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Design of the IMPACT Controlling Structure Applying Conventional Digital Control Laws

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Abstract: The design of a simplified IMPACT (Internal Model Principle and Control Together) structure comprising conventional digital control laws is presented. The design procedure is accomplished to enable the extraction of a known class of immeasurable external disturbances and easy setting of the controller parameters. In the proposed controlling structure, the set point transient response and speed of disturbance rejection can be adjusted independently. The efficiency and robustness of the proposed controlling structure are verified and tested by the simulation and experimental setup.

Keywords: IMPACT controlling structure, conventional digital control laws, disturbance extraction.

1 Introduction

The concept of internal models implies the inclusion of the nominal plant model and/or model of immeasurable external disturbance into the control portion of the system. In the IMC (Internal Model Control) approach, the internal plant model is used to achieve a high system performance [1]-[3]. In the IMP (Internal Model Principle) approach, the model of external disturbance is incorporated into the minor local loop of control system in order to suppress or to reject completely the influence of disturbance on the steady-state value of the system controlled variable [2, 4]. Since a real plant differs from its nominal model, in all the approaches IMC, IMP, and IMPACT, the system robustness with respect to the uncertainties

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and variations of plant parameters must be provided [1]. The IMPACT conrolling structure incorporates both the internal nominal plant model explicitly and internal model of disturbance implicitly. The structure has been developed by Ya.Z. Tsypkin [4] independently of the IMC and IMP. The IMPACT structure enables an easy achievement of the desired set-point transient response, rejection of the known class of disturbances, and high degree of robustness of the system with respect to interval changes of plant parameters [5]. Unlike the classical IMC, which is applicable only for stable plants, the IMPACT structure may be applied for all kinds of control plants including unstable plants and plants of nonminimal phase [6].

In many control applications, particularly in the control of slow varying industrial processes, the conventional P, PI, and PID control laws are applied [7]-[10]. In designing a single-loop control system applying the conventional control laws, the control plant is approximated by typical, relatively simple, nominal plant model developed in a low frequency range. This paper shows the design of IMPACT structure of the system having a PI controller in the main control loop and the internal models of the nominal plant and disturbance in the local minor loop. The structure enables 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.

2 Principle of Absorption

Suppose that kth sample of external disturbance $f(t)$ may be determined by finite number m_0 of previous samples. Then, the disturbance is regular and may be described by extrapolation equation [6]

$$f(kt) = D_f(z^{-1}) f((k-1)T) \tag{1}$$

where $D_f(z^{-1})$ is the prediction polynomial of order $m_0 - 1$. Relation (1) is called the equation of extrapolation or prediction and it may be rewritten as

$$(1 - z^{-1} D_f(z^{-1})) f(z^{-1}) = 0 \tag{2}$$

where $f(z^{-1})$ denotes the z-transform of disturbance. Relation (2) is called the compensation equation and the FIR filter having pulse transfer function $1 - z^{-1} D_f(z^{-1})$ is the absorption filter or the compensation polynomial.

Absorption filter $\Phi_f(z^{-1}) = 1 - z^{-1} D_f(z^{-1})$ is designed for a known class of disturbances and its impulse response becomes identically equal to zero after n sampling instants, where $n \geq m_0$. Hence, compensation Eq. (2) may be considered as the absorption condition of a given class of disturbances. The condition can be expressed as

$$\Phi_f(z^{-1})f(z^{-1}) = 0, \quad \text{for} \quad t = kT \geq (\deg \Phi_f)T. \tag{3}$$

Extrapolation polynomial $D_f(z^{-1})$ is determined by an apriori information about disturbance $f(t)$ [3, 6]; nevertheless, it is simply resolved as

$$\Phi(z^{-1}) = w_{den}(z^{-1}), \quad \text{from} \quad f(z^{-1}) = \frac{w_{num}(z^{-1})}{w_{den}(z^{-1})}. \tag{4}$$

In the case of stochastic disturbance $s(t)$, absorption filter (4) should suppress all possible effects of disturbance on the system output. Thus, for a low frequency disturbance $s(t)$, which can be generated by double integration of white noise, an appropriate choice of absorption filter is $\Phi_f(z^{-1}) = (1-z^{-1})^2$, which corresponds to absorption of linear (ramp) disturbance. Namely, in majority of practical applications an appropriate choice might be $D(z^{-1}) = 2 - z^{-1}$. According to (4), prediction polynomial $D(z^{-1}) = 2 - z^{-1}$ rejects ramp disturbances; but, it enables also the extraction of slow varying disturbances and it even suppresses the effects of low frequency stochastic disturbances.

