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Multiple model adaptive control of complex systems

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***Abstract*— This paper addresses the multiple model adaptive control of a complex system with variable parameters discrete algebraic approach Kharitonov. This latter is based on the construction of a base model containing four extreme models with the possibility of adding a model moyen. Once the base is generated, a mechanism of adaptation through the type RST polynomial control was performed for each model of the base. The validities indices control the total order by fusion of all the basic controls.**

***Index Terms*— multiple models, geometric method, RST, RLS algorithm, adaptive control.**

I. INTRODUCTION

The multiple model approach is an effective method of solving problems related to the modeling, analysis and synthesis of complex systems. It consists of representing the system studied by a family of mathematical models simpler and easier to handle [1], [2]. The study proposed in this paper focuses on a class of continuous complex systems and uncertain bounded parameters. The overall model can be obtained either by using either the switching operation or merger. In this work, we are interested in the merger that uses the geometric [3], [4], [5]. The fusion is seen at both elementary commands at the level of outputs and driven by partial validity indices. The first section of this article deals with the generation of a model-based approach by algebraic Kharitonov.

The second section presents parametric identification techniques to achieve a regulation phase of the RST type adjustable to provide adaptive control. An example of a complex discrete second order system is considered in the last section to illustrate the implementation of the proposed approach.

II. ADAPTIVE CONTROL OF COMPLEX SYSTEMS

Often the parameters of the mathematical model of the studied system are not known as a priority and / or time varying, an adaptive approach should be considered to ensure that control objectives are achieved and maintained.

The adaptive control approach has two phases: parametric identification and adjustable phase control [11].

A. *Identification of a parametric closed loop system*

Parametric identification phase involves determining the dynamic characteristics of a system. The knowledge of the parameters of the dynamic model is necessary for the design and implementation of an effective system of regulations [12]. If the initial conditions of the system are known, the principle of identification is to extract a mathematical model for calculating the output of the process at any time. For this, we use the input values at present times $\left(u(k)\,,\, u(k-1),\,...\right)$ and past and previous values of the output, that is to say, $\left(y(k)\,,\, y(k-1),\,...\right)$ and, in the case of a regressive model.

For a good mathematical model consisting of the estimation, it is important to excite the process with all its frequency range. The input signal should be rich in frequencies, called Sequence Binary Pseudo-Random (SBPA). The excitation of the system by a SBPA provides a good estimation of the static gain.

The parametric identification of the system requires the following steps:

i) determining the number of measurement points which must be significant to the test,
ii) determining the structure of the model: order and delay,
iii) the choice of an appropriate algorithm for minimization of errors between the measurements and the estimated model,
iv) the validation of the model.

B. *Identification algorithm recursive least squares*

We consider the transfer function of the discrete model given by:

$$H\left(z^{-1}\right) = \frac{B\left(z^{-1}\right)}{A\left(z^{-1}\right)} = \frac{y_k}{u_k} \tag{1}$$

with:

$$B\left(z^{-1}\right) = b_0 + b_1 z^{-1} + ... + b_n z^{-n_B} \tag{2}$$

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$$A\left(z^{-1}\right) = a_0 + a_1 z^{-1} + ... + a_n z^{-n_A} \quad (3)$$

A and B are two polynomials prime to one another, n_A and n_B their respective degrees.

The equation for the output y, depending on the written measurement vectors ϕ_k and estimated parameters θ_k is given by [16]:

$$y_{k+1} = \theta_k^t \phi_k \quad (4)$$

with:

$$\phi_k^t = \left[-y_k, ..., -y_{k-n_A}, u_k, ..., u_{k-n_B}\right] \quad (5)$$

$$\theta_k^t = \left[a_0, a_1, ..., a_{n_A}, b_0, b_1, ..., b_{n_B}\right] \quad (6)$$

