

THE ROBUST CONTROLLER DESIGN FOR PROCESSES WITH DEAD TIMES

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Abstract. *In this paper a new structure of the Smith predictor based on IMPACT structure for control with the long dead time is proposed. The proposed structure enables the extraction of the known class immeasurable disturbances and easy setting of controller parameters in order to achieve robust stability and performance. Both analytical analysis and simulation results show that the tuning of proposed structures is extremely simple due to relatively small number of tuning parameters all having clear physical meanings. Absorption principle is derived and implemented in the general case of continuous SISO systems with dead time.*

Key words: *Robust process control, Time-delay systems, Internal Model Principle (IMP), IMPACT structure*

1. INTRODUCTION

Many physical systems, such as thermal processes, chemical processes, systems having transportation or diffusion, long transmission lines in pneumatic systems etc. contain time delays. Delays cause systems to destabilise or to degrade their feedback performance [1]. The risk of instability or performance degradation is more expressed if the time-delay is comparable to or greater than the dominant process time constants [2]. Conventional controllers, like the PID controllers could be used when the dead-time is small, but they show poor performance when the process exhibits long dead-times because a significant amount of detuning is required to maintain closed-loop stability. Therefore, several methods have been suggested to deal with such processes. The Smith predictor is a simple solution to this problem and was used to improve the performance of classical PID controller for plants with time delay [3]. Attention has been paid to this control structure over the years, but many researchers pointed out that the Smith pre-

dictor is very sensitive to modeling errors. The most sensitive parameters are the time delay and the steady-state gain of the process [1]. As modified, Smith predictor have been proposed by several authors: some of them focused their attention on the study of auto tuning and adaptive structures, others on the study of robust control structures [1-8]. Although the Smith predictor has the capability of transforming a time-delay control design to a delay free problem, three principal problems of the Smith predictor structure were analyzed by many authors during the last twenty years [8, 3, 4, 7, 5]: 1) the robustness; 2) the disturbance rejection characteristics, and 3) the extension of the idea of the Smith predictor to the case of integrative plants. An effective answer to these issues has just given by the structure proposed in [5], which is based on IMPACT (Internal Model Principle and Control Together) structure [9]. The proposed structure can be interpreted as a new structure of the modified Smith predictor for processes that can be described by an integrator, a velocity gain and a long effective transport lag. The structure enables absorption of arbitrary class of deterministic disturbances and can be easily tuned to achieve the desired speed of set-point response and to maintain the preferred system robustness with respect to interval changes and/or uncertainties of plant parameters.

This paper summarizes the previous results and proposes robust continuous controller design for processes with dead times. The proposed controlling structure is based on an IMPACT structure, or the use of internal model principle (IMP) and internal model control (IMC) together. The most important problem in continuous control systems with long dead time concerns is internal model principle (IMP) implementation. The IMP and absorption principle are based upon the same fundamental idea of inclusion disturbance model into the system controlling structure. In the case of IMPACT structure, the model of external disturbance is implicitly incorporated into the minor local loop of control system in order to eliminate or to reject completely the influence of disturbance on the steady-state value of system controlled variable [9, 5]. In this paper, the absorption principle is formulated more generally than before in a continuous form and then the possibility of its application is made using two most typical models of processes with delay that are found in the process industry. Generally, the proposed structure will exclude the effects of a known class of external disturbance on controlled variable and will improve the system robustness. The proposed structures enable the set point transient response and speed of disturbance rejection to be adjusted independently by setting a small number of parameters having clear physical meanings. The efficiency and robust properties of the proposed structure are verified and tested by simulation.

2. THE PLANT MODELS AND CONTROL SYSTEM STRUCTURE

In most cases, it is possible to find two kinds of typical processes in industry: the ones that can be modeled by a static gain K_p , a dead-time L and a time constant T

$$W^0(s) = \frac{K_p e^{-Ls}}{Ts + 1} = G_p(s) e^{-Ls} \quad (1)$$

and the ones that can be described by an integrator, a velocity gain K_v and a dead-time L .

$$W^0(s) = \frac{K_v e^{-Ls}}{s} = G_p(s) e^{-Ls} \quad (2)$$

In both cases $G_p(s)$ represents the delay free part of process, and both of nominal models ((1) and (2)) can be considered as simplification of more accurate models

$$W(s) = \frac{K_p}{(T_1s+1)(T_2s+1)\dots(T_ns+1)} e^{-s\tau} \quad (3)$$

$$W(s) = \frac{K_v}{s(T_1s+1)(T_2s+1)\dots(T_ns+1)} e^{-s\tau}$$

Practically, the model is just a simplification of the real system and that the artificial model elements do not necessarily have a one-to-one correspondence in the real system. Also, the identified parameters may possibly vary depending on the operating point, and the model describes the dynamic behavior of the real system only to a certain degree. The controller must thus be robust and be able to deal with these constraints (it must be robust enough to allow for considerable parameter variation and model uncertainty).

