University of Craiova
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Abstract of doctorate thesis

Adaptive control algorithms of dynamical friction systems

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The phenomenology of friction is an important aspect in systems control for both high precision servomechanisms and hydraulic or pneumatic simple systems and the performance of these highly accurate mechanisms is inherently affected by the friction of bodies which come in contact. Therefore friction is an inevitable physical phenomenon, causing unwanted behavior in systems control like the position errors, unstable limit cycles, stick-slip motion etc. Thus, one of the main problems of systems control research has represented friction force compensation, in order to attenuate adverse effects caused by it, effects that were listed above.

The basic approach used for dynamical friction systems control, to avoid difficulties that arise due to friction is given by adaptive control strategies, called compensation techniques of the model based friction force. These techniques require accurate values of the parameters that appear in models of friction, and of these parameters, viscous and Coulomb friction coefficients are always present. Also the adaptive control strategy involve identification procedures of the controlled system, which include the identification of friction model parameters.

This work was aimed primarily at ***the application and development of identification algorithms for the adaptive control of dynamical electrical and mechanical friction systems.*** Thus, the research undergone in this work is inline with the research direction mentioned above by providing an adequate solution to the modeling, identification and adaptive control problems, of the electrical and mechanical friction systems.

The six chapters of this work demonstrate the importance and knowledge of the friction phenomenon, which refers to the modelling, identification and adaptive control of dynamical friction systems, electrical and mechanical type.

The first chapter is an introduction to the problems of systems with friction. In order to apply and develop some identification algorithms used in the adaptive control of dynamical friction systems, are presented notions that define the concept of friction, such as friction present in almost mechanism with moving components, the movement influencing of friction forces in the mechanical, hydraulic or pneumatic systems due to the interaction with the environment or the interaction between these force components, engineering examples where friction occurs in abundance. The importance and undesirable behaviors induced by friction forces in systems control, the measures taken to prevent these behaviors, such as the adaptive control strategy based on identification methods of dynamical friction systems, the friction models adopted in systems control are also presented in this first chapter.

The chapter ends with the problem illustrates a friction system a concrete example on wheel-slip mechanism for rolling stocks, the scope and content of the work, and the publications that containing original contributions of the author.

In **the second chapter** the modelling of the friction phenomenon is illustrated and experimental observations and theoretical concepts on static and dynamic friction are presented, the transition from static friction to dynamic friction, as well as modelling principles of the two forces. Also were reviewed some of the static and dynamic friction models in the literature and used throughout this work, such as Coulomb viscous friction, simplified Dahl and LuGre models.

In this work we designed, analyzed and implemented ***a new dynamic friction model from LuGre model which is called in the thesis "The modified LuGre model"***. This model was designed in the idea of allowing the identification of parameters that determine the Stribeck effect (displacement effect at low velocities), impossible with the models in literature due to the presence of exponential function $e^{-(v/v_S)^2}$. In the proposed model, in the function $g(v)$ which models the Stribeck effect, a rational structure is considered in which the Stribeck velocity parameter appears, that expresses the function variation $g(v)$ within the range $F_C < g(v) \leq F_S$, where v represents the velocity of displacement, F_C the Coulomb friction force, and F_S the static friction force. Thus the proposed hierarchical identification method with distributions, proposed by the research team which includes the author, can be applied. The modified LuGre model ensures the convergence improving at low velocities of the function $g(v)$ to its limits.

Based on friction of models like: simplified Dahl, LuGre and modified LuGre which induce the bidirectional motion (hysteretic), the last part of this chapter was dedicated to representation of the hysteretic and stick-slip phenomenon induced by the friction force in a mass-spring mechanical system described by block diagram in Fig. 1. This system was represented as an interconnection with negative feedback between the linear part given by the transfer function of the fixed part of the system $H(s)$ and the nonlinear part expressed by the friction force F_f as in Fig. 2, where m represents the mass of the system attached to a spring with stiffness K_p, moving on a horizontal surface, F_e represents the external force that acts on the mass, and x the displacement of the mass. Originally the mass is at rest in a position expressed by the variable $x = 0$. The results obtained have highlighted the advantages of modified LuGre model to the model LuGre by better response time and the elimination of the inflection points.