The prediction model is given by:

$$\hat{y}_{K+1} = \hat{\theta}_k^t \phi_k \quad (7)$$

The prediction error is given by:

$$\varepsilon_{k+1} = y_{k+1} - \hat{y}_{k+1} \quad (8)$$

The parameter estimate is based on minimizing a quadratic criterion:

$$J_{k+1} = \left[\varepsilon_{k+1}\right]^2 \quad (9)$$

To obtain a recursive algorithm, the estimate $\hat{\theta}_{k+1}$ is considered as follows:

$$\hat{\theta}_{k+1} = F_{k+1} \sum_{i=1}^{k+1} y(i)\phi(i-1) \quad (10)$$

with:

$$F_{k+1} = F_k - \frac{F_k \phi_k \phi_k^t F_k}{1 + \phi_k^t F_k \phi_k} \quad (11)$$

This algorithm is used to determine the process parameters, based on the following equations [17]:

$$\begin{cases} \hat{\theta}_{k+1} = \hat{\theta}_k + F_{k+1} \phi_k \varepsilon_{k+1} \\ F_{k+1} = F_k - \dfrac{F_k \phi_k \phi_k^t F_k}{1 + \phi_k^t F_k \phi_k} \\ \varepsilon_{k+1} = y_{k+1} - \hat{\theta}_k \phi_k \end{cases} \quad (12)$$

With $\hat{\theta}_k$ the vector of estimated parameters, F_k the adaptation matrix and ε_k the prediction error vector and the measures.

C. Adjustable RST structure controller

RST digital controller allows to impose the poles of the closed loop system [13]. Its structure is shown in the following figure:

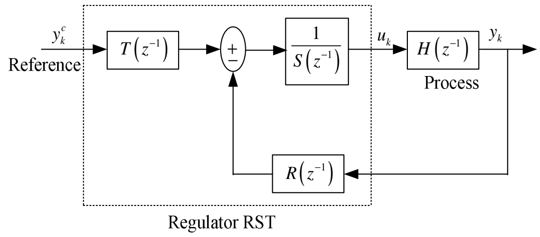

Fig. 1. RST structure controller

The polynomials $R\left(z^{-1}\right)$, $S\left(z^{-1}\right)$ and $T\left(z^{-1}\right)$ are given by:

$$R\left(z^{-1}\right) = r_0 + r_1 z^{-1} + ... + r_{n_R} z^{-n_R} \quad (13.a)$$

$$S\left(z^{-1}\right) = s_0 + s_1 z^{-1} + ... + s_{n_S} z^{-n_S} \quad (13.b)$$

$$T\left(z^{-1}\right) = t_0 + t_1 z^{-1} + ... + t_{n_T} z^{-n_T} \quad (13.c)$$

where $n_R = \deg(R)$, $n_S = \deg(S)$ and $n_T = \deg(T)$ for solving problems relating to regulation and prosecution.

The transfer function of the closed loop system is then given by:

$$H_{BF}\left(z^{-1}\right) = \frac{T\left(z^{-1}\right)B\left(z^{-1}\right)}{A\left(z^{-1}\right)S\left(z^{-1}\right) + B\left(z^{-1}\right)R\left(z^{-1}\right)} \quad (14)$$

The question is what are the techniques presented in the literature for the calculation of polynomials R and S.
A first technique, the most common technique is called pole placement control.

D. Calculation of polynomials R and S

The choice of denominator $P\left(z^{-1}\right)$ of the transfer function of the closed loop system imposes R and S satisfies the equation Diophantine follows:

$$A\left(z^{-1}\right) S\left(z^{-1}\right) + B\left(z^{-1}\right) R\left(z^{-1}\right) = P\left(z^{-1}\right) \quad (15)$$

Eq. (15) is called regular if $\deg(P) < \deg(A) + \deg(B)$.

In this polynomial equation, the polynomials A, B and P are known however R and S are to be determined.

To solve this equation, several cases can be considered.