The IMPACT control structure of the modified Smith predictor is shown in Fig.1. [5,9]. The control portion within the system structure in Fig. 1 comprises the Smith predictor internal controller, in the main loop, and two internal models, in the local minor loop: the internal nominal plant model explicitly and the internal model of external disturbance $d(t)$ embedded implicitly into predictive filter $A(s)/C(s)$. Both the internal nominal plant model and disturbance model are treated as disturbance estimator. Really, disturbance estimator estimates the influence of generalized disturbance φ that comprises the influence of the external disturbance d and the influence of uncertainties of plant parameters on the system output. Uncertainties of plant modeling may be adequately described by the additive bound of uncertainties $\bar{l}_a(\omega)$

$$W(j\omega) = W^0(j\omega) + l_a(j\omega), \quad |l_a(j\omega)| \leq \bar{l}_a(\omega) \quad (4)$$

The controlling structure has two control loops that can be designed independently. The minor loop compensates the influence of generalized disturbance and increases the robust system performance. The minor local control loop is designed by the proper choice of polynomials $A(s)$ and $C(s)$. Polynomial A includes implicit disturbance model, while the choice of C affects the speed of disturbance rejection, system robustness, and sensitivity with respect to measuring noise. Good filtering properties and the system efficiency in disturbance rejection are the mutually conflicting requirements. The lower bandwidth of the $A(s)/C(s)$ filter corresponds to a higher degree of system robustness and vice versa. The dynamic of minor local control loop within the low frequency band is described by nominal plant model. Thus, the main control loop “sees” the minor control loop as nominal plant model and determines dynamic behavior of the closed loop system. In the main control loop, the main controller $G_r(s)$ will be determined to achieve the desired system set point response.

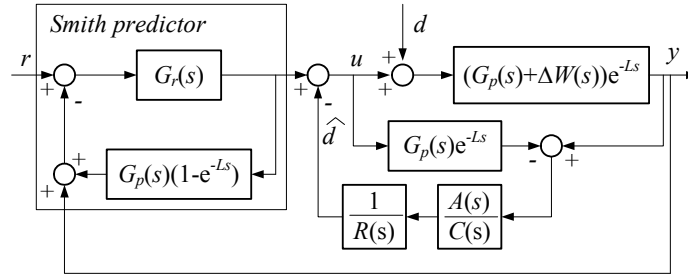


Fig. 1. IMPACT structure of the modified Smith predictor with one-input internal nominal plant model

For the integrative plant (2), the proportional main controller

$$G_r(s) = K_r \quad (5)$$

may be applied. In that case, under nominal conditions, the closed-loop transfer function $Y(s)/R(s)$ and $Y(s)/D(s)$ will be

$$\frac{Y(s)}{R(s)} = \frac{K_r K_v}{s + K_r K_v} e^{-Ls} \quad (6)$$

and

$$\frac{Y(s)}{D(s)} = \frac{(1 - \frac{1}{R(s)} \frac{A(s) K_v}{s} e^{-Ls}) K_v (1 + K_r \frac{K_v}{s} (1 - e^{-Ls}))}{s + K_r K_v} e^{-Ls} \quad (7)$$

In virtue of (6), the speed of set-point response can be adjusted by choosing appropriate values of controller gain K_r or dominant time constant $T_r = 1/(K_r K_v)$. According to [5], the proper choice of $R(s)$ is $R(s) = K_v$. Since the term $(1 - e^{-Ls})/s$ in the numerator of closed-loop system transfer function (7) has the frequency characteristics of zero-order hold, the speed of disturbance transient response is governed by the roots of characteristic equation

$$(s + K_r K_v) C(s) = 0 \quad (8)$$

If polynomial C is chosen as $C(s) = (T_0 s + 1)^n$, the lower order n and smaller value of T_0 will correspond to a faster rejection of disturbance and a lower degree of system robustness, and vice versa [5]. For the sake of simplicity and easier physical realization, it is usually assumed $n=2$. Then we can distinguish two tuning parameters: T_r and T_0 for simple and straightforward adjustment of the set point transient response, the speed of absorption of disturbance influences on steady state process output value, and the degree of system robustness. This is accomplished independently; first by choice of an appropriate value of T_r and then by setting of tuning parameter T_0 .