3 IMPACT Controlling Structure

In the IMPACT controlling structure shown in Fig. 1, the controlling process is given by its pulse transfer function or by polynomials $P_u(z^{-1})$ and $Q(z^{-1})$, and the process dead-time is given by integer k. Within the control portion of the structure

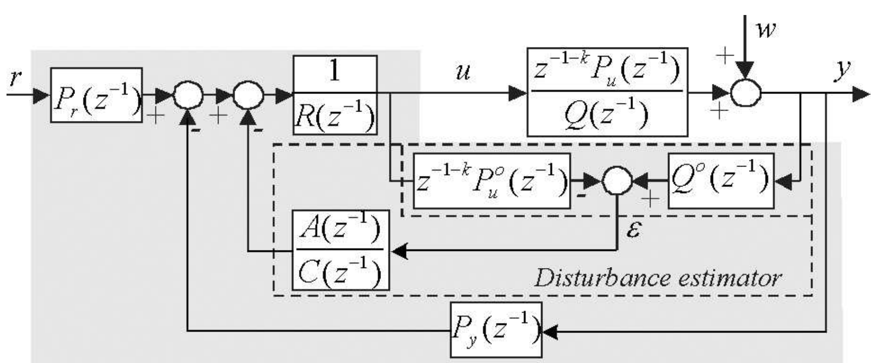


Fig. 1. Modified controlling structure with conventional digital controller.

of Fig. 1 (shaded part) two internal models are included: the two-input nominal plant model

$$W^0(z^{-1}) = \frac{z^{-1-k}P_u^0(z^{-1})}{Q^0(z^{-1})} \tag{5}$$

explicitly and model of immeasurable external disturbance embedded into discrete filter $A(z^{-1})/C(z^{-1})$. The internal nominal plant model and disturbance model is treated together as a disturbance estimator. The portion has two control loops which can be designed independently. The minor local control loop is designed by the proper choice of polynomials $A(z^{-1})$ and $C(z^{-1})$, while polynomials $P_r(z^{-1})$ and $P_y(z^{-1})$ in the main control loop are determined to achieve the desired system set point response. For a minimal phase plant, the proper choice of polynomial $R(z^{-1})$ is $R(z^{-1}) = P_u^0(z^{-1})$ [2, 3].

Under the nominal case $P_u(z^{-1}) = P_u^0(z^{-1})$, $Q(z^{-1}) = Q^0(z^{-1})$ and for $R(z^{-1}) = P_u^0(z^{-1})$, closed-loop transfer functions $y(z^{-1})/r(z^{-1})$ and $y(z^{-1})/w(z^{-1})$ are easily derived from Fig. 1 as

$$\frac{y(z^{-1})}{w(z^{-1})} = \frac{Q^0(z^{-1})[C(z^{-1}) - z^{-1-k}A(z^{-1})]}{C(z^{-1})[Q^0(z^{-1}) + z^{-1-k}P_y(z^{-1})]} \tag{6}$$

and

$$\frac{y(z^{-1})}{r(z^{-1})} = \frac{z^{-1-k}P_r(z^{-1})}{Q^0(z^{-1}) + z^{-1-k}P_y(z^{-1})}. \tag{7}$$

In virtue of Eq. (7), the system set-point response can be adjusted by determining appropriate polynomials $P_r(z^{-1})$ and $P_y(z^{-1})$ according to the desired system closed loop transfer function $y(z^{-1})/r(z^{-1}) = G_{de}(z^{-1})$. Then, the absorption of an external disturbance, speed of disturbance transient response, and system robustness with respect to uncertainties and interval variations of plant parameters are adjusted by choosing the structure and parameters of the disturbance estimator.

3.1 Rejection of disturbance

From Eq. (6), the steady-state error in the presence of a known class of external disturbances will become zero if

$$\lim_{z\to 1}(1 - z^{-1})\frac{Q^0(z^{-1})[C(z^{-1}) - z^{-1-k}A(z^{-1})]}{C(z^{-1})[Q^0(z^{-1}) + z^{-1-k}P_y(z^{-1})]}w(z^{-1}) = 0 \tag{8}$$

In the case of a stable polynomial $C(z^{-1})$ and a plant of nonminimal phase

$$\lim_{z\to 1}\frac{Q^0(z^{-1})}{C(z^{-1})[Q^0(z^{-1}) + z^{-1-k}P_y(z^{-1})]}w(z^{-1}) \neq 0 \tag{9}$$

Eq. (8) is reduced to

$$\lim_{z\to 1}(1-z^{-1})[C(z^{-1})-z^{-1-k}A(z^{-1})]w(z^{-1})=0. \tag{10}$$

As shown later, a stable polynomial $C(z^{-1})$ is to be chosen according to the desired speed of disturbance rejection and degree of system robustness and then polynomial $A(z^{-1})$ is determined to satisfy Eq. (10).

According to the principle of absorption, it is possible to design the observer estimator that rejects any kind of expected disturbances. To this end, suppose the class of disturbances having z-transform $w(z^{-1})=N(z^{-1})/D(z^{-1})$. Then, Eq. (10) is satisfied if the following Diophantine equation holds

$$z^{-1-k}A(z^{-1})+B_1(z^{-1})\Phi(z^{-1})=C(z^{-1}) \tag{11}$$

where $\Phi(z^{-1})$ represents the absorbtion polynomial determined by $\Phi(z^{-1})=D(z^{-1})$. For example, to the polynomial and sinusoidal disturbances ($w(t)=\sum_{i=1}^{m}d_i t^{i-1}$ and $w(t)=\sin\omega t$) correspond respectively $\Phi(z^{-1})=(1-z^{-1})^{m+1}$ and $\Phi(z^{-1})=1-2z^{-1}\cos\omega T_s+z^{-2}$, where T_s is the sampling period.

