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Modelling of Cascade-Connected Systems using Quasi-Orthogonal Functions

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***Abstract*—This paper presents a new method for modelling dynamic systems based on quasi-orthogonal functions. First, we defined a new class of Legendre type quasi-orthogonal functions that can be used for signal approximation as well as for modelling, analysis, synthesis, and simulation of dynamic systems, especially systems that suffer from some imperfections. In this paper, functions have been applied in modelling of cascade-connected dynamic system, typical for tire industry. Considered rubber cooling system is a represent of complex, nonlinear, and stochastic systems with imperfections. Developed quasi-orthogonal adjustable models can be used for modelling of arbitrary dynamic systems. Optimal model parameters in the sense of the mean–squared error were obtained using genetic algorithm. For experimental purposes, simplified cascade-connected system with four transporters has been practically realized. The experimental results proved the accuracy, simplicity, and quality of realized quasi-orthogonal model.**

***Index Terms*—Genetic algorithms, filters, modelling, transportation system.**

I. INTRODUCTION

In every tire factory in the world, there are one or more tire thread (rubber) cooling systems. These tire threads are used to form external (stripped) part of a tire. It is estimated that there are about 12000 systems, like that, all over the world, mostly in China, India, USA, and Brazil. They consist of a large number (4-24) of cascade-connected transporters. Tire thread moves over them, passing from one transporter to another. Thereby, the rubber is cooling under the influence of the water that flows in opposite direction. It is important to notice that cascade-connected systems have very complex dynamics. All the noise and imperfections in one cascade are being transmitted to the next and thereby increased because of the resonance effect. When system has a large number of cascades, these disturbances can cause system failures [1], [2]. In order to design a proper control system, we need to have high quality mathematical model with all the system imperfections calculated [2].

On the other side, history of orthogonal polynomials is very old [3], [4]. There are many papers considering orthogonal systems and their applications in electronics, circuit theory, signal processing, communications, and control system theory [5]–[7]. Concept of quasi-orthogonality is introduced for the first time in 1923 [8] as a tool for solving the problem of moments in mechanics. Quasi-orthogonal functions and especially quasi-orthogonal polynomials as well as numerous applications have been discussed in many papers [9]–[12]. It is important to notice that classical orthogonal signal generators have transfer functions with the order of numerator polynomial for one order lower then denominators polynomial. In practice there is often need for transfer functions of general type i.e., with difference in orders of polynomials higher than one. This can be accomplished by using quasi-orthogonal functions.

Almost orthogonal functions designed in earlier papers [13]–[15] can be successfully used for modelling and analysis of the systems with imperfections. Quasi-orthogonal functions considered in this paper are also suitable for modelling and design of imperfect systems, especially if used in combination with almost orthogonal functions.

This paper is organized as follows. In section 1 we present Legendre type quasi-orthogonal functions and in section 2 method for modelling of dynamic systems based on these functions. Considered cascade-connected rubber cooling systems are described in details in section 3. We have designed and developed smaller, laboratory, version of this system (with four cascades) and applied our method of modelling. Experimental results that verify the given method are presented in section 4.

II. QUASI-ORTHOGONAL FUNCTIONS

The following definition of k-th order quasi-orthogonality for the polynomial set $P_n(x)$ can be found in papers [11], [12]:

$$\int_a^b P_n^k(x)\,P_m^k(x)\,w(x)\,dx = \begin{cases} = 0, & 0 \le m \le n-k-1, \\ \ne 0, & n \ge k+1, \end{cases} \tag{1}$$

where k represents the order of quasi-orthogonality, a and b – quasi-orthogonality interval and $w(x)$ – the weight function. A large number of papers consider construction of

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quasi-orthogonal polynomials [11], [12]. In this paper, we propose a new method for generating quasi-orthogonal polynomials using inverse Laplace transform of rational functions. Here, we consider only generating quasi-orthogonal Legendre type polynomials, but, in the same way, quasi-orthogonal functions of Laguerre, Chebyshev, Gegenbauer, Malmquist, and Jacobi type can also be obtained.