In the non-integrative plant (1) case, in order to achieve the desired closed-loop transfer function $Y(s)/R(s)$

$$G_{de}(s) = \frac{Y(s)}{R(s)} = \frac{1}{T_r s + 1} e^{-Ls} \quad (9)$$

may be chosen the PI main controller (Fig.1)

$$G_r(s) = K \left(1 + \frac{1}{T_i s} \right) = \frac{T_s + 1}{K_p T_r s}, \quad \left(K = \frac{T}{K_p T_r}, T_i = T \right). \quad (10)$$

and in that case

$$\frac{Y(s)}{D(s)} = \frac{\left(1 - \frac{1}{R(s)} \frac{A(s)}{C(s)} \frac{K_p}{T_s + 1} e^{-Ls} \right) K_p T_r s \left(1 + \frac{1 - e^{-Ls}}{T_r s} \right)}{(T_r s + 1)(T_s + 1)} e^{-Ls} \quad (11)$$

Note that the system with non-integrative process can be commented on similar manner as the system with integrative process. In the case of nonintegrative plant, the proper choice of $R(s)$ is $R(s) = K_p$. The gain and integral time of the PI controller have clear physical meanings (see (10)), and the parameter T_r defines the set-point response (see (9)). The speed of disturbance transient response is defined by the roots of characteristic equation

$$(T_r s + 1)(T_s + 1)C(s) = 0 \quad (12)$$

Practically, apart from the identified plant parameters, there will be two tuning parameters (T_r and parameter of polynomial C) for setting set-point response, speed of disturbance rejection, and system robustness. Disturbance absorption and robustness will be in detail commented in the next Sections.

3. THE ABSORPTION PRINCIPLE

The absorption principle is basically identical to IMP, and its intention is to include the disturbance model in control algorithm in order to suppress or reject disturbance influence on steady state value of process output [9].

Namely, the broad class of continuous functions can be presented as solution of homogeneous differential equations; and it is the basic result for analogous absorption filter synthesis and absorption principle implementation in control systems. For continuous class, signals defining the expected type of disturbances may design an absorption filter $\Phi(s)$ which steady state response on specified class of signal will equal zero. For example, the absorption filter $\Phi(s) = s$ is suitable for the class of step disturbances, $\Phi(s) = s^2$ is suitable for ramp disturbances, $\Phi(s) = s^2 + \omega^2$ corresponds to $d(t) = A \sin \omega t$, etc. Generally, suppose the class of disturbances $d(t)$ having the Laplace transform $D(s) = d_{num}(s)/d_{den}(s)$. Then, absorption polynomial $\Phi(s)$ can be determined explicitly by

$$\Phi(s) = d_{den}(s), \quad D(s) = \frac{d_{num}(s)}{d_{den}(s)} \quad (13)$$

The principle of absorption means the design of absorption filter whose input is disturbance signal in order to compensate disturbance influence. By implementation of absorption filter in the control system, the disturbance model is included in controlling structure too. Following the compensation equation may be considered as the absorption condition of the given class of disturbances

$$\frac{Y(s)}{D(s)} = \frac{\Phi(s)N_d(s)}{D_d(s)} \quad (14)$$

where the polynomials $N_d(s)$ and $D_d(s)$ form a stable transfer function $N_d(s)/D_d(s)$ having less or more influence on the quality of disturbance transient response. Consider now the applications of absorption principle in the process control with dead time.

The principle of absorption in IMPACT structure is implemented in the minor loop, that enables estimation of influence of generalized disturbance, its prediction and feedforward compensation. Using the absorption principle in the case of integrative plant and IMPACT controlling structure (see (7) and (14)), the absorption condition becomes

$$\frac{(sR(s)C(s) - K_v A(s)e^{-Ls})}{sR(s)C(s)(s + K_r K_v)} K_v (1 + K_r K_v \frac{1 - e^{-Ls}}{s}) e^{-Ls} = \frac{\Phi(s)}{D_d(s)} N_d(s) \quad (15)$$

Since term $(1 - e^{-Ls})/s$ has the known characteristics of zero-order hold, then the transfer function

$$(1 + K_r K_v \frac{1 - e^{-Ls}}{s})$$

is stable and it can be consider as factor of the polynomial $N_d(s)$. In order to the transfer function $N_d(s)/D_d(s)$ will be stable, it is necessary adopt following form of the polynomial $A(s)$

$$A(s) = sA_0(s) \quad (16)$$

As it is known $R(s)=K_v$, and the relation (15) is reduced to

$$\frac{(C(s) - A_0(s)e^{-Ls})}{C(s)(s + K_r K_v)} K_v (1 + K_r K_v \frac{1 - e^{-Ls}}{s}) e^{-Ls} = \frac{\Phi(s)}{D_d(s)} N_d(s) \quad (17)$$

From (17), it is obviously that the speed of disturbance absorption is defined by the roots of characteristic equation (8), and that the absorption condition becomes

$$A_0(s)e^{-Ls} + N_1(s)\Phi(s) = C(s) \quad (18)$$

The solutions of (18) are the polynomials $A_0(s)$ and $N_1(s)$, while the stable polynomial $C(s)$ is chosen free previously. The selection of polynomial $C(s)$ can be done according to the desired speed of disturbance rejection, the filter system properties and the degree of system robustness.