A unique solution of the Diophantine equation, which plays a crucial role in the design procedure of the disturbance estimator, does not exist [11]. Eq. (11) is a linear equation of polynomials $A(z^{-1})$ and $B_1(z^{-1})$. Generally, the existence of the solution of the Diophantine equation is given in [7]. According to Åström, there exists always the solution of Eq. (11) for $A(z^{-1})$ and $B_1(z^{-1})$ if the greatest common factor of polynomials z^{-1-k} and $\Phi(z^{-1})$ divides polynomial $C(z^{-1})$; then, the equation has many solutions. The particular solution of Eq. (11) is constrained by the fact that the control law must be causal, i.e., $\deg A(z^{-1})\le\deg C(z^{-1})$. Hence, after choosing a stable polynomial $C(z^{-1})$ and degrees of polynomials $A(z^{-1})$ and $B_1(z^{-1})$, and inserting the absorption polynomial $\Phi(z^{-1})$ which corresponds to an expected external disturbance, polynomials $A(z^{-1})$ and $B-1(z^{-1})$ are calculated by equating coefficients of equal order from the left- and right-hand sides of Eq. (11).

Polynomial $A(z^{-1})$ obtained by solving (11) guarantees the absorption of the expected class of disturbances, while the choice of $C(z^{-1})$ affects the speed of disturbance rejection, system robustness, and sensitivity with respect to the measurement noise. Good filtering properties and system efficiency in disturbance rejection are mutually opposite requirements. Therefore, to reduce the noise contamination, the low-pass digital filter may be introduces to modify the internal model of disturbance into

$$\frac{A(z^{-1})}{C(z^{-1})}=\frac{A_f(z^{-1})A_1(z^{-1})}{C(z^{-1})} \tag{12}$$

where $A_f(z^{-1})/C(z^{-1})$ represents pulse transfer function of the low-pass filter and $A_1(z^{-1})$ is polynomial which satisfies (11) and thus includes the internal model of disturbance, implicitly. The lower bandwidth of the low-pass filter corresponds to higher degree of system robustness and vice versa [2, 3]. Moreover, complex disturbances require higher order of polynomial $A(z^{-1})$ which will further reduce system robustness with respect to mismatches of plant parameters.

3.2 Parameter setting

The main control loop of the system of Fig. 1 is designed to achieve a desired set-point response determined by the system closed-loop transfer function

$$G_{de}(z^{-1}) = \frac{z^{-1-k}H_{de}(z^{-1})}{K_{de}(z^{-1})} \tag{13}$$

According to (7), the desired closed-loop transfer function is achieved if the following identity holds

$$\frac{z^{-1-k}P_r(z^{-1})}{Q^0(z^{-1}) + z^{-1-k}P_y(z^{-1})} \equiv \frac{z^{-1-k}H_{de}(z^{-1})}{K_{de}(z^{-1})} \tag{14}$$

To satisfy (14), it is necessary to solve the Diophantine equation

$$Q^0(z^{-1}) + z^{-1-k}P_y(z^{-1}) = T(z^{-1})K_{de}(z^{-1}) \tag{15}$$

for polynomials $P_y(z^{-1})$ and $T(z^{-1})$ and then to determine polynomial $P_r(z^{-1})$ in the main control loop of the system of Fig. 1 as

$$P_r(z^{-1}) = T(z^{-1})H_{df}(z^{-1}) \tag{16}$$

where $T(z^{-1})$ in (15) is previously chosen as a stable polynomial. Recall that, for a minimal phase plant, $R(z^{-1}) = P_u^0(z^{-1})$.

Characteristic polynomial $K_{de}(z^{-1})$ is read from (13) or it may be determined by the desired closed-loop system pole spectrum. To improve the system robustness with respect to uncertainties of plant parameters, polynomial $K_{de}(z^{-1})$ may be extended by factors

$$\prod_{i=1}^{n}(1 - b_i z^{-1})^i, \quad 0 \le b_i \le 0.9. \tag{17}$$

At the beginning, the values of b_i and integer n are to be chosen as small as possible and then they can be increased gradually until the required criterion of robust stability is satisfied. At the same time, calculated polynomial $P_r(z^{-1})$ should be modified into

$$P_r(z^{-1}) = \frac{\prod_{i=1}^{n}(1-b_i^{-1})^i}{\prod_{i=1}^{n}(1-b_1)^i} \tag{18}$$

in order to save the achieved set-point response and to keep unchanged the steady-state value of system output.

4 IMPACT Structure with Conventional Controller and Internal Models

As it is shown in the previous section, the main control loop and disturbance estimator of the IMPACT structure may be designed independently. Hence, the control structure with conventional digital PI or PID controllers, often used in control of slow varying industrial processes, may be modified by including a local control loop with internal models in order to improve the robustness of system performance and to reject an expected class of immeasurable external disturbances. In doing so, the IMPACT structure of Fig. 1 is redrawn into the controlling structure with PI controller, shown in Fig. 2.

