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A new design method of an Internal Multi-Model controller for a linear process with a variable time delay

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***Abstract*—This document introduces a new Internal Multi-Model controller design method for a linear system with a limited variable time delay. This design method is based on the use of a models collection to approximate the system functioning using Padé approximations; these models are inversed and multiplied by low pass filters in order to obtain a set of controllers that calculate the command value through a fusion procedure. These controllers are obtained by the multiplication of a low pass filters and Models inverses, in order to impose poles and zeros for the considered system and to control the command robustness through the filters parameters, which shall confirm a compromise between stability and rapidity. In this paper the Multi-Model Command controller design method will be described through six sections; first section introduces the realized research on this paper, the second section describes Internal Model Control concepts, third section describes effects of presence of a time delay on systems dynamics, the fourth section shows briefly Multi-Model concepts, the fifth section presents the new Internal Multi-Model controller design Method and finally section six deals with the obtained results of the new controller design method application for a system with a limited variable time delay and the filters parameters variations effects.**

***Index Terms*— Internal Model Control, Multi-Model approach, Internal Mutli-Model Control, System with a limited variable time delay, Padé approximation, Control of systems with time delay.**

I. INTRODUCTION

Systems including time delay are widely present in industry; systems dynamics imposes a lot of constraints that make the control of such systems difficult. [5]

For this reason control of systems including time delay became one of the most attractive research domains; [10] where many command structure were developed to surpass these constraints in order to obtain an acceptable process behavior, such as Internal Model Control which will be combined with a Multi-Model approach to control a SISO process with a limited variable time delay.

This research object is to introduce a new controller design method based on Internal Model control adopted with Multi-Model concepts in order to surpass constraints imposed by the non linear variation of the time delay and to obtain a robust process behavior.

II. INTERNAL MODEL CONTROL DESCRIPTION

Many command structures were developed using the feedback concept; which uses mathematical approaches to solve problems related to processes command, these approaches was implemented by the apparition of the first calculator.[4] Internal Model Control, noted as IMC, uses feedback concept and uses the robust command characteristics, to ensure an acceptable degree of performance even on the presence of parameters uncertainties and/or modelisations errors [1]. The basic structure of an IMC command is composed by the process compared to its model, and a controller as it shown on figure 1.[7]

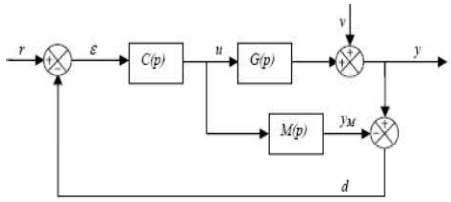


Figure 1. Basic IMC structure

Where *C(p)* is the IMC controller, *G(p)* the process and *M(p)* the process model which is an approximation of the plant *G(p).* This command structure applies the command signal *u* for both of the process *G(p)* and its model *M(p), d* is a disturbance signal which attacks the output directly and *r* is the reference signal, the output signal of the plant is compared to the set point signal in order to minimize the error between the reference and the output.

Internal model Control is one of the most popular command structure used for its simplicity and its robustness; this command structure can give a perfect reference tracking in the case of the use of a controller similar to the model inverse. [7]

Achieving the inverse of the model is the main problem associated to this command structure, because of the denominator order generally greater than the numerator on the model expression or the presence of time delay or/and instable zeros. [2]

III. CONSTRAINTS IMPOSED BY TIME DELAY

Systems with delays are found in many industrial processes and time delay presence is due to many factors such as transfer of information, energy or chemical reactions. [5,10] Then delays presence make systems analysis and controller design more complex, [10] due to the time delay effects on the systems behaviors which imposes many constraints on systems command. Delays constraints may cause instability and deterioration on the system performances especially on closed loop.

Time delay can cause a lag on the system phase especially for its high values [5] and for high frequency, which can be the reason of deterioration or instability on the closed loop. Time delay presence make also the effect of the disturbances not felt until a considerable time has elapsed, the effects of the control action takes some time to be felt in the controlled variable and the control action that is applied based on the actual error tries to correct a situation that originated some time before.[5]

Using the IMC structure, the associated controller can be used as the inverse of the process model; however in the case of presence of a time delay it gives a prediction system, when the inverse is calculated, making the realization of this type of systems difficult. For this purpose a Padé approximation is used to surpass these constraints, of inversion and realization, and giving a rational representation for the process make possible the inversion of the process model. But this approximation gives an alternative to modelisations errors which can deteriorate system performances and drive its behavior to the instability, to face these constraints we use on our command structure; were we use two Padé order approximation; a first order, and a second order approximation to decrease the effects of modelisations errors by elevating the approximation order to have models that can behave as the original process for high frequency. The obtained models using Padé approximation will be used to calculate the Internal Multi-Model Command controller, and section V objective is to give a command approach that can solve the realization problem of the IMC controller.