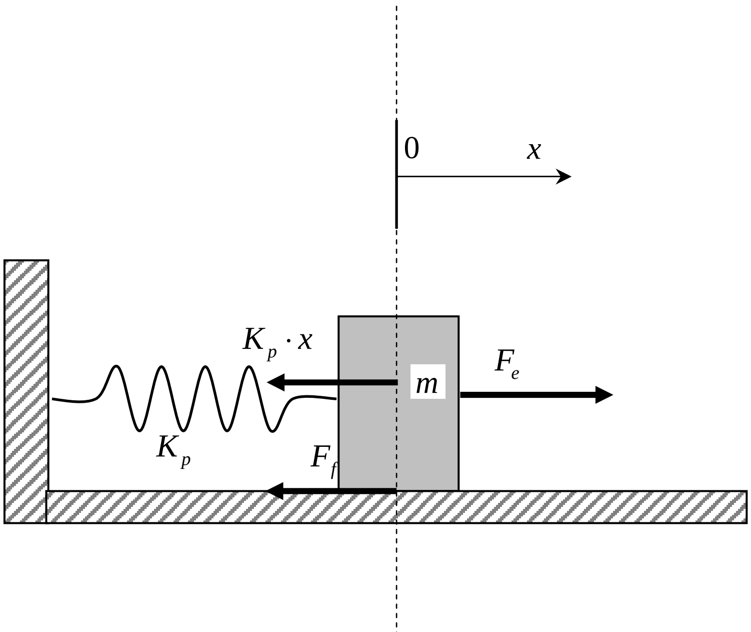

Fig. 1 Principle diagram of the mass - spring system with friction.

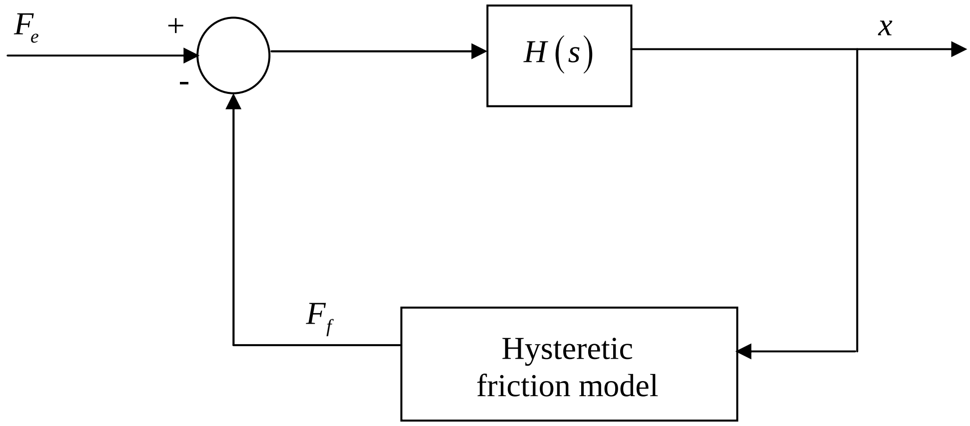

Fig. 2 Block scheme of the mass - spring system with friction.

The third chapter discusses the parameters estimation problem for friction systems. Preliminary concepts for local optimization problems without restrictions, respectively the problem formulation of the gray-box models using iterative minimization of prediction error have been studied. Using functions without restrictions, ***fminsearch*** and ***fminunc*** in Matlab's Optimization Toolbox, ***an estimate of the DC motor parameters with dynamic friction model (LuGre model) in steady state*** was achieved, and some of the results obtained were approximate.

Also, using the iterative minimization of prediction error ***the gray-box models (models with partially or totally unknown parameters) parameters estimation was extended from the of Matlab's Identification Toolbox for friction systems***. This estimation of the systems' parameters with gray-box friction models was based on samples acquired experimentally (points of the Input/Output information) which lead to obtaining approximate results for both static friction model and a system with a dynamic friction model (simplified Dahl model). The gray-box friction of models estimated can be used for system control, and gray-box items may be different friction characteristics. Therefore, models with gray-box friction have been analyzed in this chapter are most suitable for parameters estimating of systems with friction.

In **the fourth chapter** ***an extension of the identification method based on distributions at dynamic systems with friction*** was achieved. The formulation of the identification problem in terms of distributions was analyzed, and to experiment with the theoretical concepts an assessment of so-called test functions was proposed, for converting differential equations into algebraic equations with respect to unknown parameters of systems with friction. Also, the approach based on distributions of generalized dynamical systems with friction was performed, respectively the development and expansion of a DBI (Distributions Based Identification) experimental platform to identify friction systems parameters. Some of the results obtained are approximate.