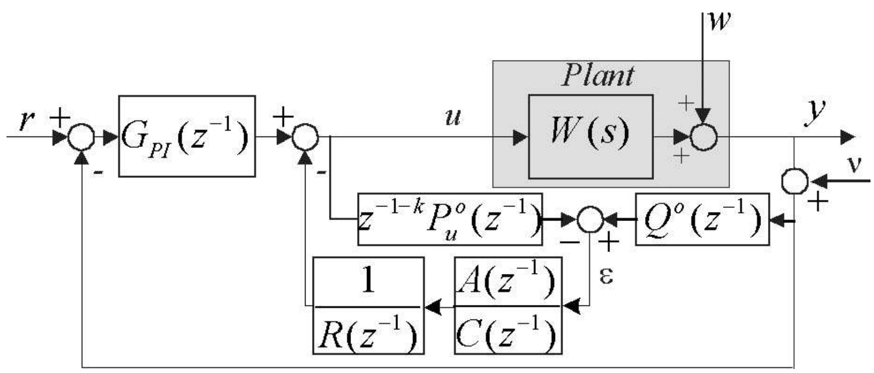


Fig. 2. Modified controlling structure with conventional digital controller.

The design procedure of the structure of Fig. 2 will be illustrated by the example of control system having the control plant described by

$$W(s) = \frac{e^{-10s}}{(1+s)(1+0.6s)(1+0.15s)(1+0.1s)}. \tag{19}$$

In the low frequency band, the nominal plant model is identified as [12, 13]

$$W^0(s) = \frac{e^{-10.5s}}{(1+1.5s)} \tag{20}$$

The zero-hold equivalence pulse transfer function of the nominal plant, with sampling time $T_s = 0.1875$ s, is calculated as

$$W^0(z^{-1}) = \frac{z^{-1-k}P_u^0(z^{-1})}{Q^0(z^{-1})} = \frac{0.1175z^{-57}}{1-0.8825z^{-1}} \tag{21}$$

The sampling time is chosen to be $T_s = \tau/56$ where τ is the process dead-time. Since the control plant is of minimal phase, $R(z^{-1}) = P_u^0(z^{-1}) = 0.1175$ is to be selected.

In the main control loop of the system of Fig. 2, the conventional digital PI controller

$$G_{PI}(z^{-1}) = K_P(1+\frac{T_s}{T_I}\frac{1}{1-z^{-1}}) \tag{22}$$

is used and its parameters are set by using Dahlin's algorithm to obtain [14]

$$\begin{aligned} K_P =& \frac{1-e^{-\lambda T_S}}{K(e^{\frac{T_S}{T_I}}-1)(1+k(1-e^{-\lambda T_S}))} \\ \frac{T_S}{T_I} =& e^{\frac{T_S}{T_I}}-1 \end{aligned} \tag{23}$$

With $K = 56$, $T_1 = 1.5$, $K = 1$, and Dahlin's tuning parameter $\lambda = 1/1.5$, one obtains $K_P = 0.1164$ and $T_S/T_I = 0.1331$.

The inner control loop of the system of Fig. 2 is designed by the nominal plant model (21), polynomial $R(z^{-1}) = P_u^0(z^{-1}) = 0.1175$, and digital filter (12). In (12), polynomial $A_1(z^{-1})$ represents the implicit model of disturbance obtained by solving Diophantine equation (11), and $A_f(z^{-1})/C(z^{-1})$ is the low-pass digital filter which should be selected to improve the system robustness and to reduce the system sensitivity with respect to the measurment noise.

The solution of Diophantine equation (11) with relatively large dead-time k is rather difficult. To simplify the solution, we propose an alternative approach. Namely, if we assume prediction polynomial $D(z^{-1}) = 2-z^{-1}$ or prediction filter $\Phi(z^{-1}) = (1-z^{-1})^2$ that corresponds to the extraction of ramp disturbances, then polynomial $A_1(z^{-1}) = A_1^{(k)}(z^{-1})$ in (12) may be split into

$$A_1^{(k)}(z^{-1}) = A_1^{(0)}(z^{-1}) + k(1-z^{-1}) \tag{24}$$

where $A_1^{(0)}(z^{-1})$ and $A_1^{(k)}(z^{-1})$ are the solutions of Diophantine equation for $k = 0$ and arbitrary k, respectively. Of course, the solution of equation

$$z^{-1}A_1^{(0)}(z^{-1}) + B_1(z^{-1})\Phi(z^{-1}) = C(z^{-1}) \tag{25}$$

depends upon the assumed absorption filter $\Phi(z^{-1})$ and low-pass filter or polynomial $C(z^{-1})$.