IV. MULTI-MODEL COMMAND CONCEPTS

This section describes briefly concepts of a Multi-Model controller. Multi-Model concepts are used on modelisation for the non linear systems and the uncertain systems; the main purpose of using Multi-Model approach is to obtain the best representation for the system dynamics by calculating validity coefficients and then realizing commutation or fusion between these models.

These concepts were generalized for the design of a controller, that uses different commands at the same time and selects the best one for the process using many parameters and or algorithms in order to obtain an optimal behavior for the considered process. [3] Multi-Model approach is based on a collection of models that represents system dynamics on several operating point for non linear system, then calculates models validities and realizes the fusion of these collected data using specified methods. [3]

Then a Multi-Model controller uses these concepts in order to obtain a robust command that ensures optimal performances for the considered process.

In fact Multi-Model controller uses a collection of models and their validities to calculate the best command for the process by using an algorithm for the fusion between these data.

For this purpose many fusion method were developed to satisfy the Multi-Model controller requirements [3] were the designer uses different algorithms to obtain the best command that allows a robust behavior for the process.

In this document we will use a Multi-Model controller combined with Internal Model Control concepts which will be generalized as Internal Multi-Model Controller that uses commutation between controllers as a fusion method for the command of a linear system with a variable limited time delay which will be described on the next section.

V. INTERNAL MULTI-MODEL CONTROLLER DESIGN PROCEDURE

This section describes the design method of the new Internal Multi-Model Controller which is based on the use of different low pass filters associated to each model of the considered process.

In fact the new Internal Multi-Model controller design method is a combination between, the Internal Model Controller design method described on [8,9] and Multi-Model approach; this new command structure can be described by this figure:

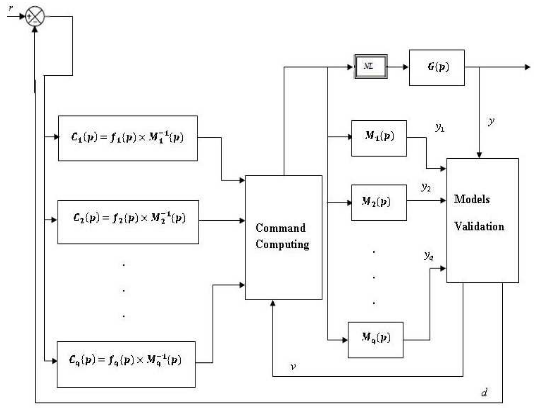


Figure 2. Internal Multi-Model Control structure

This command structure applies the same command for the process (a linear process with a variable time delay considered as non linearity) and its models $M_1(p)...M_q(p)$, then calculates validity coefficient *v* which will be used to compute the command value; that will be selected from one of the associated controllers $C_1(p)...C_q(p)$ that receives the difference between the reference and the outputs of the used models in order to minimize the errors. In fact the used command is based on the commutation between models using a validity coefficient which indicate about the controller to use; this validity coefficient is calculated by realizing the differences between the process output y and its models output $y_1 ... y_q$ then the model which has the minimum difference will be used for the command by using its index as a validity coefficient, then this validity coefficient will be used to select the appropriate controller.

Each one of these controllers $C_i(p)$ is achieved by multiplication of a low pass filter $f_i(p)$ and the inverse of the model $M_i(p)$ and can be written as:

$$C_i(p) = f_i(p) \times M_i^{-1}(p) \quad (1)$$

(i=1…q), where $f_i(p)$ is associated to the model inverse $M_i(p)$ and each filter $f_i(p)$ contains instable zeros that can appear on the process model expression $M_i(p)$.

Then for each Controller $C_i(p)$ the used filter $f_i(p)$ can be written on this form [6]:

$$f_i(p) = \frac{\sum_{j=0}^{m} \beta_j p^j}{(1+\alpha p)^n} \quad (2)$$

Where:

$\sum_{j=0}^{m} \beta_j p^j$ represents the instable zeros that can appear on the process model $M_i(p)$.

n: is a natural integer chosen to make the controller $C_i(p)$ proper.