But, in opposition to the discrete case where Diophantine equation is solvable without any approximation, the equation (18) has to reduce into polynomial equation. The

exponential term e^{-Ls} can be approximated by Pade approximation, or by Taylor series expansion as

$$e^{-Ls} \cong 1 - Ls + \frac{(Ls)^2}{2!} - \frac{(Ls)^3}{3!} + \dots + \frac{(Ls)^N}{N!} = \sum_{k=0}^N \frac{(-Ls)^k}{k!} \quad (19)$$

Substituting e^{-Ls} from (19) into (18), relation (18) obtains the specific form of the Diophantine equation

$$A_0(s) \sum_{k=0}^N \frac{(-Ls)^k}{k!} + N_1(s)\Phi(s) = C(s) \quad (20)$$

A single solution of the Diophantine equation, which plays a crucial role in the design procedure of the proposed disturbance estimator, does not exist [11]. The relation (20) is a linear equation in polynomial $A_0(s)$ and $N_1(s)$. Generally, the existence of the solution of the Diophantine equation is given in [12]. According to [12], there always exists the solution of (20) for $A_0(s)$ and $N_1(s)$ if the greatest common factor of polynomials $\sum_{k=0}^N (-Ls)^k/k!$ and $\Phi(s)$ divides polynomial $C(s)$; then, the equation has many solutions. The particular solution is constrained by the fact that the control law must be causal, i.e.

$$\deg(A(s)) = 1 + \deg(A_0(s)) \leq \deg(C(s))$$

Hence, after choosing a stable polynomial $C(s)$, N , and degrees of polynomials $A_0(s)$ and $N_1(s)$, and inserting the absorption polynomial $\Phi(s)$ that corresponds to an expected external disturbance, polynomials $A_0(s)$ and $N_1(s)$ are calculated by equating coefficients of equal order from the left- and right-hand of equation (20). In the our case, for absorptional polynomial

$$A_0(s) \sum_{k=0}^N \frac{(-Ls)^k}{k!} + N_1(s)\Phi(s) = C(s) \quad (21)$$

that corresponds to the class of polynomial disturbances

$$d(t) = \sum_{i=1}^m d_i t^{i-1}$$

and for chosen polynomial $C(s) = c_0 + c_1s + c_2s^2 + c_3s^3 + \dots$, the simplest solution of the Diophantine equation (20) is given in Tab. 1. Practically, most frequently disturbances may be considered as slow varying and in these cases the polynomial $A(s)$ should be calculated to correspond to the ramp signal $d(t)$ ($\Phi(s) = s^2$, $m = 2$). Hence, in majority of practical applications an appropriate choice of absorption filter might be $\Phi(s) = s^2$, $m = 2$, that corresponds to absorption of linear (ramp) disturbance, but, it enables also the extraction of slow varying disturbances and even suppression of the effects of low frequency.

For the sake of clarity and to reduce the number of adjustable parameters, let us assume

$$C(s) = (T_0s + 1)^n \quad (22)$$

Then, from Tab.1 can be calculated $A_0(s) = 1 + (nT_0 + L)s$, and the transfer function inside the disturbance estimator becomes

$$\frac{1}{R(s)} \frac{A(s)}{C(s)} = \frac{1}{K_v} \frac{s(s(nT_0 + L) + 1)}{(T_0s + 1)^n} \quad (23)$$

The value of parameter n is constrained by the condition of causality $n \geq 2$.

Table 1 Implicit disturbance model in general choice of polynomial $C(s)$

Class of disturbance	Polynomial $A_0(s)$
Step, $m=1$	$A_0(s) = c_0$
Rampa, $m=2$	$A_0(s) = c_0 + (c_1 + Lc_0)s$
Parabolic, $m=3$	$A_0(s) = c_0 + (c_1 + Lc_0)s + (c_2 + c_1L + 0.5c_0)s^2$

In the case of non-integrative plant (1), the similar approach to absorption principle implementation may be applied. For the sake of simplicity and correctness of relation (12), let us assume

$$A(s) = (Ts + 1)A_0(s) \quad (24)$$

Then, analogous to relation (15), the compensation equation becomes

$$\frac{s(C(s) - A_0(s)e^{-Ls})}{C(s)(T_r s + 1)(Ts + 1)} K_p T_r \left(1 + \frac{1 - e^{-Ls}}{T_r s}\right) e^{-Ls} = \frac{\Phi(s)}{D_d(s)} N_d(s) \quad (25)$$