1) If the Eq. (15) is regular then the minimal solutions S_0 and R_0 are the respective degrees:

$$\begin{cases} \deg(S_0) = \deg(B) - 1 \\ \deg(R_0) = \deg(A) - 1 \end{cases} \quad (16)$$

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2) If the Eq. (15) is not regular then it admits two minimal solutions:

2.1) A minimal solution S : $(S_0\ ,\ R_1)$ is defined by:

$$\begin{cases} \deg\ (S_0) = \deg(B) - 1 \\ \deg(R_1) = \deg(P) - \deg(B) \end{cases} \tag{17}$$

2.2) A minimal solution S : $(S_1\ ,\ R_0)$ is defined by:

$$\begin{cases} \deg(S_1) = \deg(P) - \deg(A) \\ \deg(R_0) = \deg(A) - 1 \end{cases} \tag{18}$$

In the case where the Eq. (15) is regular, it can be written in the following matrix form:

$$X = M^{-1}\, P \tag{19}$$

with:

$$M = \begin{pmatrix} a_0 & 0 & \cdots & 0 & b_0 & 0 & \cdots & 0 \\ a_1 & a_0 & \ddots & \vdots & b_1 & b_0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 & \vdots & \ddots & \ddots & 0 \\ a_{n_A} & \vdots & \ddots & a_0 & b_{n_B} & \vdots & \ddots & b_0 \\ 0 & \ddots & \vdots & a_1 & 0 & \ddots & \vdots & b_1 \\ \vdots & \ddots & \ddots & \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & a_{n_A} & 0 & \cdots & 0 & b_{n_B} \end{pmatrix},$$

$$X = \begin{pmatrix} s_0 \\ \vdots \\ s_{n_s} \\ r_0 \\ \vdots \\ \vdots \\ r_{n_r} \end{pmatrix} \text{ and } P = \begin{pmatrix} p_0 \\ p_1 \\ \vdots \\ p_{n_p} \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

with $M \in \mathbb{R}^{(n_A+n_B)} \times \mathbb{R}^{(n_A+n_B)}$ a Sylvestre matrix called, it is necessarily invertible because the polynomials A and B are coprime.

E. Calculation of the polynomial T

The polynomial $T(z^{-1})$ can be determined by the purpose of the command to calculate. The determination of its coefficients dependents on regulatory issues or prosecution [15].

In both cases, the general structure is shown in figure 2:

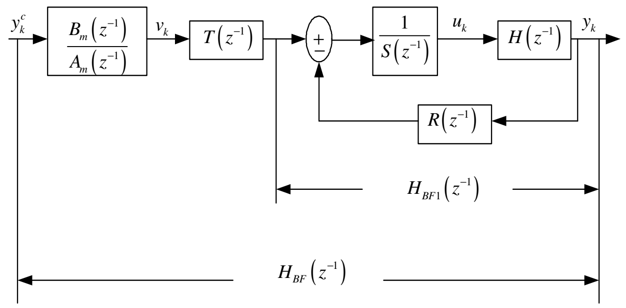

Fig. 2. Control structure of the RST type polynomial

i) Cases of regulation:

In this case, the reference y_k^c is assumed constant. $y_k = y_k^c$ for steady, one must have a unitary static gain closed loop, that is to say, $H_{BF}(1) = 1$, when it comes:

$$T(z^{-1}) = \frac{P(1)}{B(1)} \tag{20}$$

ii) Cases of trajectory tracking:

In this case, a desired path y_k^c, on the system, corresponds to a reference model of the form:

$$H_m(z^{-1}) = \frac{B_m(z^{-1})}{A_m(z^{-1})} \tag{21}$$

For a polynomial $T(z^{-1}) = \alpha\ P(z^{-1})$, we obtain:

$$H_{BF1}(z^{-1}) = \alpha\ B(z^{-1}) \tag{22}$$

from which:

$$H_{BF}(z^{-1}) = \alpha\ \frac{B(z^{-1})\,B_m(z^{-1})}{A_m(z^{-1})} \tag{23}$$

with: $\alpha = \dfrac{1}{B(1)}$, thus a static gain is imposed in a state unitary loop feedback.