α :is a float used to adjust the performance of the controlled process.

And each controller $C_i(p)$ can be computed using this method:

$$M_i(p) = \frac{N_{ZS}(p) \times N_{ZI}(p)}{D(p)} \quad (3)$$

$$M_i^{-1}(p) = \frac{D(p)}{N_{ZS} \times N_{ZI}(p)} \quad (4)$$

$$f_i(p) = \frac{N_{ZI}(p)}{(1+\alpha p)^n} \quad (5)$$

$$C_i(p) = f_i(p) \times M_i^{-1}(p) = \frac{D(p)}{N_{ZS}(p) \times (1+\alpha p)^n} \quad (6)$$

Where:

$N_{ZS}(p)$: is the stable zeros on the numerator of the process model $M_i(p)$.

$N_{ZI}(p)$: is the instable zeros that can be present on the process model $M_i(p)$.

D(p): represent the denominator of the process model $M_i(p)$.

n: is a natural integer chosen to make the controller proper $C_i(p)$

α: is a float used to adjust the system performances.

In this command structure, the aim of using a Multi-Model approach is to surpass constraints due to the variation of the time delay, besides the combination between Multi-Model concepts and Internal Model Control is to ensure the robustness of the command in spite of disturbance presence and modelisation errors. In fact this command structure allow us to impose the poles and zeros of the process through the filters parameters, such as the filters orders, the filters poles or the filters zeros, these characteristics allow the designer to control the robustness level of the command by choosing parameters that ensures the best compromise between robustness and rapidity.

Then for each filter the choice of its pole must confirm an acceptable compromise between stability and rapidity, the filter pole can be chosen using these recommendations:

if α=0 the system response will be H_2– optimal [6]

if α is chosen greater than the poles of the controlled system the filter dynamics will dominates the closed loop response of the system [6]

and if α is chosen inferior to the poles of the system the filter effect will not dominates the closed loop response of the system.[6]

Then the filter parameter α allow us to control the speed of the closed loop response then the adjusting of α is the same as adjusting the speed of the closed loop response. [6]

VI. Obtained results for a variable time delay first order system using different Padé approximation

This section shows the obtained results of the simulations of a linear process with a non linear variation time delay functioning; using the new command structure, the considered process is characterized by this expression: $G(p) = \frac{e^{-\tau(t)p}}{1+5p}$ where $\tau(t)$ is a limited variable time delay ($\tau(t) \leq 4{,}2s$) its variation is described by figure 3.

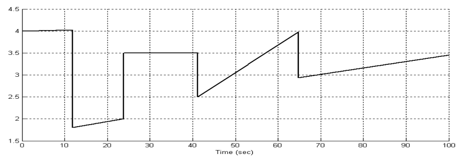


Figure .3 Time delay variation

This time delay will be estimated using four models each one of them will be calculated for $\tau = 1s$, $\tau = 2s$, $\tau = 3s$ and $\tau = 4s$, then the considered process will be estimated to four systems with a fixed time delay expressed by: $G_1(p) = \frac{e^{-p}}{1+5p}$, $G_2(p) = \frac{e^{-2p}}{1+5p}$, $G_3(p) = \frac{e^{-3p}}{1+5p}$, $G_4(p) = \frac{e^{-4p}}{1+5p}$ then for each one of these transfer functions a first order and a second order Padé approximations will be used to obtain models expression. This section contains two subsections, the first one shows the obtained results of using a first order Padé approximation to calculate system models and the second one shows the obtained results of using a second order Padé approximation to calculate system models.

A. *Obtained results using a first order Padé approximation*

The considered process is estimated to four systems with a fixed time delay, then a first order Padé approximation will be used to calculate system models described by:

$M_1(p) = \frac{1-\frac{p}{2}}{1+5.5p+2.5p^2}$ for $\tau = 1s$, $M_2(p) = \frac{1-p}{1+6p+5p^2}$ for $\tau = 2s$, $M_3(p) = \frac{1-\frac{3}{2}p}{1+6.5p+7.5p^2}$ for $\tau = 3s$, $M_4(p) = \frac{1-2p}{1+7p+10p^2}$ for $\tau = 4s$.