Consider the rational function with the given poles s_i and appropriate zeroes $f(s_i)$ (all orthogonal rational functions have zeroes and poles in strictly defined correlation) [4]–[6]. In the case of classical orthogonal polynomials, we use rational function with order of numerators polynomial for one lower than denominators

$$W_n(s) = \frac{\prod_{i=1}^{n-1}(s + f(s_i))}{\prod_{i=1}^{n}(s + s_i)}. \tag{2}$$

For the given set of poles s_i, zeroes can be obtained via mapping (transformation) $\bar{s} = f(s)$ i.e., $F(s,\bar{s}) = 0$ from one area D_p of the complex plane to another D_z, i.e., from one side of the given contour C to another.

Necessary condition is for the mapping $f(s_i)$ to be symmetrical. Therefore, the function $F(s,\bar{s})$ must be symmetrical i.e., relations $\bar{s} = f(s)$ and $s = f(\bar{s})$ have to be valid. Domain D_p includes all the poles and domain D_z all the zeroes while these two areas must be disjunctive [5]. Contour C can be determined in the case of any concrete transformation by using the substitutions $s = x + jy$ and $\bar{s} = x - jy$. Therefore, contour equation inside s (xy) plain is $F(x + jy, x - jy) = 0$.

In order to generate quasi-orthogonal polynomials in the sense of definition (1), consider now rational function given by

$$W_n(s) = \frac{\prod_{i=1}^{n-k-1}(s + f(s_i))}{\prod_{i=1}^{n}(s + s_i)}. \tag{3}$$

Lets note that the order of the polynomial in numerator is for k+1 lower than the order of polynomial in denominator. This fact has direct consequence in later forming of quasi-orthogonal, order k, functions. Sequence $W_n(s)$ is quasi-orthogonal which can be proved by applying Cauchy's theorem

$$\oint_C W_n(s)\overline{W}_m(s)\,ds = \oint_C \frac{\prod_{i=1}^{n-k-1}(s + f(s_i))}{\prod_{i=1}^{n}(s + s_i)} \frac{\prod_{i=1}^{m-k-1}(s + s_i)}{\prod_{i=1}^{m}(s + f(s_i))}\,ds \tag{4}$$

i.e.:

$$\oint_C W_n(s)\overline{W}_m(s)\,ds = \begin{cases} = 0, & for\ 0 \le m \le n - k - 1, \\ \ne 0, & for\ n\text{-}k \le m \le n. \end{cases} \tag{5}$$

After applying Heaviside development on (3), we obtain

$$W_n(s) = \sum_{i=1}^{n} \frac{A_i^n}{s + s_i}, \tag{6}$$

where

$$A_j^n = \operatorname{Res}(W_n(s)) = \frac{\prod_{i=1}^{n-k-1}(s_j + f(s_i))}{\prod_{\substack{i=1 \\ i \ne j}}^{n}(s_j + s_i)}. \tag{7}$$

In the case of our transformation $\bar{s} = f(s) = -s$ i.e. $F(s,\bar{s}) = s + \bar{s}$, transfer function has the following form

$$W_n^k(s) = \frac{(s - a_1)(s - a_2)\cdots(s - a_{n-k-1})}{(s + a_1)(s + a_2)\cdots(s + a_n)}. \tag{8}$$

After applying Heaviside development, we have

$$W_n^k(s) = \sum_{i=1}^{n} \frac{A_{n,i}^k}{s + a_i}, \tag{9}$$

where

$$A_{n,i}^k = \frac{(-1)^{2n-k+2}\prod_{j=1}^{n-k-1}(a_i + a_j)}{\prod_{j=1}^{i-1}(a_i - a_j)\prod_{j=i+1}^{n}(a_i - a_j)}. \tag{10}$$

III. Modelling Based on Quasi-Orthogonal Functions

Sequence of quasi-orthogonal functions given with (8) is suitable for direct designing of quasi-orthogonal signal generator and adjustable model. For example, first order (k=1) Legendre type adjustable model is given in Fig. 2.

Signals labelled as $\varphi_i^1(t)$ (i=1,2,…,n-1) in the Fig. 1 represent the sequence of exponential quasi-orthogonal functions over interval (0, 1) with weight $w(t) = e^{-t}$. They are inverse Laplace transforms of output signals from corresponding sections of the first order quasi-orthogonal signal generator

$$\varphi_i^1(t) = L^{-1}\{\varphi_i^1(s)\}, \quad i = 1,\ldots,n-1, \tag{11}$$

where $\varphi_i^1(s) = u(s)\prod_{j=1}^{i} W_j^1(s)$ for i=1,...,n-1. Term $W_j^1(s)$ represents transfer function of a single section of signal generator.