For example, a generalized dynamical system with friction is presented, analyzed in terms of distributions. The distribution means a function $q:\mathbb{R}\to\mathbb{R}, t\to q(t)$ that admits an integral in the Riemann sense on any compact interval T from $\mathbb{R}$ of the form:

$$F_q : \Phi_n \to \mathbb{R},\ \varphi \to F_q(\varphi) \in \mathbb{R} \tag{1}$$

which can be built by the relation:

$$F_q(\varphi) = \int_R q(t)\varphi(t)\,dt, \forall \varphi \in \Phi_n \tag{2}$$

where Φ_n represents the fundamental space from distribution theory, and φ represents the real testing function $\varphi : \mathbb{R} \to \mathbb{R},\ \varphi \in \Phi_n$ characterized by bounded support T in which $T = [t_a, t_b],\ t_a < t_b$. A generalized dynamic friction system (GFDS) is a system characterized by a state equation of the form:

$$\dot{x} = f(x, u, r_1, .., r_i, .., r_p) \tag{3}$$

where $x(t) \in \mathbf{X} \subseteq \mathrm{R}^{\mathrm{n}},\ \forall t \geq t_0$, is the state vector and $u(t) \in \mathbf{U} \subseteq \mathrm{R}^{\mathrm{q}},\ \forall t \geq t_0$ is the input vector. The vectors $r_i(t) \in \mathbf{R}_{\mathrm{i}} \subseteq \mathrm{R}^{\mathrm{n}},\ \forall t \geq t_0,\ i = 1 : p$ are called friction reaction vectors. They depend on x and u through a specific operator $\Psi_{\mathrm{i}}\{\}$, called friction operator, having the following form:

$$r_i = \Psi_{\mathrm{i}}\{x, u\}, i = 1 : p \tag{4}$$

For static friction models (SFM), this operator (4) can be expressed as a function of v_i, and a_i only, by the relation:

$$r_i = \rho_{\mathrm{i}}(v_i, a_i) = F_i(x, u), i = 1 : p \tag{5}$$

where $v_i = v_{\mathrm{i}}(x, u) : \mathbf{X} \times \mathbf{U} \to \mathbf{V}_{\mathrm{i}} \subseteq \mathrm{R}^{\mathrm{m_i}}, i = 1 : p$ determines the so called generalized velocity vector v_i, and $a_i = \alpha_{\mathrm{i}}(x, u) : \mathbf{X} \times \mathbf{U} \to \mathbf{A}_{\mathrm{i}} \subseteq \mathrm{R}^{\mathrm{m_i}}, i = 1 : p$ expressing the so called active component of the velocity vector v_i. A particular structure for the relation (5) is of the form:

$$r_i = r_i^s + r_i^c \tag{6}$$

which is equivalent with:

$$\rho_i(v_i, a_i) = \rho_i^s(v_i, a_i) + \rho_i^c(v_i, a_i), \forall v_i \in \mathbf{V}_{\mathrm{i}}, \forall a_i \in \mathbf{A}_{\mathrm{i}} \tag{7}$$

where r_i^s represents static friction reaction, and r_i^c represents cinematic friction reaction ($i = 1 : p$).

There are different specific expressions for the functions $\rho_i^s(v_i, a_i)$ and $\rho_i^c(v_i, a_i)$ considering the relations (6) and (7), but three conditions must be accomplished:

a. Outside the surface $\mathrm{S_i}$, r_i is a vector opposite to $v_i \neq 0$:

$$r_i = -\lambda_i \cdot v_i\ ,\ \lambda_i > 0,\ v_i \neq 0 \tag{8}$$

b. Inside the surface $\mathrm{S_i}$, r_i is a vector opposite to a_i:

$$r_i = -\gamma_i \cdot a_i\ ,\ \gamma_i > 0,\ v_i = 0 \tag{9}$$

c. There is a closed subset $\mathrm{S}_i^0(u) \subseteq \mathrm{S}_i$, called sticky area (SA), which keeps the system state inside. This means:

$$\tfrac{d}{dt} v_i(x(t)) = [\tfrac{d}{dx} v_i(x)]^T \cdot \dot{x}(t) = 0, \forall x \in \mathrm{S}_{\mathrm{i}}^0(u) \tag{10}$$

inside the SA $r_i = -a_i$. The condition c, is called the smooth sticky condition (SSC).

