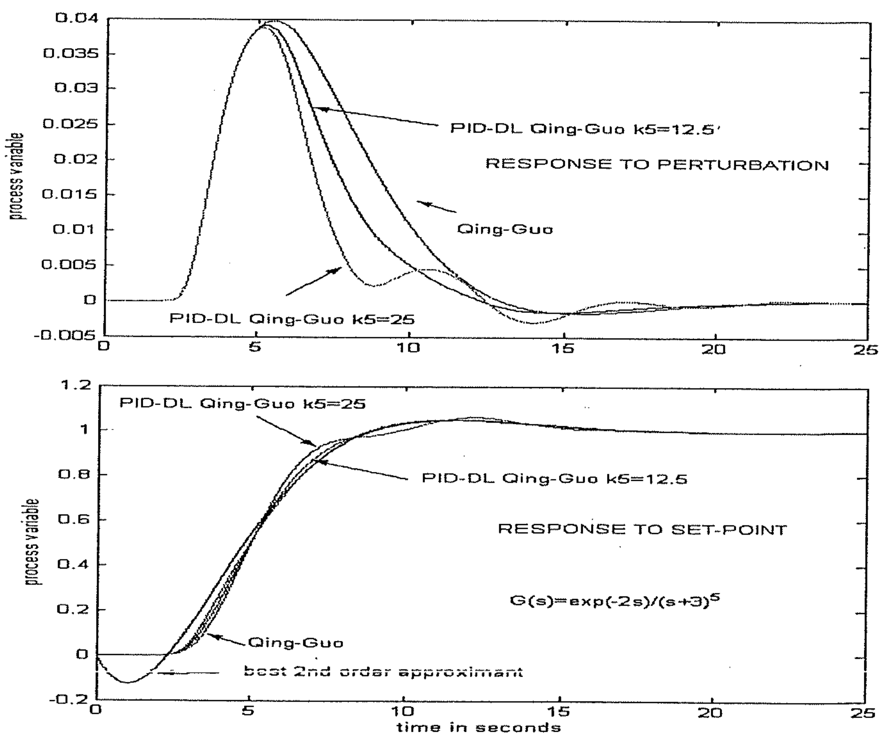

Figure 6: Plant response as a function of outer loop PID gain k_5 (example 2)

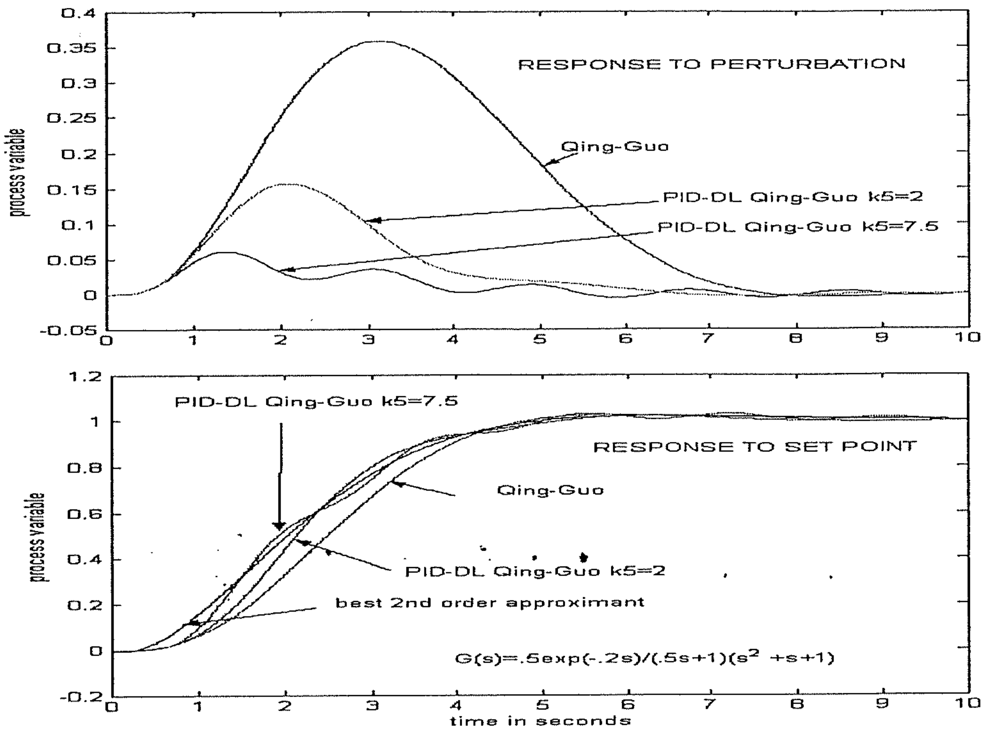

Figure 7: Plant response as a function of outer loop PID gain k_5 (example 2)