From (25), it is obvious that the speed of disturbance rejection is defined by the roots of characteristic equation (12), and the absorption condition becomes

$$s(C(s) - A_0(s)e^{-Ls}) = N_1(s)\Phi(s) \quad (26)$$

But, by selection of PI controller (10) within the main control loop, the absorption of the step disturbance is already designed through the main control loop ($\Phi_{ml}(s) = s$). As it is known, the absorption principle in IMPACT structure is implemented in the inner loop, but generally the disturbance absorption can be achieved by main ($\Phi_{ml}(s)$) and the inner ($\Phi_{il}(s)$) control loop together. In our case

$$\Phi(s) = \Phi_{ml}(s)\Phi_{il}(s), \quad \Phi_{ml}(s) = s \quad (27)$$

where $\Phi_{ml}(s)$ and $\Phi_{il}(s)$ are absorption polynomials defining absorption by main and inner control loop respectively. From here, the relation (26) is reduced to

$$A_0(s)e^{-Ls} + N_1(s)\Phi_{il}(s) = C(s) \quad (28)$$

By using a Taylor series expansion of e^{-Ls} and by substituting from (19) into (28), the relation (28) becomes the Diophantine equation

$$A_0(s) \sum_{k=0}^N \frac{(-Ls)^k}{k!} + N_1(s)\Phi_{il}(s) = C(s) \quad (29)$$

which is of the same form as (20), and which guarantee the absorption of disturbances class specified by the absorption filter $\Phi_{it}(s)$. The previous comments about choosing a stable polynomial $C(s)$ and Tab.1. are also applicable to the solving of Diophantine equation (29). For example, by choosing of $C(s) = (T_0s + 1)^n$ and $\Phi_{it}(s) = s$ (i.e. $\Phi(s) = s^2$) the transfer function inside the disturbance estimator becomes

$$\frac{1}{R(s)} \frac{A(s)}{C(s)} = \frac{1}{K_p} \frac{Ts + 1}{(T_0s + 1)^n} \quad (30)$$

or in the case of parabolic disturbances ($\Phi(s) = s^3$, $\Phi_{it}(s) = s^2$)

$$\frac{1}{R(s)} \frac{A(s)}{C(s)} = \frac{1}{K_p} \frac{(Ts + 1)((nT_0 + L)s + 1)}{(T_0s + 1)^n} \quad (31)$$

The value of parameter n is constrained by the condition of causality ($R(s) = K_p$, $n \geq \deg(A(s))$).

4. THE ROBUSTNESS ANALYSIS

The design of the controller is based on the nominal model $W^0(s)$, but the true open-loop transfer function is $W(s)$. The closeness of the nominal plant $W^0(s)$ and the real plant $W(s)$ may be described by relation (4) and by the additive bound of uncertainty $\bar{l}_a(\omega)$. The real plant is considered as member of infinite family of plants within which each member more or less deviates from the nominal plant. Suppose that $W^0(s)$ and $W(s)$ have the same number of unstable poles and that the desired closed-loop system transfer function $G_{de}(s)$ is stable. Then, each member of the family is stable if and only if the following criterion of robust stability is satisfied

$$\bar{l}_a(\omega) < \beta(\omega) \quad (32)$$

where

$$\beta(\omega) = \left| \frac{W^0(j\omega)}{G_{de}(j\omega)} \right| \left| \frac{G_{ff}(j\omega)}{G_{fb}(j\omega)} \right| \quad (33)$$

while $G_{ff}(s)$ and $G_{fb}(s)$ are defined from

$$U(s) = G_{ff}(s)R(s) - G_{fb}(s)Y(s) \quad (34)$$

as the transfer functions of feedforward and feedback portions of the system control structure respectively.

In the case of integrative plant and the IMPACT controlling structure of Fig.1, one obtains

$$\beta(\omega) = K_v \left| \frac{T_r j\omega + 1}{j\omega} \right| \left| \frac{C(j\omega)}{C(j\omega) + (T_r j\omega + 1 - e^{-Lj\omega})A_0(j\omega)} \right| \quad (35)$$

As known, the linear models of finite orders fairly well approximate dynamic behavior of plants at low frequency range, while disagreements appear at high frequencies. It is significant to notice that $\beta(\omega)$ tends to a constant value at high frequencies. Namely, if one chooses polynomial $C(s) = (T_0s + 1)^n$ and $A_0(s) = a_{m-1}s^{m-1} + \dots + a_1s + a_0$ ($A(s) = sA_0(s)$), then

$$\lim_{\omega \rightarrow \infty} \beta(\omega) = \frac{K_v T_r T_0^n}{T_0^n + T_r a_{m-1}}, \text{ for } \deg C(s) = \deg A(s) \quad (36a)$$

$$\lim_{\omega \rightarrow \infty} \beta(\omega) = K_v T_r, \text{ for } \deg C(s) > \deg A(s) \quad (36b)$$