The use of RST controller is very interesting in the case of the linear model. Indeed, it is possible in this case to consider the adaptive control in which the polynomials R, S and T are updated according to the identified model.

III. Multiple Models Adaptive of Complex Systems

A. Process modeling

To determine non-localized extreme models, it is applying the indirect method based on the algebraic approach of Kharitonov [6] who has no operating points or areas of validity predetermined.

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Consider the case of continuous-time process, whose evolution is described by a differential equation of the form [6]:

$$\alpha_0(.)\, y + \alpha_1(.)\, y^{(1)} + ... + \alpha_{n-1}(.)\, y^{(n-1)} + y^{(n)} = \beta_0(.)\, u + \beta_1(.)\, u^{(1)} + ... + \beta_{n-1}(.)\, u^{(n-1)} \quad (24)$$

The symbol $(.)$ represents the set of variables, uncertainties, noise or disturbances affecting the coefficients of the process.

Parameters α_i and β_i, $i = 0, 1, ..., n-1$ with: $\overline{\alpha}_i = \max_i(\alpha_i)$, $\underline{\alpha}_i = \min_i(\alpha_i)$, $\overline{\beta}_i = \max_i(\beta_i)$ and $\underline{\beta}_i = \min_i(\beta_i)$.

The method is to consider the four extreme models defined by the following transfer functions [7]:

$$H_1(s) = \frac{\underline{\beta}_0 + \underline{\beta}_1 s + \overline{\beta}_2 s^2 + \overline{\beta}_3 s^3 + ...}{\underline{\alpha}_0 + \underline{\alpha}_1 s + \overline{\alpha}_2 s^2 + \overline{\alpha}_3 s^3 + ...} \quad (24.a)$$

$$H_2(s) = \frac{\underline{\beta}_0 + \overline{\beta}_1 s + \overline{\beta}_2 s^2 + \underline{\beta}_3 s^3 + ...}{\underline{\alpha}_0 + \overline{\alpha}_1 s + \overline{\alpha}_2 s^2 + \underline{\alpha}_3 s^3 + ...} \quad (24.b)$$

$$H_3(s) = \frac{\overline{\beta}_0 + \overline{\beta}_1 s + \underline{\beta}_2 s^2 + \underline{\beta}_3 s^3 + ...}{\overline{\alpha}_0 + \overline{\alpha}_1 s + \underline{\alpha}_2 s^2 + \underline{\alpha}_3 s^3 + ...} \quad (24.c)$$

$$H_4(s) = \frac{\overline{\beta}_0 + \underline{\beta}_1 s + \underline{\beta}_2 s^2 + \overline{\beta}_3 s^3 + ...}{\overline{\alpha}_0 + \underline{\alpha}_1 s + \underline{\alpha}_2 s^2 + \overline{\alpha}_3 s^3 + ...} \quad (24.d)$$

In addition to these four extreme models, defined above $H_5(s)$, it is often useful to add the average model, denoted as a fifth model in the library [8]. The latter, whose parameters can be defined by the arithmetic mean of the model parameters extreme representative somehow their barycentre, can improve the performance of the multiple model control.

The transfer function of the fifth sample is given by:

$$H_5(s) = \frac{\beta_{5.0} + \beta_{5.1} s + \beta_{5.2} s^2 + \beta_{5.3} s^3 + ...}{\alpha_{5.0} + \alpha_{5.1} s + \alpha_{5.2} s^2 + \alpha_{5.3} s^3 + ...} \quad (25)$$

with $\alpha_{S,i} = \dfrac{\underline{\alpha}_i + \overline{\alpha}_i}{2}$ and $\beta_{S,i} = \dfrac{\underline{\beta}_i + \overline{\beta}_i}{2}$.

After discretisation with a sampling period of choice, we have chosen to apply the geometric method [9], [10], [4] which allows the calculation of the distance between the output vector $y_{S,k}$ of the system and r partial exits $y_{i,k}$ base model:

$d_{i,k} = \left\| y_{i,k} - y_{S,k} \right\|$ for $i = 1, 2, \ldots, r$.