The following approximation is used in order to obtain the model of a given system:

$$y_M(t) \approx \sum_{i=1}^{n-1} c_i \varphi_i^1(t) \,. \tag{12}$$

The adjustable model shown in Fig. 1 is designed on the basis of approximation (12) and signal generator transfer function (8).

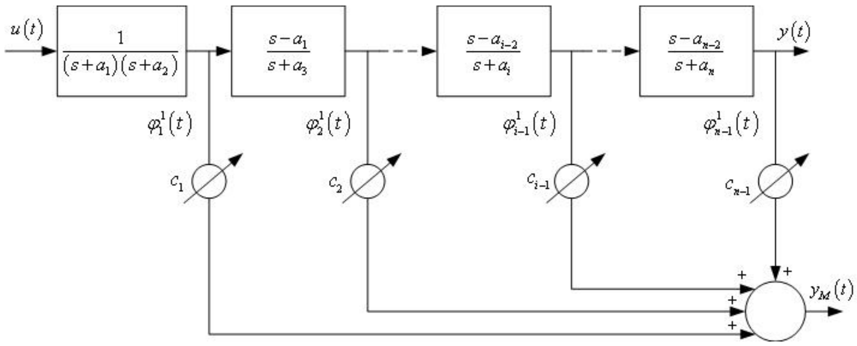

Fig. 1. Adjustable, Legendre type, first order quasi-orthogonal signal generator.

Adjustable model can be used for modelling arbitrary dynamic system. Specific models are obtained with the help of adjustable parameters c_i (i=1,2,…,n-1) and section poles a_i (i=1,2,…,n). During the modelling of concrete unknown system, these parameters are being adjusted in such a way that model in Fig. 1 corresponds to the unknown system as exactly as possible. The process of modelling starts with applying the same input signal to both the unknown system (which is to be modelled) and the model given in Fig. 1. Next, the difference of system and model outputs is formed as well as the modified mean-squared error relation

$$J = \frac{1}{T}\int_0^T t\,(y_S - y_M)^2\, dt \,, \tag{13}$$

where $y_S(t)$ and $y_M(t)$ are system and model output, respectively.

Parameters a_i and c_i are being adjusted until the minimization of the function (13) is achieved, i.e., as long as necessary to obtain the best model of unknown system in the sense of mean-squared error. Optimal adjustment of the parameters can be accomplished by using genetic algorithms. Genetic algorithms [16] are optimization technique based on simulation of the phenomena taking place in the evolution of species and adapting it to an optimization problem. They have demonstrated very good performances as global optimizers in many types of applications [16]–[18].

The complete block diagram, that illustrates the process of modelling, is given in Fig. 2.

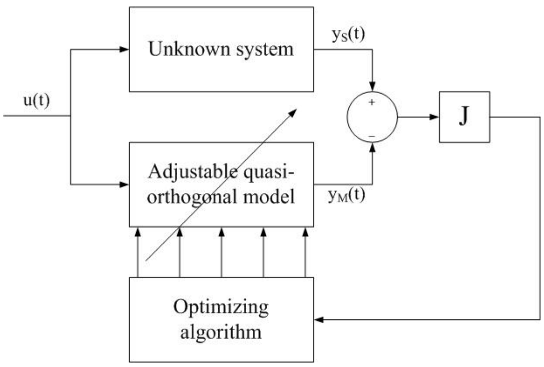

Fig. 2. .Block diagram of the modelling process.

IV. CASE STUDY

Fig. 3 shows a cascade-connected transporters for the rubber strip cooling, considered in this paper. This system in a real factory is given in Fig. 4.

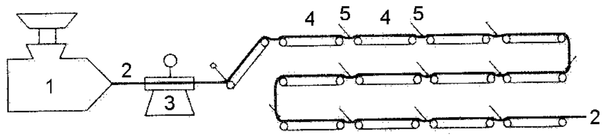

Fig. 3. Cascade system for the rubber strip transportation (1-extruder 2-rubber strip 3-balance 4-transporters 5-transitions).

The rubber strip comes from extruder (point 1 in Fig. 3.), pass through the balance (point 3 in Fig. 3.) and goes to the cooling system. It is necessary to cool down the rubber strip to the room temperature. When rubber runs through the cooling system, it is being cooled and contracts with contraction coefficient μ<1. During that contraction, rubber strip velocities at transporters ends are not equal to the transporters velocities, producing the effect of rubber slipping relatively to the transporter. The velocities of individual transporters are adjusted using local controllers that determine the velocity of the next transporter according to the length of the rubber between two consecutive transporters.