From (36) and previous, one can conclude that as the suitable choice of parameter n may be adopted

$$n = 1 + \deg A(s) \quad (37)$$

It is evident that a greater value of $T_r = 1/(K_r K_v)$ yields a higher degree of system robustness. The influence of disturbance observer on system robustness will be illustrated by the illustrative example in the section that flows. Generally, it will be shown that for a higher degree n of chosen polynomial $C(s)$ and a greater value of time constant T_0 of $C(s)$ (see (22)), the system robustness improves, and vice versa. Also, the implementation of more complicated disturbance models within polynomial $A(s)$ means a higher degree of $A(s)$ and less system robustness.

In the case of non-integrative plant and the IMPACT controlling structure of Fig. 1. defined with the relations (1), (9), (10), (24) and $R(s) = K_p$, one derives

$$\beta(\omega) = K_p \left| \frac{T_r j\omega + 1}{T_j \omega + 1} \right| \left| \frac{C(j\omega)}{C(j\omega) + (T_r j\omega + 1 - e^{-Lj\omega}) A_0(j\omega)} \right| \quad (38)$$

It is evident that for defined structures of both plant case with dead time, the influence of minor local control loop on system robustness is the same. Similarly to previous, respecting the choice of $A_0(s) = a_{m-1}s^{m-1} + \dots + a_1s + a_0$, (22), (24), and (37), one derives

$$\lim_{\omega \rightarrow \infty} \beta(\omega) = \frac{K_p T_r}{T}, \text{ for } \deg C(s) > \deg A(s) \quad (39)$$

It is clear that to improve the system robustness, the speed of set point response must be slowed down (i.e. the desired time constant T_r must be increased). When controlling the processes with long dead times, a general rule used in the process industry is that the closed-loop time constant T_r is chosen near the open-loop time constant T [4]. The relations (38) and (39) confirm this rule.

5. THE CONTROLLER TUNING AND SIMULATION RESULTS

The control part of IMPACT structure of modified Smith predictor in Fig. 1 contains five parameters K_v , L , K_r , T_o , and n in the case of integrative plant, and six parameters K_p , T , L , T_r , T_o , and n in the case of nonintegrative plant. Plant parameters K_v and L , or K_p , T ,

and L , are measured or estimated by simple experiment. Other parameters K_r , T_o , and n , or T_r , T_o , and n are to be adjusted with respect to prescribed speeds of set-point transient and disturbance transient responses and to the desired degree of system robustness. Practically, parameter n may be fixed by (37), and then both of the structures have the same tuning parameters T_r and T_o (in the first case $T_r=1/(K_r K_v)$) with clear physical meaning. By increasing of time constants T_r and T_o the system robustness and the system filter properties will be improved, and at the same time the disturbance rejection and the set point response will be slower. Time constant T_o doesn't influence on the set point response. First, by tuning of T_r may be set the set-point response and robust stability area; and then by tuning of T_o may be influenced to the system robust performance and to the speed of disturbance rejection. The efficiency of proposed structures and procedures of parameter tuning will be investigated by simulation.

Let us consider particular examples of the processes given by [3]

$$W(s) = \frac{0.1e^{-8s}}{s(1+s)(1+0.5s)(1+0.1s)} \quad (40)$$

with identified nominal plant model

$$W^0(s) = \frac{0.1e^{-9.7s}}{s} \quad (41)$$

and

$$W(s) = \frac{e^{-10s}}{(1+s)(1+0.6s)(1+0.15s)(1+0.1s)} \quad (42)$$

with identified nominal plant model

$$W^0(s) = \frac{e^{-10.5s}}{1.5s+1} \quad (43)$$

In both plant cases, within IMPACT controlling structure disturbance observer is applied with an implicit model of ramp disturbances (the relations (23) and (31)). The main controller parameters: $T_r=2$, $K_v=0.1$, $L=9.7$ in the integrative plant case, and $T_r=1.5$, $K_p=1$, $T=1.5$, $L=10.5$ in the non-integrative plant case are chosen. The influence of disturbance observer (23) and (31) on robust stability is illustrated on Fig. 2. In virtue of Fig. 2, for a higher degree n of chosen polynomial $C(s)$ and a greater value of time constant T_0 , the system robustness improves. The efficiency of the IMPACT structure is illustrated on Fig.3 and Fig.4. In all simulation runs the reference is $r(t)=0.5 \cdot 1(t)$, and disturbance is the same marked by $d(t)$. Fig.3 explains the capability of IMPACT structure (Fig.1) in the integrative plant case. First, the structure is designed to absorb a constant disturbance ($n=2$ and $T_0=1$) and trace $y1(t)$ is obtained. Second, the structure is designed to absorb a ramp disturbance by using transfer function (23), with $n=2$ and $T_0=6$, and trace $y2(t)$ is obtained. Generally, the design of the local minor loop for absorption of more complex external disturbances $d(t)$ requires a higher order of polynomial $A_0(s)$, and results in a lower degree of robustness. Because of that, the similar level of robust stability is reached by different values T_0 in the shown example on Fig.4.