The normalized distance d_i^{norm} are given by:

$$d_{i,k}^{norm} = \frac{d_{i,k}}{\sum_{j=1}^{r} d_{j,k}} \quad (26)$$

The Validity h_i are given by:

$$h_{i,k} = \frac{t_{i,k}}{\sum_{j=1}^{r} t_{j,k}} \quad (27)$$

Satisfying the conditions of convexity:

$$\begin{cases} 0 \le h_{i,k} \le 1 \\ \sum_{i=1}^{r} h_{i,k} = 1 \end{cases} \quad (28)$$

with:

$$t_{i,k} = \left(1 - d_{i,k}^{norm}\right) \prod_{j=1}^{r} \left[1 - \exp\left(- \left(\frac{d_{j,k}^{norm}}{\sigma} \right)^2 \right) \right] \quad (29)$$

σ is a variable parameter set between 0 and 0.99.

B. *Operation of basic fusion models*

The multiple model adaptive control of a complex system is based on RST regulators ensuring local stability models to apply basic operation of fusion.

The fusion of basic commands multiple model structure is adopted in the simulation. This structure corresponds to the calculation of the overall control u_k, as fusion basic coefficients of each controller RST based models through validities $h_{i,k}$, calculated at each instant as follows:

$$R_g\left(z^{-1}\right) = \sum_{i=1}^{r} h_{i,k}\, R_i\left(z^{-1}\right) \quad (30.a)$$

$$S_g\left(z^{-1}\right) = \sum_{i=1}^{r} h_{i,k}\, S_i\left(z^{-1}\right) \quad (30.b)$$

$$T_g\left(z^{-1}\right) = \sum_{i=1}^{r} h_{i,k}\, T_i\left(z^{-1}\right) \quad (30.c)$$

for $i = 1, 2, \ldots, r$.

C. *Adaptive control structure multiple model*

The reference model is given, in closed loop, the dynamic part of the modeled system. The identification of the basic models used to adjust the controller parameters by an adaptive mechanism in order to turn the tracking error between the reference model and the process to be controlled to zero [12].

The overall structure of a multi-model is presented by RST regulators and an elementary model is given by the following block diagram:

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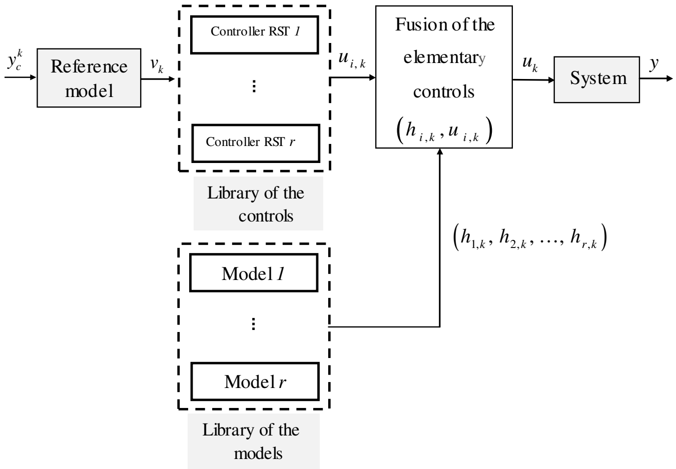

Fig. 3. Multiple model adaptive control structure

IV. APPLICATION OF AN ELECTRIC MOTOR

A DC motor is an electromechanical device that converts electrical energy into mechanical energy input. The electrical energy is supplied by a power converter which feeds the winding arranged on the rotor (armature) by means of brushes and collector adapted, permanent or not, due to the stator. The current flows through the spires of the motor armature, electric forces are applied thereto and, thanks to the device brushes / collector, these additional forces to participate in the rotation. The input of motor is the armature voltage and the output is the rotational speed of the rotor [18].