Thus, if we assume $\Phi(z^{-1})$ and Butterworth filter $A_f(z^{-1})/C(z^{-1})$ of third order, having the bandwidth of $f_o = 0.05/(2T_s) = 0.05/(2 \times 0.1875) = 0.1333$ Hz, the implicit internal model of disturbance (12) is derived as

$$\frac{A(z^{-1})}{C(z^{-1})} = \frac{0.0295 + 0.0593z^{-1} + 0.0012z^{-2} - 0.0577z^{-3} - 0.0290z^{-4}}{1 - 2.6862z^{-1} + 2.4197z^{-2} - 0.7302z^{-3}} \tag{26}$$

In all the simulation runs that follow, reference signal $r(t) = 1 \times (t - 10)$ is applied and the system is subjected by the slow varying disturbance contaminated by the measurement noise. With PI controller (22) and implicit model of disturbance (26), the system of Fig. 2 was simulated and the results of the simulation runs are shown in Fig. 3. Trace 1 of Fig. 3 shows that, dispite of the I-action in the main controller, the system does not reach the required steady-state value, due to the presence of disturbance. However, after introducing the local control loop, the system eliminates the disturbance in the steady-state (see trace 2 of Fig. 3). Notice that prediction polynomial $D(z^{-1}) = 2 - z^{-1}$ embededed into the implicit model of disturbance (26) has a derivative character and thus produces fluctuations around the steady-state value of the system output.

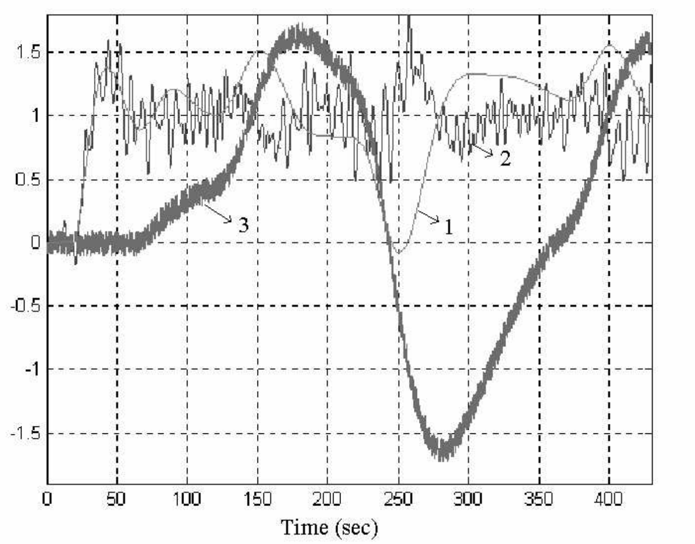


Fig. 3. 1 - Output of the system without the local loop. 2 Output of the system with the local loop designed with the internal model of ramp disturbance. 3 Disturbance.

In the second simulation, the same sampling time $T_s = 0.1875$ s is applied and the local control loop is designed with the same low-pass filter and absorption filter

$\Phi(z^{-1}) = 1 - z^{-1}$ or prediction polynomial that corresponds to a constant disturbance. In this case, the following implicit model of disturbance is derived

$$\frac{A(z^{-1})}{C(z^{-1})} = \frac{0.00042 + 0.00125z^{-1} + 0.00125z^{-2} + 0.00042z^{-3}}{1 - 2.6862z^{-1} + 2.4197z^{-2} - 0.7302z^{-3}} \tag{27}$$

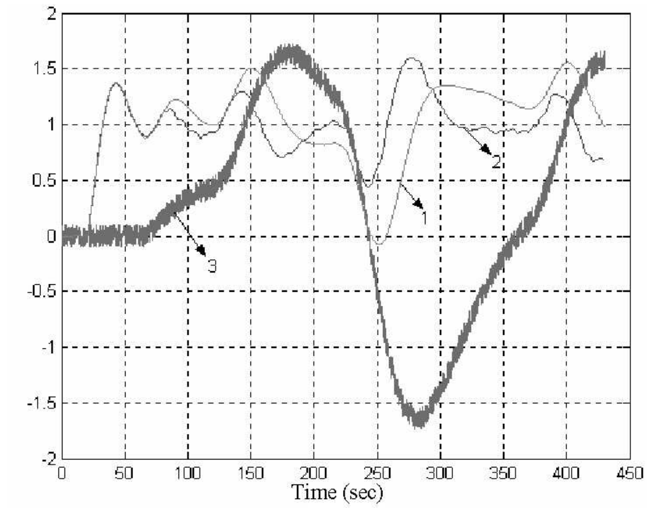


Fig. 4. Output of the system without the local loop. 2 Output of the system with the local loop designed with the internal model of constant disturbance. 3 Disturbance.

With (27), the system is unable to eliminate the disturbance completely (see trace 2 of Fig. 4). However, fluctuations of the system output are now notably suppressed (see traces 2 of Figs. 3 and 4).

Fig. 5 shows the simulation of the system in which the local loop is designed by the internal model of ramp disturbance and the low-pass filter of reduced bandwidth $f_o = 0.025/(2T_s) = 0.025/(2 \times 0.1875) = 0.0667$ Hz. Now, one obtains

$$\frac{A(z^{-1})}{C(z^{-1})} = \frac{0.0047 + 0.0049z^{-1} + 0.0002z^{-2} - 0.0092z^{-3} - 0.0046z^{-4}}{1 - 2.8430z^{-1} + 2.6980z^{-2} - 0.8546z^{-3}} \tag{28}$$

By comparing Figs. 3 and 5, one can notice that the fluctuations of the system output in Fig. 5 are radically reduced.