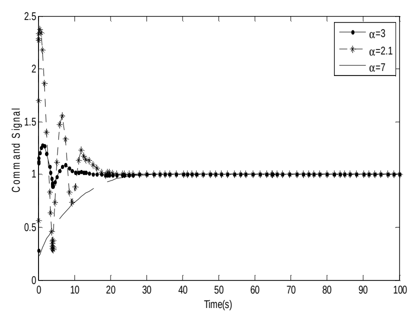
Then a filter $f_i(p)$ will be associated to each model $M_i(p)$; that contains instable zeros of each models that will be eliminated from the controller $C_i(p)$ expression which will be calculated as it was described on the previous section by multiplying the model $M_i(p)$ inverse and low pass filter $f_i(p)$.

Then the used filters and the calculated controllers are expressed on the table below:

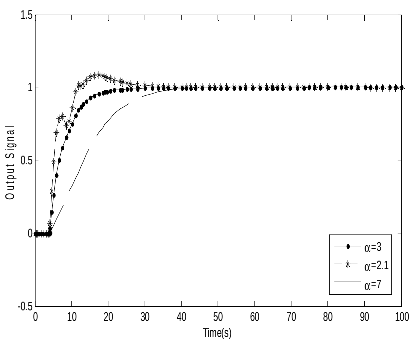
TABLE I. LIST OF FILTERS AND CONTROLLERS FOR EACH PROCESS MODEL

$M_i(p)$	$f_i(p)$	$C_i(p) = f_i(p) \times M_i^{-1}(p)$
$M_1(p)$	$f_1(p) = \frac{1-\frac{p}{2}}{(1+\alpha p)^2}$	$C_1(p) = \frac{1+5.5p+2.5p^2}{(1+\alpha p)^2}$
$M_2(p)$	$f_2(p) = \frac{1-p}{(1+\alpha p)^2}$	$C_2(p) = \frac{1+6p+5p^2}{(1+\alpha p)^2}$
$M_3(p)$	$f_3(p) = \frac{1-\frac{3}{2}p}{(1+\alpha p)^2}$	$C_3(p) = \frac{1+6.5p+7.5p^2}{(1+\alpha p)^2}$
$M_4(p)$	$f_4(p) = \frac{1-2p}{(1+\alpha p)^2}$	$C_4(p) = \frac{1+7p+10p^2}{(1+\alpha p)^2}$

The simulations results will be shown on figure 4 where the controllers are used for different value of the filters parameter α to show its variation effects on the process behavior.



Command signal



Output signal

Figure 4. System evolution for different values of α

It can be seen that the new Internal Multi-Model Control structure show a robust behavior characterized by a fast set-point tracking even on the presence of the variable time delay, which can be seen on the system step response and the command signal for α=3; where the filter effects dominates the system behavior and modelisations errors effects did not dominate the process behavior. However using small values of α could make the effects of modelisations errors dominates the system behavior; which is remarkable on the system response for α=2,1 were the process shows dumped oscillation on the transition phase before pursuing the reference after 30 seconds. In addition using high values of α could make the system response slow and not robust such is the case of α=7 were the process response pursue the reference after 40 second which is not acceptable.

B. Obtained results using a second order Padé approximation

As it was done on the previous section .The process is estimated to four systems with a fixed time delay then a second order Padé approximation will be used to compute system models $M_i(p)$; described by:

$$M_1(p) = \frac{1-\frac{p}{2}+\frac{p^2}{12}}{1+5.5p+\frac{31}{12}p^2+\frac{5}{12}p^3} \quad \tau = 1s,$$

$$M_2(p) = \frac{1-p+\frac{p^2}{3}}{1+6p+5.33p^2+\frac{5}{3}p^3} \text{ for } \tau = 2s,$$

$$M_3(p) = \frac{1-\frac{3}{2}p+\frac{3}{4}p^2}{1+6.5p+8.25p^2+\frac{15}{4}p^3} \text{ for } \tau = 3s \text{ and}$$

$$M_4(p) = \frac{1-2p+\frac{4}{3}p^2}{1+7p+\frac{44}{3}p^2+\frac{20}{3}p^3} \text{ for } \tau = 4s.$$