$U_{nom} = 24\ V$, $U_{\max} = 32\ V$, $I_{\max} = 2.2\ A$

$J = 10^{-4}\ k\,g\,m^2$, $L = 0.63\ mH$, $f = 2.5\ 10^{-6}\ N\,m\,s$

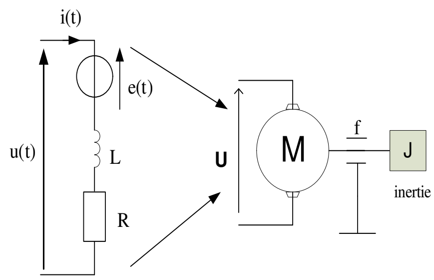

Fig. 4. Diagram of a DC motor

The transfer function of controlling the voltage and connecting the rotational speed of the motor is given by:

$$G(s) = \frac{\Omega(s)}{U(s)} = \frac{K_{em}}{R f + K_{em}^2 + (R J + L f) s + L J s^2} \quad (31)$$

We assume that, due to the heating, the resistance R is varied between $R_{\min}$ and $R_{\max}$, then K_{em} varies between $K_{e\min}$ and $K_{e\max}$.

The values chosen in the simulation are:

$R_{\min} = 0.8\,ohm$, $K_{e\min} = 30\ mNm.A^{-1}$

$R_{\max} = 1.9\,ohm$, $K_{e\max} = 60.3\ mNm.A^{-1}$

To describe our system by a library of models, we used the indirect method (generic modeling). This approach is based on algebraic Kharitonov.

For a sampling time $Te = 0.1 s$, the discrete linear models are given by:

$$H_1(z^{-1}) = \frac{b_{11} z^{-1} + b_{12} z^{-2}}{1 + a_{11} z^{-1} + a_{12} z^{-2}} \quad (32.a)$$

$$H_2(z^{-1}) = \frac{b_{21} z^{-1} + b_{22} z^{-2}}{1 + a_{21} z^{-1} + a_{22} z^{-2}} \quad (32.b)$$

$$H_3(z^{-1}) = \frac{b_{31} z^{-1} + b_{32} z^{-2}}{1 + a_{31} z^{-1} + a_{32} z^{-2}} \quad (32.c)$$

$$H_4(z^{-1}) = \frac{b_{41} z^{-1} + b_{42} z^{-2}}{1 + a_{41} z^{-1} + a_{42} z^{-2}} \quad (32.d)$$

The transfer function of the controlled system is as follows:

$$H_5(z^{-1}) = \frac{b_{5.1}\, z^{-1} + b_{5.2}\, z^{-2}}{1 + a_{5.1}\, z^{-1} + a_{5.2}\, z^{-2}} \quad (33)$$

with: $a_{5.1} = -1.1753$, $a_{5.2} = 0.8153$, $b_{5.1} = 0.0072$ and $b_{5.2} = 0.0054$.

A. Parametric identification of based models

The model parameters of the electric motor vary slightly in time. To make parameter identification online, a modified version of the algorithm for recursive least squares identification is used with the introduction of a forgetting factor matrix λ in $F_{i,\,k+1}$ adaptation gains. [12], [14]

$$\begin{cases} \hat{\theta}_{i,k} = \hat{\theta}_{i,k-1} + F_{i,k}\ \phi^t_{i,k-2}\ \ \phi_{i,k-1}\ \ \varepsilon_{i,k} \\ F_{i,k-1} = \dfrac{1}{\lambda}\left(\dfrac{F_{i,k-2}\ \ \phi_{i,k-1}\ \ \phi^t_{i,k-1}\ \ F_{i,k-2}}{\lambda + \phi^t_{i,k-1}\ \ F_{i,k-2}\ \ \phi_{i,k-1}} \right) \\ \varepsilon_{i,k} = y_{i,k} - \hat{\theta}_{i,k-1}\ \ \phi_{i,k} \\ i = 1, 2, 3, 4. \end{cases} \quad (34)$$

with ε_k the prediction error between the actual output measured and the output y_k of the i^{th} estimated model $\hat{y}_k$, $i = 1, 2, 3, 4$, such as:

$$\hat{y}_{i,k} = \hat{\theta}_{i,\,k-1}\ \ \phi_{i,k} \quad (35)$$

$$\hat{\theta}_{i,k} = \left[a_{e1i,k}, a_{e2i,k}, b_{e3i,k}, b_{e4i,k} \right]^t \quad (36)$$

$$\phi^t_{i,k} = \left[-y_{i,k}\,, -y_{i,k-1}\,, -y_{i,k-2}, u_{i,k}\,, u_{i,k-1}\,, u_{i,k-2} \right] \quad (37)$$