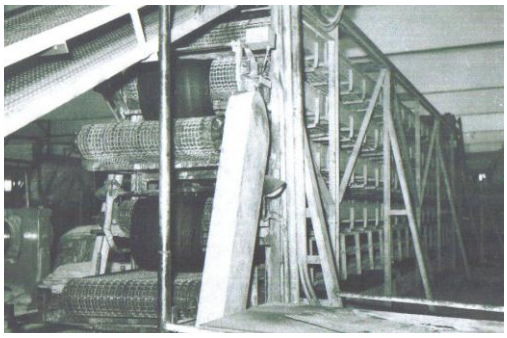

Fig. 4. Rubber cooling system installed in tire industry “Tigar-Michelline”, Serbia.

The length change of the rubber strip between two transporters can be described with the following equations:

$$\frac{dl_i}{dt} = V_{g,i-1}^{(2)} - V_{g,i}^{(1)},\, i = 1, 2, \ldots, n \,, \tag{14}$$

$$V^{(2)}_{g,i-1} = V_{i-1}, \quad V^{(1)}_{g,i} = \frac{1}{\mu} V_i, \tag{15}$$

$$\frac{dl_i}{dt} = V_{i-1} - \frac{1}{\mu} V_i, \tag{16}$$

$$\Delta l_i = \frac{1}{s}\left(V_{i-1} - \frac{1}{\mu_i} V_i \right), \tag{17}$$

where l_i is the length of rubber strip between i-th and (i+1)-th transporter, $V^{(2)}_{g,i-1}$ - rubber velocity at the end of the (i-1)-th transporter, $V^{(1)}_{g,i}$ - rubber velocity at the beginning of the i-th transporter, n - the number of transporters, Δl_i - length change of rubber strip between two consecutive transporters, V_i - the velocity of the i-th transporter, μ_i - the rubber contraction coefficient for the i-th transporter.

Fig. 5 shows a transition between two transporters. To regulate transporters velocities, it is necessary to measure the lengths of the rubber between transporters (Δl_i). These measurements are performed by special sensors (potentiometers P in Fig. 5). Potentiometer angle β_i satisfies the following relation

$$\beta_i = \Phi(\Delta l_i), \tag{18}$$

where Φ represents nonlinear function. The value of β_i is between 0 and 90 degrees. Potentiometer voltage is given by

$$u_i = K_{pi} \beta_i, \tag{19}$$

where K_{pi} represents potentiometer coefficient [V/rad].

Potentiometer voltage is being amplified and finally the velocities of drive motors are being controlled using thyristor regulators.

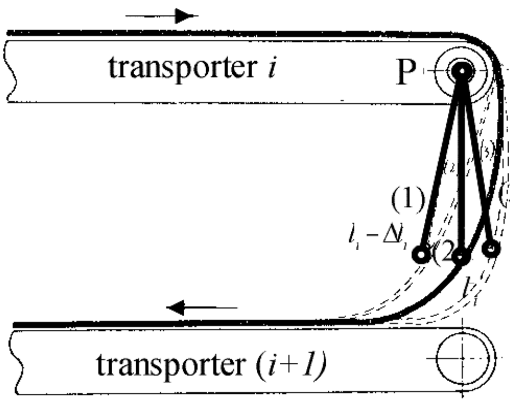

Fig. 5. Rubber transition between transporters.

Dynamics of i-th transporter with controller and drive motor can be described with the following well-known equation [2]

$$T_1 T_2 \frac{dV_i^2}{dt^2} + (T_1 + T_2)\frac{dV_i}{dt} + V_i = u_i, \tag{20}$$

where T_1 and T_2 are mechanical and electrical time constants of electromechanical drive. According to (20), the transfer function for i-th transporter has the following form

$$G_i(s) = \frac{V_i(s)}{u_i(s)} = \frac{1}{T_1 T_2 s^2 + (T_1 + T_2)s + 1}. \tag{21}$$

Using stated equations (14) to (21), the block diagram of the single transporter, given in Fig. 6, is obtained.