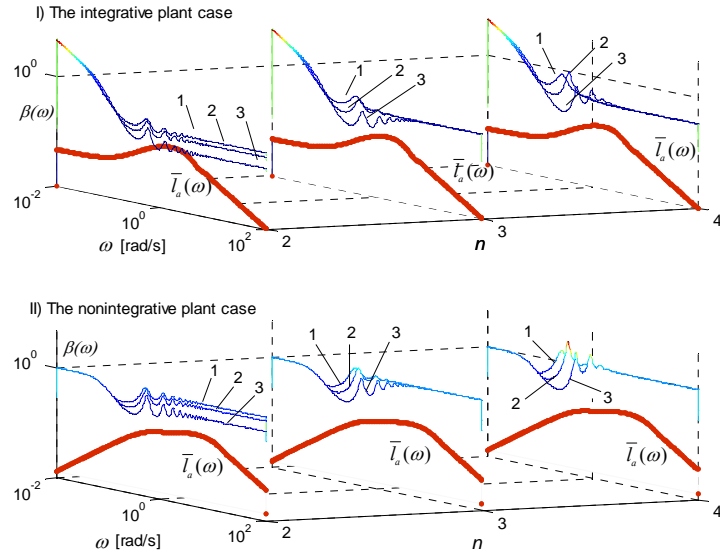


Fig. 2 The influence of disturbance observer parameters on the robust stability – 1) $T_0=9$, 2) $T_0=6$, 3) $T_0=3$.

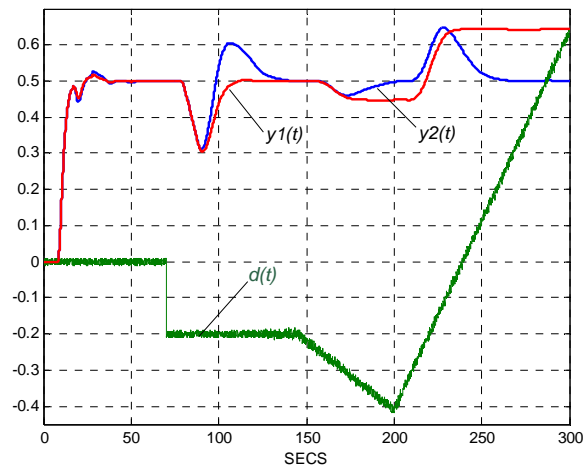


Fig. 3 The disturbance absorption in the case of IMPACT structure with integrative plant and an implicit model of step (y_1) and ramp (y_2) disturbance

Fig.4 explains the capability of IMPACT structure (Fig.1) in the non-integrative plant case. Trace $y_2(t)$ of Fig.4 shows the reference and the disturbance response of the structure on Fig.1 with the main controller (10), but without the local minor loop. Then, the proposed IMPACT structure for a non-integrative plant (1) is designed to absorb a

ramp disturbance. More exactly, the disturbance observer for a step disturbance absorption (30), with $n = 2$ and $T_0=1.5$, is implemented in controlling structure, and trace $y1(t)$ is obtained. Notice that each linear segment of the disturbance is absorbed after certain time period. The disturbance rejection may be improved by choosing $n=1$ and/or a smaller values of T_0 and T_r . However, in doing so, one must maintain the robust stability with respect to uncertainties of plant parameters.

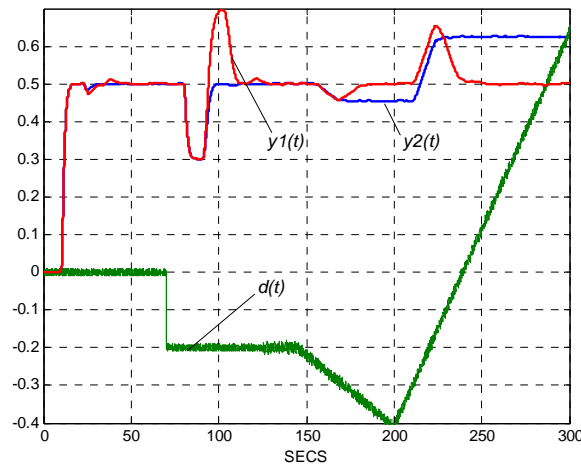


Fig. 4 The response of the structure with non-integrative plant and PI main controller (10) with ($y1$) and without ($y2$) local minor loop

