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Robust control of single input multi outputs systems

Introduction. *Most of mechanical systems are nonlinear and complex, the complexity of these latter lies on highly nonlinear characteristics, or on dynamics that stimulate the development or change of the process through an applied force in a disturbed environment. Single input multi outputs (SIMO) systems, which are structured into subsystems, are considered as complex systems. The task to control their degrees of freedom is more complicated, and it is not easily reachable, due to the fact that nonlinear laws are not directly applicable to those systems, which requires to trait them in a particular way.* ***Problem****. First order sliding mode control (FOSMC) has already been applied in several previous works to this kind of systems, and due to its robustness property, this control gave good results in term of stabilization and tracking, but the chattering phenomenon remains a big problem, which affects the control structure and the actuators.* ***Purpose.*** *In order to address the problem of chattering encountered when applying the FOSMC to a category of second order subsystems, a second order sliding mode control (SOSMC) is designed.* ***Methods.*** *This work consists of developing an appropriate second order system structure, which can go with the sliding control expansion, and then studying the SOSMC for this chosen system. The hierarchical structure of the sliding surface which is made using a linear combination between subsurfaces, according to the system structure, allows the only control input to affect subsystems in graded manner from the last one to the first one.* ***Results.*** *We have applied the constructed control law to a SIMO system for two cases with and without disturbances. Simulation results of the application have shown the effectiveness and the robustness of the designed controller*. References 30, figures 10.

Key words: **nonlinear system, single input multi outputs system, stability, robustness, sliding mode control.**

Вступ*. Більшість механічних систем нелінійні та складні, що полягає у значно нелінійних характеристиках або в динаміці, яка стимулює розвиток або зміну процесу за допомогою прикладеної сили у збудженому середовищі. Системи з одним входом та кількома виходами (SIMO), які структуровані у підсистеми, розглядаються як складні системи. Завдання управління їх ступенями свободи складніше, і воно складно досяжне через те, що нелінійні закони не застосовуються безпосередньо до цих систем, що вимагає характеризувати їх певним чином.* ***Проблема****. Управління ковзним режимом першого порядку (FOSMC) вже застосовувалося в кількох попередніх роботах до цього типу систем, і завдяки своїй надійності дане управління показало хороші результати з точки зору стабілізації та відстеження, але явище вібрації залишається великою проблемою, яка впливає на структуру управління та приводи.* ***Мета****. Для вирішення проблеми вібрації, що виникає при застосуванні FOSMC до категорії підсистем другого порядку, розроблено керування ковзним режимом другого порядку (SOSMC).* ***Методи****. Ця робота складається з розробки відповідної структури системи другого порядку, яка може йти з розширенням ковзного керування, а потім вивчення SOSMC для цієї обраної системи. Ієрархічна структура ковзної поверхні, яка зроблена з використанням лінійної комбінації між підповерхнями, відповідно до структури системи, дозволяє єдиному вхідному сигналу управління впливати на підсистеми градуйованим чином від останньої до першої.* ***Результати****. Застосовано побудований закон управління до системи SIMO для двох випадків із збудженням та без нього. Результати моделювання показали ефективність та надійність розробленого контролера.* Бібл. 30, рис. 10.

Ключові слова: **нелінійна система, система з одним входом та кількома виходами, стійкість, надійність, керування ковзним режимом.**

Introduction. The control of single input multi outputs (SIMO) systems has been constantly evolving for several years. The complexity of these systems (nonlinearity, single input of control and decomposition), makes the task of designing and developing a control more difficult, and performed more slowly.

A structured system with subsystems is nonlinear system, which has a minimum number of control inputs compared to what it needs. This property limits the application of conventional and classical theories of control, which has been established for nonlinear systems. The use of the control with variable structure, such as the sliding mode control (SMC), it has been adopted and applied to control SIMO systems, using their new structure, but unfortunately this control has the drawback of chattering.

Mainly, applications in robotics, automotive and automation are essential sources that motivate the analysis and control of this category of systems. Generally, researchers rely on benchmarks set up in laboratories, which are the subject of in-depth studies and a source of knowledge that makes it possible to develop more and more control techniques. For this raison this category of subsystems is of great importance.