Finally, the local loop is designed by the low-pass filter having $f_o = 0.025/(2T_s) = 0.025/(2 \times 0.1875) = 0.0667$ Hz and prediction polynomial $D(z^{-1}) = 1$ corresponding to constant disturbances. In this case, one obtains

$$\frac{A(z^{-1})}{C(z^{-1})} = \frac{0.0000561 + 0.0001682z^{-1} + 0.0001682z^{-2} + 0.0000561z^{-3}}{1 - 2.8430z^{-1} + 2.6980z^{-2} - 0.8546z^{-3}} \tag{29}$$

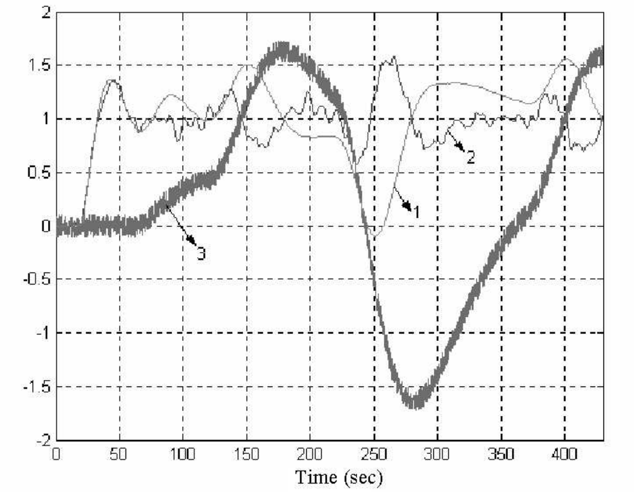


Fig. 5. Output of the system without the local loop. 2 Output of the system with the local loop designed with the internal model of ramp disturbance. 3 Disturbance.

The simulation results are shown in Fig. 6. Notice that now fluctuations of the system output disapear, but the disturbance is not completely rejected from the steady-state value of the system output.

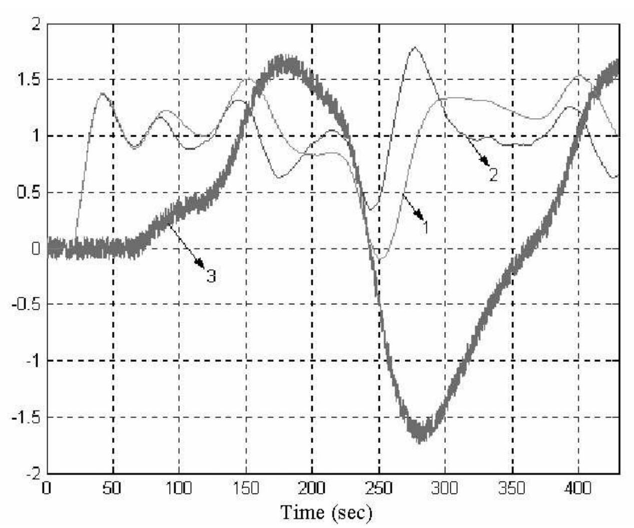


Fig. 6. Output of the system without the local loop. 2 Output of the system with the local loop designed with the internal model of ramp disturbance. 3 Disturbance.

5 Experimental Setup

The experimental setup is organized by laboratory Process Trainer Feedback PT-326. The trainer consists of the process and control equipment. It has the characteristics of a large plant, enabling transport lag, process time constant, system response, P and PI control laws etc. to be demonstrated. In the trainer, the air drawn from the atmosphere by a centifugal blower is driven past a heater grid and through a length of tubing to the atmosphere again. The process consists of heating the air flowing in the tube to a desired temperature level, and the purpose of the control equipment is to measure the air temperature, compare it with the set-value and generate a control signal which determines the amount of electrical power supplied to the correcting element, in this case a heater mounted adjacent to the blower. The experimental setup is shown in Fig. 7. The digital control law is implemented

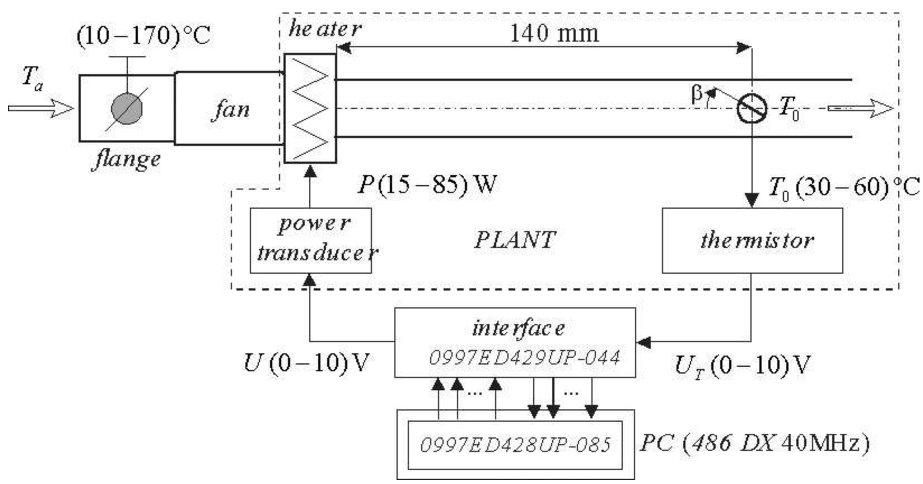


Fig. 7. Experimental setup.

on a personal computer. The sampling time of 0.11 is chosen and A/D and D/A coverters having resolution of 12 bits are used. The electric power of the range from 15 W to 85 W supplied to the wire grid heater having resistance of 120 Ω, is controlled by the thyristor rectifier having voltage output of 0-10 V. The air flow is changed by the segment cap with angular displacement $\alpha \in [10°, 170°]$. The temparatire sensor is thyristor mounted into a plastic cork and its sensitivity depends on angular position β between the cork and the direction of air flow.