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The initial conditions of the recursive least squares algorithm are selected such that:

$\hat{\theta}_i(0) = [0 \quad 0 \quad 0 \quad 0]^t$, $i = 1, 2, 3, 4$ and $\lambda = 0.95$.

B. Multiple model adaptive control of the electric motor

To find the changes validities $h_{i,k}$, we added a positive coefficient ξ with a low value (around 10^{-3}) to avoid division by zero. The geometric distance $d_{i,k}$ is calculated by the following relationship:

$$d_{i,k} = \sqrt{\sum_{i=1}^{4} \left(\xi + \left(y_{i,k} - y_{S,k} \right) \right)^2} \qquad (38)$$

The developments validities of the four basic models are shown, respectively, in the following figure:

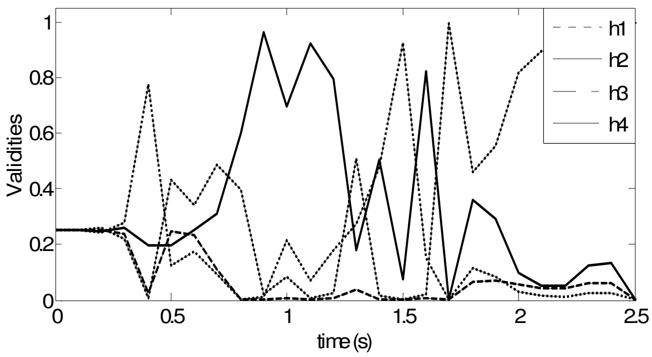

Fig. 5. Evolution of validities h_i

The transfer function of the reference model second order asymptotically stable was chosen by:

$$\frac{B_m(z^{-1})}{A_m(z^{-1})} = \frac{0.0376\ z^{-1} + 0.0314\ z^{-2}}{1 - 1.5137\ z^{-1} + 0.5827\ z^{-2}} \qquad (39)$$

The desired polynomial is given by:

$$P(z^{-1}) = 1 - 0.7999\, z^{-1} \qquad (40)$$

The system shall be controlled by a signal which is obtained by melting the basic coefficients of each controllers of the base model through validities $h_{i,k}$, calculated at each instant as follows:

$$R_g(z^{-1}) = \sum_{i=1}^{4} h_i(k)\ R_i(z^{-1}) \qquad (41.a)$$

$$S_g(z^{-1}) = \sum_{i=1}^{4} h_i(k)\ S_i(z^{-1}) \qquad (41.b)$$

$$T_g(z^{-1}) = \sum_{i=1}^{4} h_i(k)\ T_i(z^{-1}) \qquad (41.c)$$

The changes of the control signals of the four elemental models and the control signal u_s of the electric motor are shown in Fig. 6.

Fig. 7 shows the evolution of output signals of a reference model, basis models and the output y_S output of the DC motor.

A white noise disturbance type is added to the outputs of sub models. The noisy output signals are shown in Fig. 8.