For example, expressions as (11) and (12) satisfy the conditions a, b, c, where by a_i it must understand $a_i = a_i(x,u)$,

$$r_i^s = \rho_i^s(v_i, a_i) = -\max\{F_{C_i}, \|a_i\|\}\cdot \mathrm{sgn}(a_i)\cdot[1-\mathrm{sgn}(\|v_i\|)] \quad (11)$$

$$r_i^c = \rho_i^c(v_i, a_i) = -[F_{C_i} + F_{v_i}\cdot\|v_i\| + B_i\cdot(e^{-\beta_i\cdot\|v_i\|}-1)]\cdot \mathrm{sgn}(v_i) \quad (12)$$

As it can be observed, the cinematic reaction r_i^c is a sum of three components, $r_i^{cc}, r_i^{cv}, r_i^{cs}$ expressing respectively Coulomb friction, viscous friction and the so called Stribeck effect,

$$r_i^c = r_i^{cc} + r_i^{cv} + r_i^{cs} \quad (13)$$

Therefore, if the number of components $m_i = 1$, all r_i, a_i, v_i are scalar variables so the static reaction (11), r_i^s, is illustrated in Fig. 3a and the cinematic reaction (12), r_i^c, is presented in Fig. 3b.

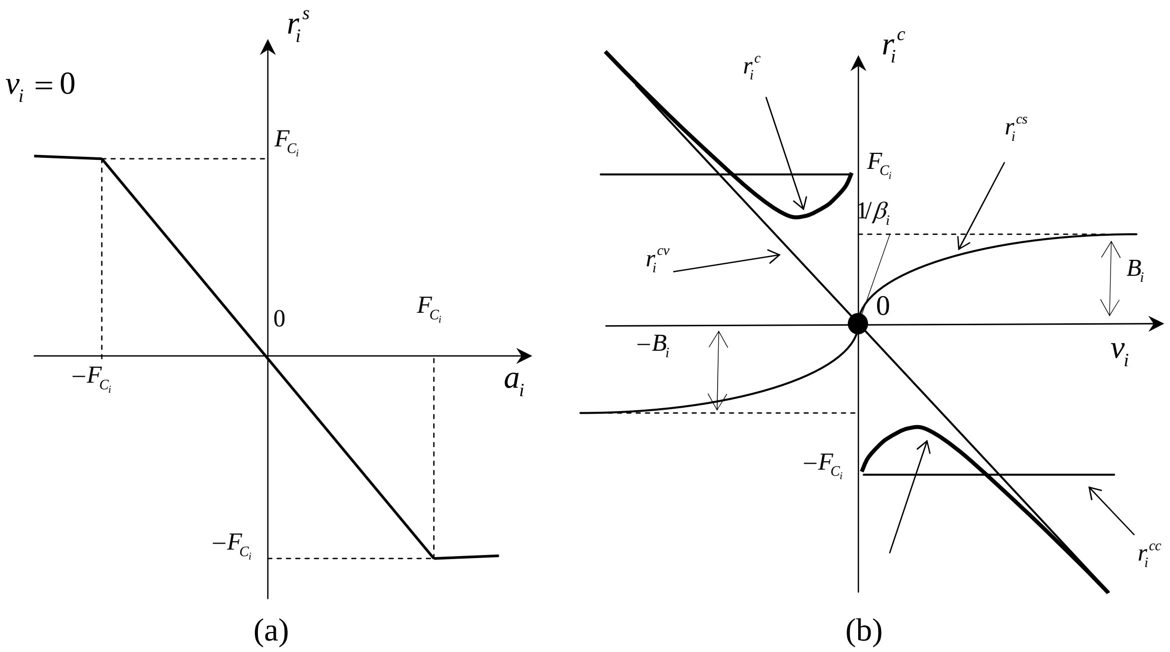

Fig. 3 Static and cinematic components of a scalar friction reaction.