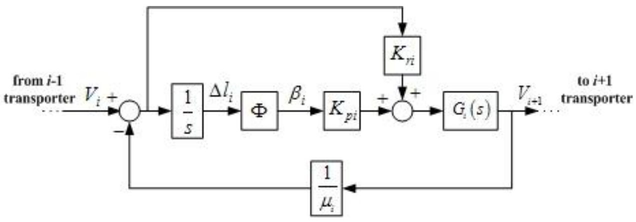

Fig. 6. Block diagram of the single transporter in cascade-connected system.

Integration of velocities between transporters can cause static error when parameter μ changes (change of used rubber quality or change of ambience temperature). In Fig. 5 middle position of the sensor (position (2)) corresponds to normal operating. If μ increases, sensor moves to position (1) and static error $-\Delta l_i$ occurs (the rubber stretches). If μ decreases, sensor moves to position (3) and static error $+\Delta l_i$ occurs (the rubber accumulates). Compensational potentiometers (K_{ri} in Fig. 6) are introduced in order to compensate static errors, so their adjustment brings system back to normal operating (position (2) in Fig. 5). Following properties of these systems affect dynamics, stability, and system quality:

1)Tire thread accumulates at transition places (points 5 in Fig. 3), because of integration of velocities difference.

2)Nonlinear dependencies are formed at the cascade transitions, between transporters.

3)During the tire thread movement along a transporter, rubber runs cold and contracts. Because of that, velocity at transporter end is smaller than velocity at transporter beginning, with contraction coefficient μ. Coefficient μ is stochastic because it depends on rubber quality and environment temperature, which are stochastic parameters. Influence of stochastic parameters μ_i on cascade systems stability is analysed in [1], [2].

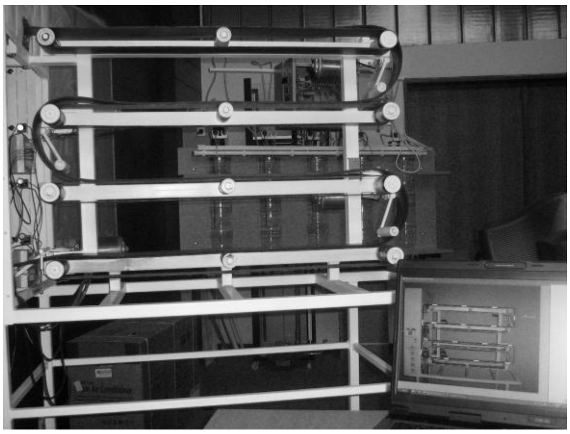

Fig. 7. Laboratory setup – cascade-connected system with four transporters.

Due to cascade structure and nonlinearities, the system is prone to oscillations [1] and under certain conditions, deterministic chaos may appear [2]. Because of the stated properties, the referred system is very complex and difficult to model [2]. For experimental purposes, cascade-connected system with four transporters (Fig. 7) has been practically realized in our Laboratory for modelling, simulation and systems control. Our system is capable for imitating real factory systems in all above-mentioned aspects

V. EXPERIMENTAL RESULTS

The goal of performed experiment was to obtain the model and transfer function of our laboratory system given in Fig. 5 with developed quasi-orthogonal functions, as described in section 2. Thereby, we assumed that the system itself represents a black box and we neglected everything that we know about it, previously described in section 3. The only known data about the system were measured outputs (single transporters velocities) for a given step input (see Fig. 8).

We have chosen adjustable model with four (one for each transporter) first order (k=1) quasi-orthogonal signal generators with two sections (n=3) given in Fig. 9. Every generator has five adjustable parameters (a_1, a_2, a_3, c_1, and c_2 in Fig. 1). Then, the same step input signal is applied to both the unknown system and adjustable model as presented in Fig. 2. The next step was to form a difference between measured system output and model output as well as to calculate mean-squared error given with (13). Optimal values of adjustable parameters, needed for the best model of unknown system, were determined using genetic algorithm.

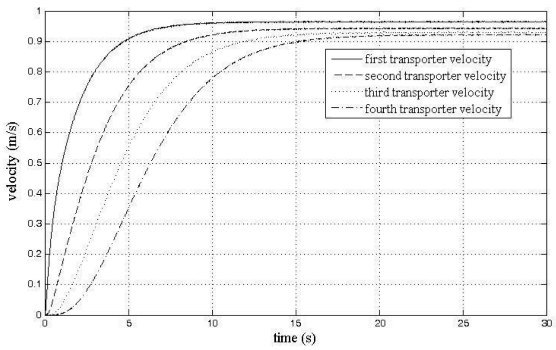

Fig. 8. Step response of laboratory cascade-connected system.