After this a filter $f_i(p)$ will be associated to each model $M_i(p)$; which contains instable zeros of these models that will be removed from the controller $C_i(p)$ expression; the used filters are described by:

$$f_1(p) = \frac{1-\frac{p}{2}+\frac{p^2}{12}}{(1+\alpha p)^3} \text{ for } M_1(p),$$

$$f_2(p) = \frac{1-p+\frac{p^2}{3}}{(1+\alpha p)^3} \text{ for } M_2(p),$$

$$f_3(p) = \frac{1-\frac{3}{2}p+\frac{3}{4}p^2}{(1+\alpha p)^3} \text{ for } M_3(p),$$

and $f_4(p) = \frac{1-2p+\frac{4}{3}p^2}{(1+\alpha p)^3}$ for $M_4(p)$. Then the controllers can be computed as it is described on section V, and are described by: $C_i(p) = f_i(p) \times M_i^{-1}(p)$ for i=1, 2, 3 and 4 where

$$C_1(p) = \frac{1+5.5p+\frac{31}{12}p^2+\frac{5}{12}p^3}{(1+\alpha p)^3},$$

$$C_2(p) = \frac{1+6p+5.33p^2+\frac{5}{3}p^3}{(1+\alpha p)^3},$$

$$C_3(p) = \frac{1+6.5p+8.25p^2+\frac{15}{4}p^3}{(1+\alpha p)^3},$$

and $C_4(p) = \frac{1+7p+\frac{44}{3}p^2+\frac{20}{3}p^3}{(1+\alpha p)^3}$.

The simulations results will be shown on figure 5 were the controllers are used for different value of the filters parameter α to show the effects of its variation on the process behavior.

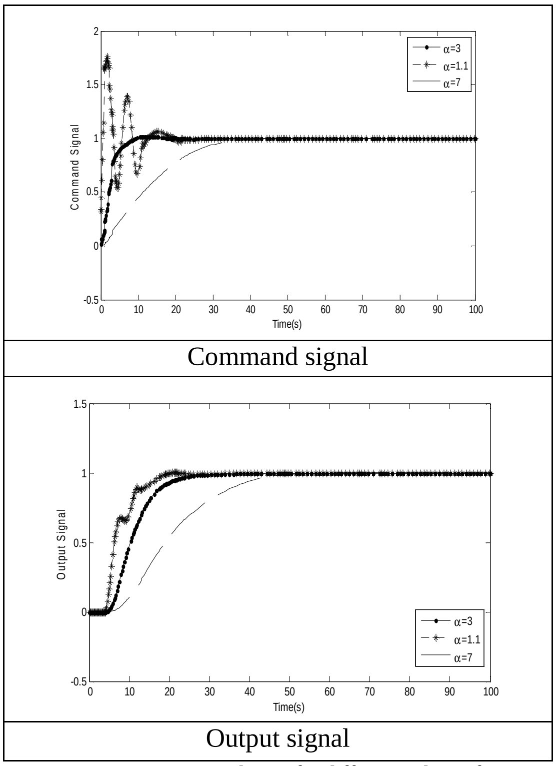


Figure 5. System evolution for different values of α

It can be noted that by using a second order Padé approximation, modelisations errors effect decrease which give us the opportunity to use values of α close to the models poles, but these values give dumped oscillation on the transitory phase such is the case of the process response characterized by the command signal and the output signal for α=1,1 were these dumped oscillation can deteriorate the process components and the filter effects had not dominate the system behavior. Then using a higher value of α could give an acceptable process behavior such is the case of using α=3 were the filter dynamics dominates the system behavior and the process shows a robust behavior even on the variation of the time delay; characterized by a fast set-point tracking which can be seen on the output signal and the command signal. However the use of much higher value of α could make the system response slow and not robust, this can be seen on the case of α=7 were the system response became slow and not robust.

VII. Conclusion

In this work a new command structure was developed for the control of linear system with a limited variable time delay. This command structure is based on the combination of Multi-Model concepts and Internal Model Control in order to obtain a robust system behavior. Unfortunately a collection of models, that was calculated using Padé approximations, are used to approximate the process expression and their inverses will be associated to a collection of low pass filters; in order to obtain a set of controllers, composed by the multiplication of low pass filters and models inverses.

This new Internal Multi-Model Command design method gives interesting results for a linear process with a limited variable time delay, shows a robust behavior; and allows the designer to control the robustness level of the command through the variation of the filters parameters in order to obtain an acceptable compromise between stability and rapidity which is the main advantage of this command structure.

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