Substituing the relation (5) into (3) and denoting

$$\mathbf{f}(x,u) = f(x,u,F_1(x,u)_1,..,F_i(x,u),..,F_p(x,u)) \quad (14)$$

GDFS takes the compact form

$$\dot{x} = \mathbf{f}(x,u),\ x(t_0) = x_0, t \geq t_0 \quad (15)$$

This is a differential system with a discontinuous function on the right side so for its analytical description, special mathematical approaches are necessary. For the identification it is supposed a solution exist for (15) and are available as measurements the input variable u and the output variable y where,

$$y = h(x,u) \quad (16)$$

The structure of a GDFS with static friction model is illustrated in Fig. 4.

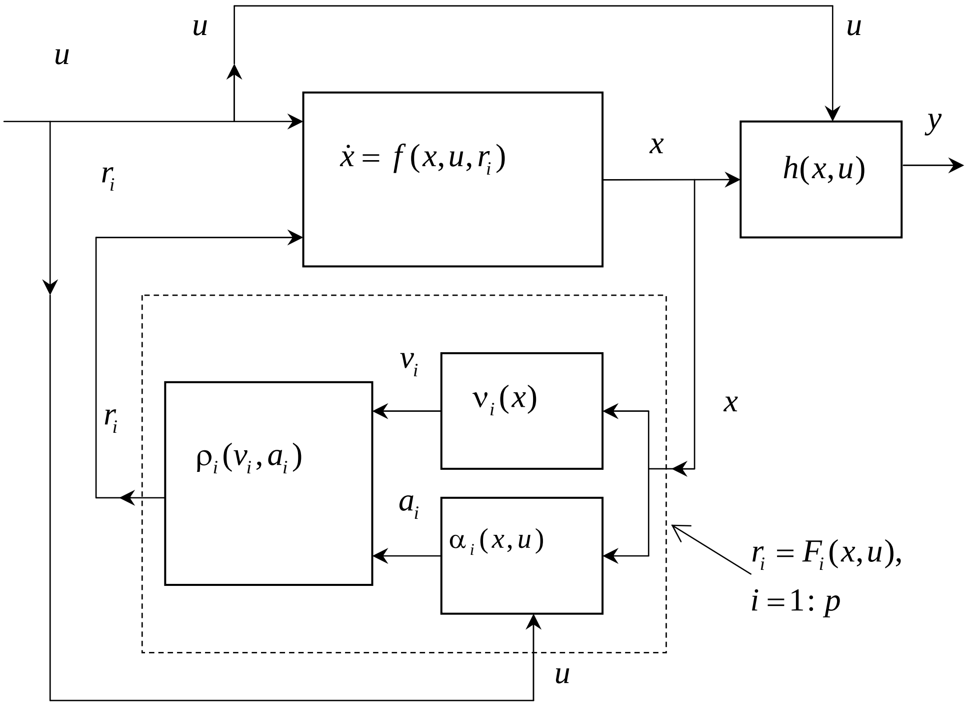

Fig. 4 The feedback structure of a GDFS with static friction model.

For dynamic friction models, (DFM) the operator (4) is a dynamic system characterized by an additional state vector z_i, expressing internal changes in some surfaces of relative movements. The friction reaction vector r_i is the output of a dynamic system,

$$r_i = h_i(z_i, x, u) \tag{17}$$

$$\dot{z}_i = f_i(z_i, x, u) \tag{18}$$

The structure of equation (18) is similar to (15), that means a smooth system with a sticky feedback as (11), (12).

The fifth chapter of this work addresses the adaptive control of dynamical friction systems. After introducing related adaptive friction compensation ***has been developed and implemented a control structure with and without adaptive mode both off-line and on-line by placing an on-line adaptive estimator for the parameter of Coulomb friction in terms of the angular position control of the gear experiment Quanser SRV-02***. In addition, ***a control structure has been developed and implemented with and without adaptive mode only off-line based on the distributions theory regarding of angular velocity control of a dynamical system with friction and extend this structure by adding self tuning block (adaptation of regulation law's parameters) for the mass-spring mechanical system***. This chapter has attempted to highlight the improved efficiency of adaptive control to classic control for dynamic systems with friction.

For example, in Fig. 5 is presented the structure of adaptive control off-line type using the theory of distributions for a DC motor with dynamic friction model (Dahl simplified model), and in Fig. 6 is illustrated extended version of the structure from Fig. 5 by adding self tuning block for the mass-spring mechanical system.