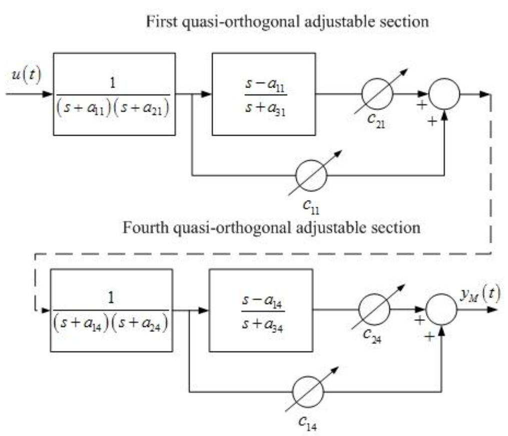

Fig. 9. Quasi-orthogonal model of the laboratory cascade-connected system.

The goal of the experiment was to make a mean-squared error as small as possible for a chosen step input i.e. to obtain the best model of the unknown system in the sense of mean-squared error. So, relation (13) was used as the fitness function for the genetic algorithm.

By using the method described in section 4, data set of measured velocities and genetic algorithm, optimal model parameters given in Table I were obtained.

TABLE I. OBTAINED PARAMETERS OF THE QUASI-ORTHOGONAL MODEL FOR ALL FOUR TRANSPORTERS.

	Tr. 1	Tr. 2	Tr. 3	Tr. 4
a_1	1.5687	1.5889	1.5845	1.6226
a_2	0.4371	0.4143	0.4209	0.3767
a_3	0.0531	0.0543	0.0534	0.0579
c_1	0.2121	0.1924	0.1733	0.1533
c_2	-0.0156	-0.0154	-0.0161	-0.0158

With these parameters, corresponding transfer functions for quasi-orthogonal generators that are models of single transporters are given by the following relations:

$$\begin{cases} TF_1(s) = \dfrac{0.1965s + 0.0357}{s^3 + 2.0586s^2 + 0.7922s + 0.0364}, \\ TF_2(s) = \dfrac{0.1768s + 0.0355}{s^3 + 2.0585s^2 + 0.7691s + 0.0359}, \\ TF_3(s) = \dfrac{0.1571s + 0.0352}{s^3 + 2.0589s^2 + 0.7741s + 0.0356}, \\ TF_4(s) = \dfrac{0.1375s + 0.0346}{s^3 + 2.0573s^2 + 0.7271s + 0.0354}. \end{cases} \tag{22}$$

Overall transfer function of entire cascade-connected system can be obtained as a serial connection of the single transporters $TF(s) = \prod_{i=1}^{4} TF_i(s)$. Step response of our model is almost identical to the real system (Fig. 8) with standard deviation lower than 1.5%. The results prove the accuracy, simplicity, and quality of realized quasi-orthogonal model.

VI. CONCLUSIONS

This paper considers the possibility of modelling dynamic systems using quasi-orthogonal functions. Theory of Legendre type quasi-orthogonal functions is described as well as a new method for designing generators of these functions. Functions are based on elemental transformation $\bar{s} = -s$ in a complex plane, and they can be used for signal approximation as well as for modelling, analysis, synthesis, and simulation of dynamic systems. A new method for obtaining a general (adjustable) model of dynamic systems, based on our quasi-orthogonal functions is proposed and described in details. Specific models are obtained with the help of adjustable parameters and with respect to the mean-squared error of the difference between real system and model output signals. Optimal model parameters can be calculated using genetic algorithm.

In this paper, adjustable model has been applied in modelling of cascade-connected dynamic system, typical for tire industry. Considered rubber cooling system is a represent of complex, nonlinear, and stochastic systems with imperfections. Properties and equations of these systems with regard to existing nonlinearities, possibilities of oscillations and chaos have been analysed in details. For experimental purposes, cascade-connected system with four transporters has been designed and practically realized in our Laboratory for modelling, simulation and systems control. Experiments were performed to validate theoretical results and to demonstrate that the method described in the paper is suitable for modelling of dynamic systems. It achieves excellent results in the sense of modelling algorithm simplicity and speed as well as model accuracy.

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