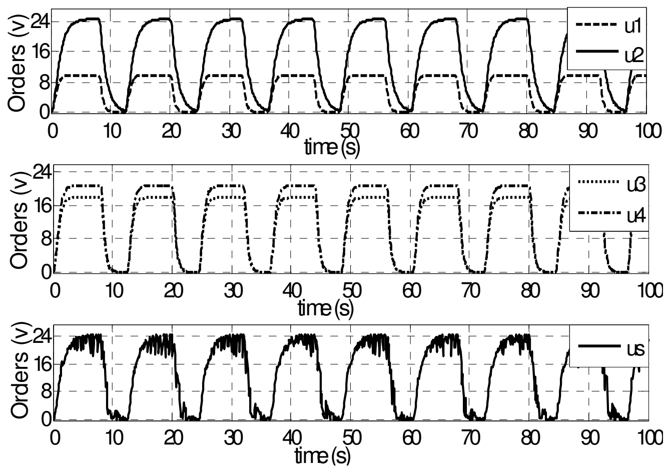

Fig. 6. Evolution control signals

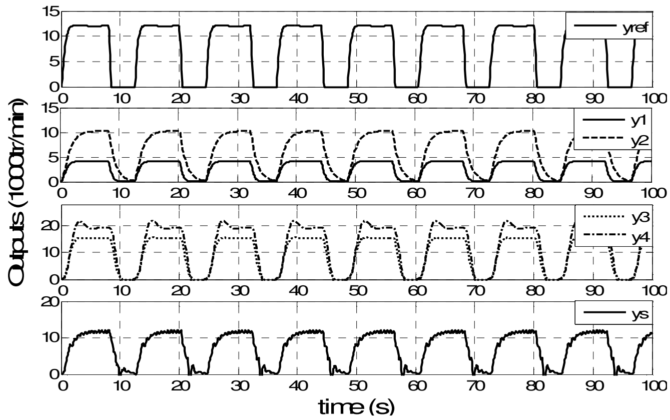

Fig. 7. Evolution of output signals

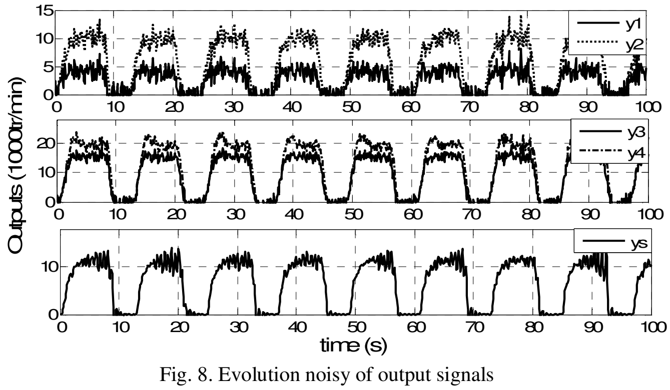

Fig. 8. Evolution noisy of output signals

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The sub models identified provide a good local characterization of system behavior. The multiple models manage to represent the overall dynamics of the system.

We note that the controllers RST applied to the based models show robustness, maintaining the level of performance and to have similar paces acceptable to output signals without noise with a sudden impact taken into account.

The shape of the trajectory tracking error measured between the reference model and the model of the electric motor control is shown in Fig. 9.

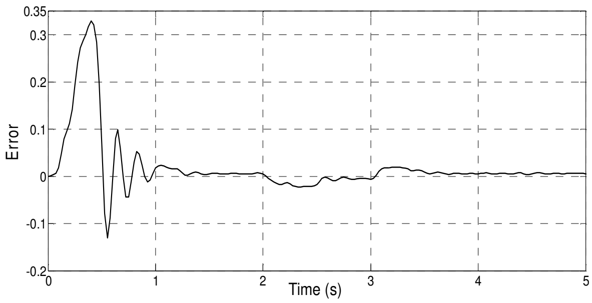

Fig. 9. Allure of the tracking error

The tracking error is relatively large at the beginning of the fact that the system is sensitive to noise. The error stabilizes after 0.8 s which shows that he calculated control ensures a good trajectory tracking.

V. CONCLUSION

This paper addresses a problem of adaptive control of a complex non-stationary discrete system. Based on the algebraic approach to Kharitonov, a basis of four models was constructed. A graphical comparison shows the influence of average model on the dynamic behavior of the overall system. However, it improves the speed. A regulatory approach has been implemented by performing the polynomial RST controller synthesis in the context of adaptive control. The simulation results were reported.

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