The control plant is nonlinear and time-varying, and it belongs to the class of industrial processes that can be approximated, in the vicinity of working point, by the first-order nominal plant model

$$W_{ou}(s) = \frac{Ke^{-\tau s}}{1+Ts}. \tag{30}$$

The plant parameters are changeable and they vary with the nominal working conditions (amount of airflow, environment temperature, tube temperature, angular position β, desired temperature, temperature of grid heater etc.). For assumed transfer function (30) of the controlling process and working regime determined by $u_{nom} = 5V$, $\alpha = 50°$, $\beta = 30°$, the parameter identification is performed [13]. By averaging identification results from nine sets of measurement data, the following values of plant parameters are obtained: $K = 0.44$, $T = 0.72$, and $\tau = 0.22$.

These values are used for setting of P- and I-action in the PI digital controller according to Dahlin's algorithm [14]. Dahlin's tuning parameter $\lambda = 0.25$ is adopted. In the local control loop of the IMPACT structure, the third-order low-pass Butterworth filter having bandwidth of $f_o = 0.05fs/2 = 0.23$ Hz is employed. In the design of disturbance estimator, the internal models of constant and ramp disturbances are used. The experimental measurements are also given in the case when the local control loop is excluded. To enable the comparision of the results obtained from different conrol structures, the deterministic disturbance is set by the software. Namely, to the measured output, after A/D conversion, external disturbance $w(t)$ is added by the program. Actually, this disturbance corresponds to a real situation that might occur in the system when additional disturbances due to

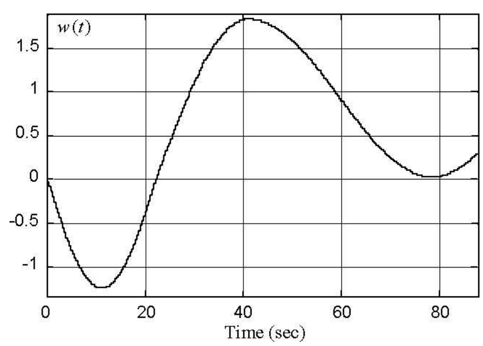
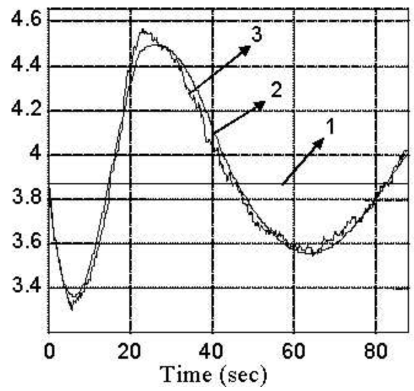
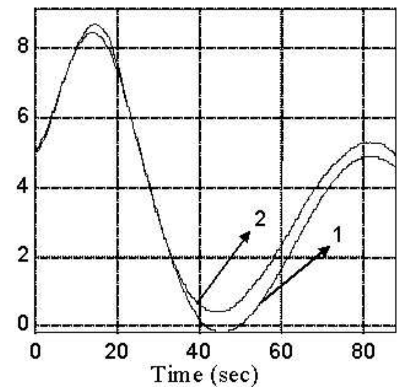


Fig. 8. Disturbance.

system nonlinearities are neglected. By inserting disturbance $w(t)$ one moves the process working point from the given set-point. In other words, it is equivalent to the change of air temperature for amount of $w(t)$ that could occur due to variations of air and/or tube temperatures. In doing so, the comparision of experimental measurements and simulation results are possible. The simulation runs are performed in the vicinity of the nominal workig regime, when interval changes of the plant parameters and measurement noise do not exist, and when the system linearity is implied. For the sake of evidency, the experimental measurements and simulation results are given together in Figs. 9 and 10.



(a)



(b)

Fig. 9. System behaviour in the presence of disturbance w(t), with diconnected inner control loop. (a) 1 - Reference. 2 - System output (simulated). 3 - System output (real). (b) 1 - Control variable (V) (real). 2 Control variable (simulated).

Fig. 9 illustrates the system behaviour in the presence of disturbance w(t), when the local control loop is disconnected. Fig. 9 (A) shows the system constant reference and system output (simulated and real). In Fig. 9 (B) the simulated and real control variables are shown. Fig. 9 visualizes the agreement of the traces obtained by simulation runs and by measurements on the experimental setup. However, due to the presence of disturbance, the system output greatly fluctuates around its reference value.