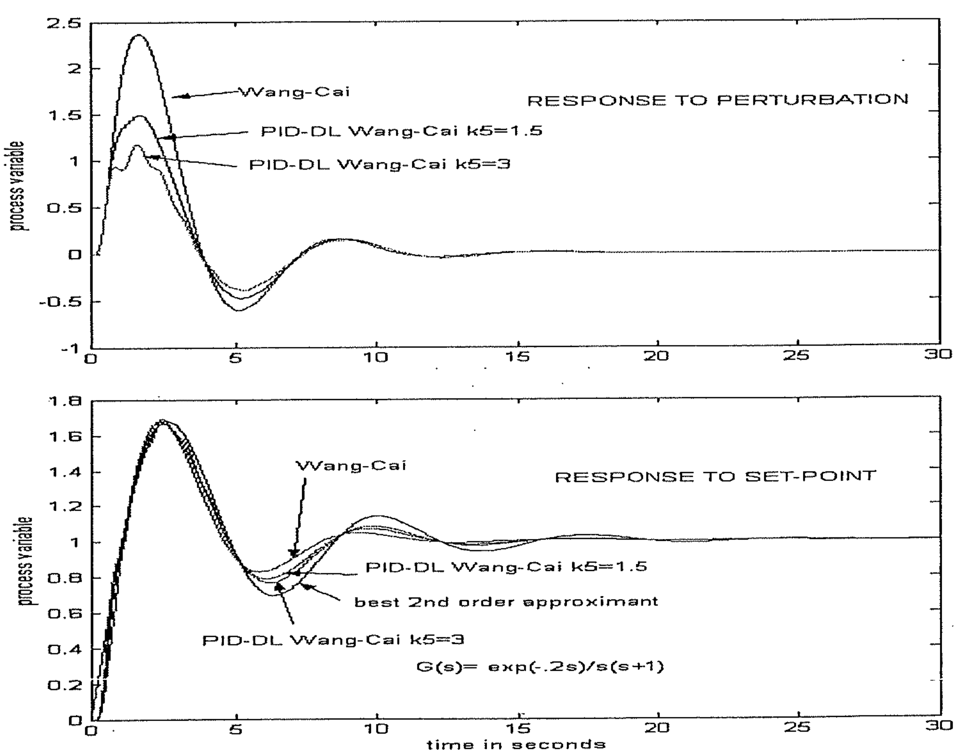

Figure 8: Plant response as a function of outer loop PID gain k_5 (example 3)

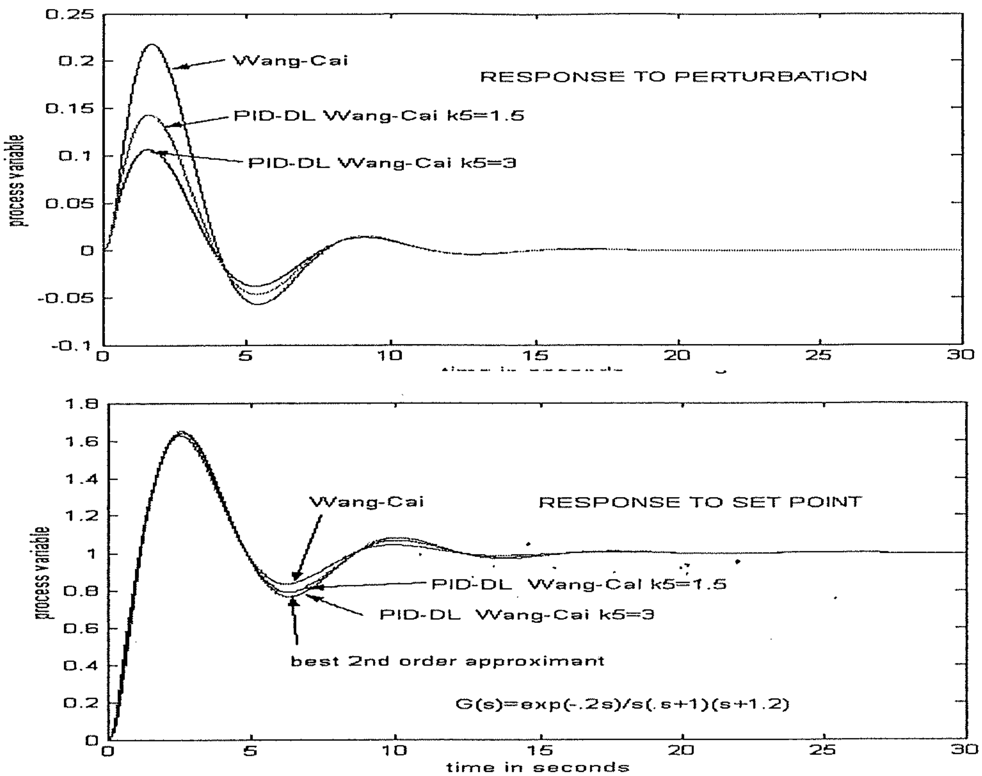

Figure 9: Parameter perturbed plant response as a function of outer loop PID gain k_5 (example 3)

École Polytechnique de Montréal
C.P. 6079, Succ. Centre-ville
Montréal (Québec)
H3C 3A7