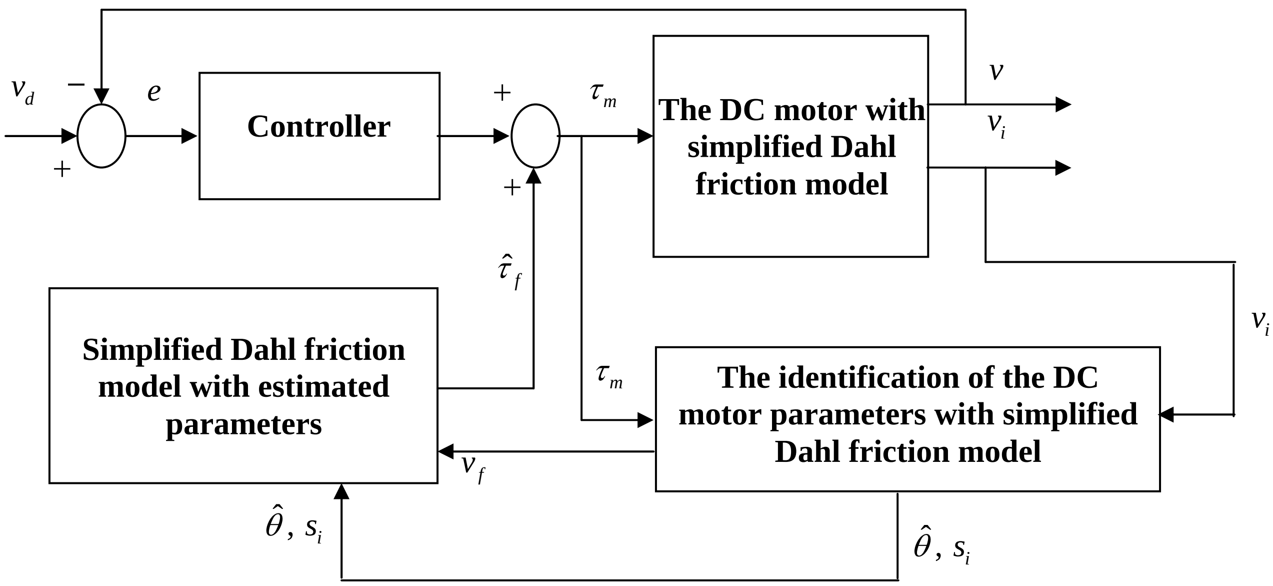

Fig. 5 The structure of regulation of the angular velocity of the DC motor with simplified Dahl friction model using adaptive control.

The block „The DC motor with simplified Dahl friction model" has a manipulated variable τ_m (the motor torque) and v (the real velocity of the motor) as feedback variable for the closed loop system. Some other variables, denoted v_i, are utilized for the identification of dynamical friction system. The set point is v_d (the desired velocity of the motor), and the block „The identification of the DC motor parameters with simplified Dahl friction model " receives the pair (τ_m, v_i), as measured signals, and realizes the identified parameters $\hat{\theta}$, the identification status s_i and additional variables, v_f necessary for the block „Simplified Dahl friction model with estimated parameters". The output of this block, of friction compensation, the estimated friction torque $\hat{\tau}_f$, is applied to the plant with friction (The DC motor with simplified Dahl friction model) as a correction signal. We will consider that $\hat{\tau}_f$ depends of the identified parameter (the viscous friction parameter) $\hat{\beta} = \hat{F}_v$, as well as of the real velocity of the motor, respectively the bristle deviation z, and considering the stiffness parameter σ determined off-line.

For the mass-spring mechanical system with friction, as a controlled plant, called „Plant with friction" (PF), has a manipulated variable u (a horizontal force acts on the system mass m) and x (the mass displacement) as feedback variable for the closed loop system. Some other variables, denoted x_i, are utilized for the identification of the mass-spring system parameters with friction. The set point is x_d (the desired position of the mass) and the command variable, delivered by the „Controller" (C) is x_r. The block „The identification of the mass-spring system parameters with friction" receives the pair (u, x_i), as measured signals, and realizes the identified parameters $\hat{\theta}$, the identification status s_i and additional variables, x_f necessary for the block „Friction model with estimated parameters". The output of this block, of friction compensation, the estimated friction force $\hat{F}_f$, is applied to the plant with friction (IF) as correction signal. The block „Controller tuning” (CT) adjusts some of the controller parameters, depending on the pair $\left(\hat{\theta},\, s_i\right)$.