The traces of Fig. 10 illustrate the system behaviour in the presence of $w(t)$ and when the local control loop is connected. Figs. 10 (A) and (B) correspond to the case when the local control loop is designed by the digital filter and internal model of constant disturbance. The traces of Figs. 10 (C) and (D) are obtained when the local control loop is designed by digital filter and internal model of ramp disturbance. From Fig. 10 (A) it is seen that the use of internal model of constant disturbance radically reduces effects of disturbance on the system output. However, when the local control loop is designed by the internal model of ramp disturbance, the disturbance is completely rejected from the steady-state value of system output (see Fig. 10 (B)). The fluctuations of the system output around its steady-state value, in Fig. 10 (C), arise due to the measurement noise that could be further filtered by a digital filter of a lower bandwith.

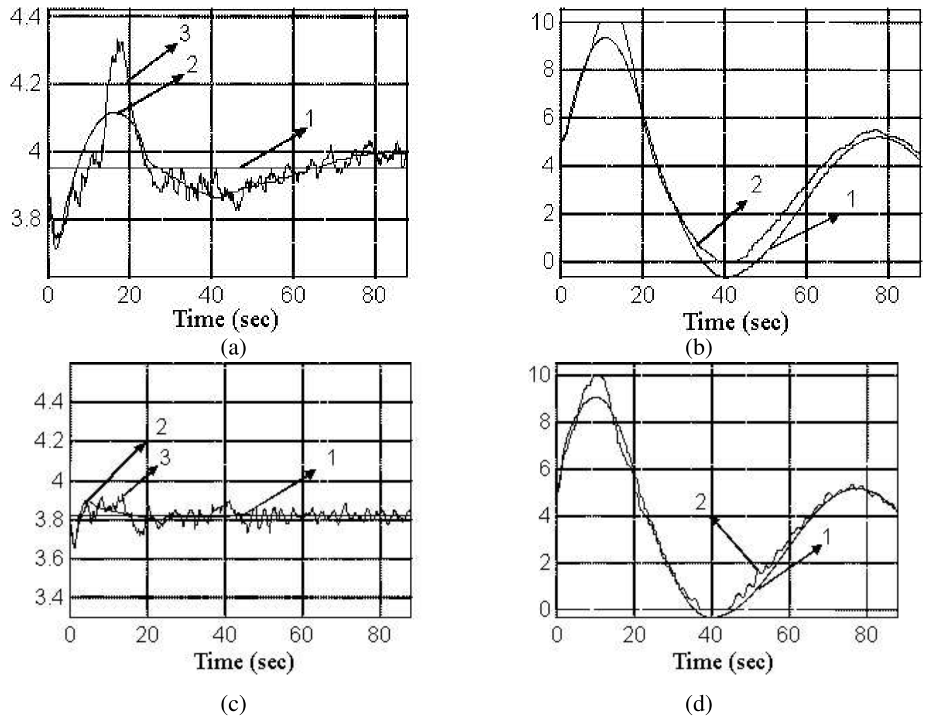


Fig. 10. (a) and (b) System behaviour in the presence of disturbance w(t), with inner control loop designed by the internal model of constant disturbance. (a) 1 - Reference. 2 - System output (simulated). 3 - System output (real). (b) 1 - Control variable (V) (real). 2 Control variable (simulated). (c) and (d) System behaviour in the presence of disturbance $w(t)$, with inner control loop designed by the internal model of ramp disturbance. (c) 1 - Reference. 2 - System output (simulated). 3 - System output (real). (d) 1 - Control variable (V) (real). 2 Control variable (simulated).

6 Conclusions

The IMPACT controlling structure has been described and its structural and parameter synthesis are given in detail. The structure design requires the solution of two Diophantine equations and it might produce difficulties particularly when the structure is to be implemented in industrial applications. Therefore the structural modification is developed in order to simplify the parameter synthesis and to adjust the structure to common industrial applications.

The modified IMPACT structure is rather simplified and has the form of a conventional control loop comprising PI or PID control laws and added a local minor loop which consists of the internal nominal plant model and internal model of the expected class of immeasurable external disturbances embedded into the disturbance estimator. It is shown that the main control loop with various conventional controllers and the local control loop may be designed independently. The overall control algorithm has a relatively small number of control parameters having clear physical meanings.

The disturbance estimator comprises the internal plant model, internal model of disturbance implicitly, and low-pass digital filter of selected bandwidth fo. The lower bandwidth f_o enables lower system sensitivity to measurement noise, higher degree of system robustness to uncertainties and interval change of plant parameters, smooth variations of controlled variable, but it reduces the efficiency of disturbance extraction.

The experimental results show that the disturbance estimator designed by the model of constant or slow varying disturbance slows down the speed of disturbance extraction, increases the system robustness and reduces the system sensitivity to the measurement noise. To improve the system efficiency in disturbance extraction, more complex internal models of disturbances (ramp and parabolic, for example) may be embedded into the disturbance estimator. In this case, an adequate low pass filter should be included within the local control loop of the system. The results of simulation runs and experimental measurements verified the theory and efficiency of the proposed controlling structure.

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