6. CONCLUSION

The most common design goal in the process control is to obtain a critically damped closed-loop system which is as fast as possible, with a possibility to take into account the model uncertainties and to tune their characteristics with respect to set points and disturbances. In order to meet these requirements, the usage of the absorption principle and modified IMPACT structure with a simple and robust tuning is proposed. The analysis is made by using two typical processes with delay that are found in the process industry. For the process model cases, the application of absorption principle in a continuous form is formulated and implemented within appropriate simple controlling structures. The tuning of modified IMPACT structures is discussed in the paper and some simple rules are given. The proposed structures may be adjusted according to the desired speed of set-point response and the speed of disturbance rejection, in a simple way by tuning only few parameters having clear physical meanings. In both cases, the structure can easily be tuned manually. Robustness and response speed are mutually opposite requirements. However, proposed structure is suitable for successful design of robust stability and robust performance, and for the rejection of influence of arbitrary external disturbance class at the same time. Generally, the structure enables further improvements: the on-line system adaptation, the combination of advantages of approved control algorithms, etc.

Several simulation results are presented to verify previous theory analysis and to illustrate the structure efficiency.

REFERENCES

1. Balestrino, A., Verona, F.B., Landi, A., 1998, *On-line process estimation by ANNs and Smith controller design*, IEE Proc. Control Theory Appl., vol. 145, N°2, pp. 231-235.
2. Matijević, M., Jakupović, G., Car, J., 2005, *Computer Aided Measurement and Control* (textbook in Serbian, 1st edn.), University of Kragujevac, Kragujevac, 529 pp.
3. Normey-Rico, J.E., Camacho, E.F., 1999, *Smith predictor and modifications: A comparative study*, Proc. of the European Control Conference ECC'99, Karlsruhe, Germany
4. Normey-Rico, J.E., Camacho, E.F., 1999, *Robust tuning of dead-time compensators for processes with an integrator and long dead-time*, IEEE Trans. on Automatic Control, vol. 44, N°8, pp. 1597-1603.
5. Stojić, M., Matijević M., Draganović, Lj., 2001, *A robust Smith predictor modified by internal models for integrating process with dead time*, IEEE Trans. on Automatic Control, Vol. 46, N°8, P. 1293-1298.
6. Zhang, W.D., Sun Y.X., Xu, X.M., 1998, *Robust digital controller design for processes with dead times: New results*, IEE Proc. Control Theory Appl., vol. 145, N°2, pp. 159-164.
7. Astrom, K.J., Hang, C.C., Lim, B.C., 1994, *A new Smith predictor for controlling a process with an integrator and long dead-time*, IEEE Trans. on Automatic Control, vol. 39, N°2, pp. 343-345.
8. Watanabe, K., Ito, M., 1981, *A process-model control for linear systems with delay*, IEEE Trans. on Automatic Control, vol. 26, N°6, pp. 1261-1269.
9. Tsytkin, Ya.Z., Holmberg, U., 1995, *Robust stochastic control using the internal model principle and internal model control*, Int. J. Control, vol. 61, N°4, P 809-822.
10. Huang, J.J., DeBra D.B., 2002, *Automatic Smith predictor tuning using optimal parameter mismatch*, IEEE Trans. On Control Systems Technology, vol. 10, N°3, P 447-459.
11. Ogata, K., 1995, *Discrete-time Control Systems*, Upper Saddle River, NJ: Prentice-Hall
12. Astrom, K.J., Wittenmark, B., 1997., *Computer Controlled Systems – Theory and Design*, third edition, Upper Saddle River, NJ: Prentice-Hall,

PROJEKTOVANJE ROBUSTNOG KONTROLERA ZA PROCESSE SA ČISTIM VREMENSKIM KAŠNJENJEM

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Široka klasa industrijskih procesa ima slično dinamičko ponašanje koje može biti opisano jednostavnim matematičkim modelima sa čistim vremenskim kašnjenjem. U ovom radu je predložena nova struktura za upravljanje takvim procesima. Predložena struktura je zasnovana na IMPACT strukturi, a može biti tumačena i kao modifikacija poznate strukture sa Smithovim prediktorom. Radi se o robustnoj strukturi koja omogućava potiskivanje proizvoljne klase nemejljivih poremećaja na upravljanu promenljivo, i ima mali broj podešljivih parametara sa jasnim fizičkim značenjem. U radu je princip apsorpcije izveden i implementiran za generalan slučaj kontinualnih SISO sistema sa kašnjenjem, što čini bitan doprinos ovoga rada.

Key words: *IMPACT struktura, Robustno upravljanje, Princip apsorpcije, Procesi sa čistim vremenskim kašnjenjem, Smithov prediktor*