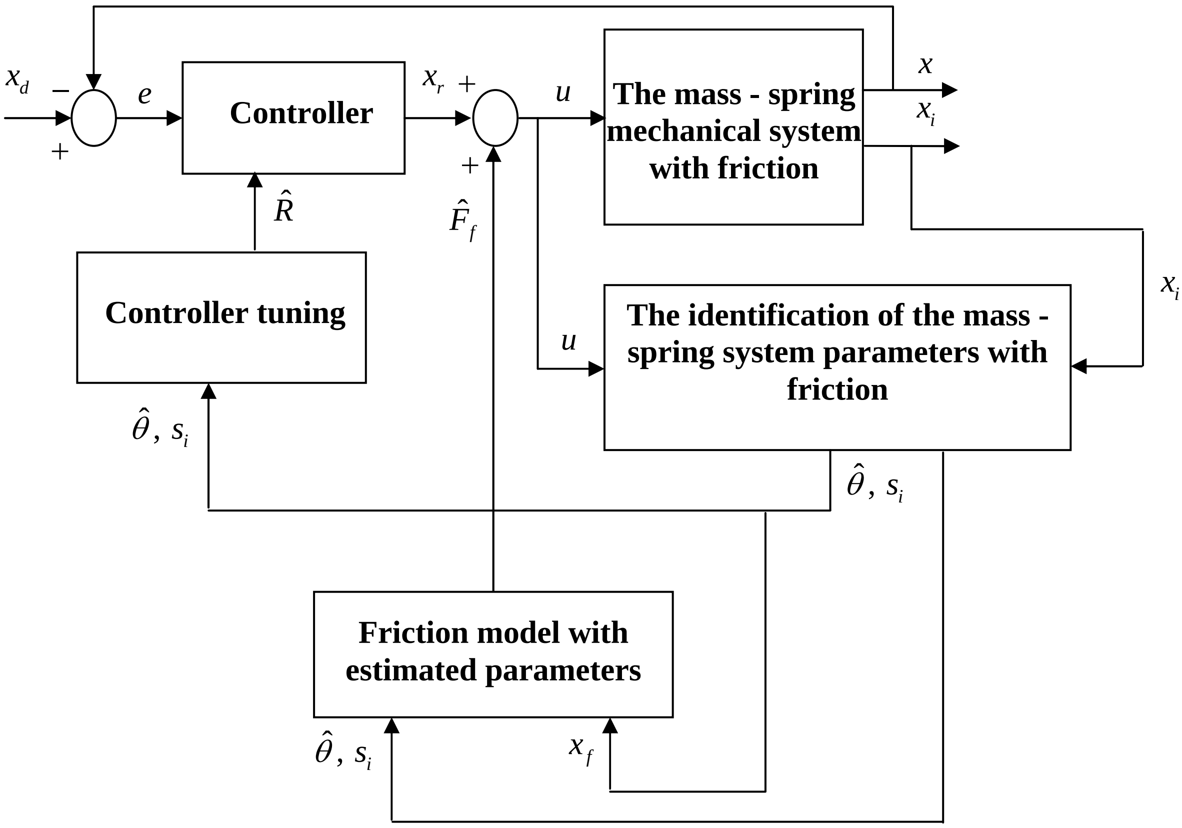

Fig. 6 Self tuning control mass - spring system structure.

Personal contributions made by research carried out during this work are presented in the conclusions of each chapter, which is summarized in **the sixth chapter** and the last of this work.

This work corresponds to current trends in the field of friction, adding a necessary contribution in the modelling, identification and adaptive control of dynamical friction systems, electrical and mechanical.

The research in this work highlighted the importance of the phenomenon of friction using algorithms for the adaptive control of dynamical friction systems, electrical and mechanical type. Compared to classic control, depending on modelled and identified friction system complexity, through this study the possibility to adapt the parameters of the phisical friction system on-line and off-line was demonstrated, and this was done without affecting its time response. This aspect has underlined the applied importance in friction systems control, in the case when at a certain moment in time one or more parametres are modified.

All concepts and structures developed and implemented during this work are the base modelling, identification and adaptive control of dynamical friction systems, leading to obtaining significant results and useful both theoretically and practically.