Among the most effectiveness robust control, we find the SMC, this later has been widely applied for different type of systems linear, nonlinear, complex, uncertain systems, as in [1–5], it also has been applied for power converter as in [6, 7] and for photovoltaic systems as in [8]. Many works based on SMC has been developed for SIMO systems. A stable sliding mode controller has been designed in [9] for a class of second-order mechanical systems, an SMC of double-pendulum crane systems has been designed in [10]. More recently, sliding mode controller has been developed, as an effective strategy against uncertainties, in such important applications as self-balancing robots, mobile robots [11, 12] and submarines as in [13]. Using incremental SMC system method, in [14] was proposed a robust controller for a class of mechanical systems for the trajectory tracking. An adaptive multiple-surface sliding controller based on function approximation techniques for a nonlinear system with disturbances and mismatched uncertainties, has been proposed in [15].

An approach to design an SMC for a specific structured mechanical system in cascade form has been presented in [9]. In this approach, the system has been decoupled using a systematic approach to transform a class of mechanical systems into a subsystems form. In this work, we have adopted this approach to develop our controller. SMC achieves robust control by adding a discontinuous control signal across the sliding surface, satisfying the sliding condition. Nevertheless, this type of control has an essential disadvantage, which is the chattering phenomenon caused by the discontinuous control action. To treat these difficulties, several modifications to the original SMC law have been proposed, the most popular being the boundary layer approach [16]. The chattering phenomenon can have a detrimental effect on the actuators and manifests itself on the controlled quantities. This difficulty can be solved using the second order sliding mode control (SOSMC), several works have adopted this strategy of control as in [17, 18]. This technique consists of moving the discontinuity of the control law on the higher order derivatives of the sliding variable [19]. The conventional SMC technique implies that the control input appears after the first differentiation of the sliding manifold, in other words, the relative degree of the sliding manifold is equal to one. For nonlinear systems where the relative degree is greater than one, higher-order sliding mode methods have been developed, which have attracted considerable research interest in the last three decades [20]. SOSMC controller is a special case of higher order SMC which preserve the desirable properties, particularly invariance and order reduction but they achieve better accuracy and guarantee finite-time stabilization of relative degree two systems [21]. A number of different algorithms based on high order SMC, have been developed to achieve finite-time stability in a variety of system, but twisting (TA) and super-twisting algorithms (STA) are two of the best-known SOSMC methods [22].

To resolve the problem of chattering, encountered in SMC while applying it on SIMO systems, we have proposed to use the SOSMC, where we have used STA taking into account the sliding surfaces combination of subsystems.

Model development of the second order mechanical system. Mechanical systems are nonlinear, and have specific properties, which make the control more difficult, these properties come from several reasons, either the dynamics are not completely actuated which belong to SIMO systems (by conception in order to reduce the cost and the weight, and maybe for security reason when one of the controller fails), or the system is non affine in control. The variety and the complexity of those systems lead to classify them in several classes and study them case by case. In this work we focus on second order mechanical systems, which have the following Lagrangian [23, 24]:

$$L(q,\dot{q}) = K - V = \frac{1}{2}\dot{q}^T H(q)\dot{q} - V(q), \tag{1}$$

where $V(q)$, $K(q)$ are respectively the potential and kinetic energies; $q = (q_1, q_2)^T$ is the configuration vector; and $H = \begin{pmatrix} h_{11}(q_2) & h_{12}(q_2) \\ h_{21}(q_2) & h_{22}(q_2) \end{pmatrix}$ – is the inertia matrix.

From some mathematical development, using Euler-Lagrange equation, we can obtain the following matrix representation:

$$\begin{pmatrix} h_{11}(q_2) & h_{12}(q_2) \\ h_{21}(q_2) & h_{22}(q_2) \end{pmatrix}\begin{pmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{pmatrix} + \begin{pmatrix} G_1(q,\dot{q}) \\ G_2(q,\dot{q}) \end{pmatrix} = \begin{pmatrix} U \\ 0 \end{pmatrix}, \tag{2}$$

where $G_i(i = 1, 2)$ is the vector which represents centrifugal, Coriolis and gravity term, where:

$$G_1(q,\dot{q}) = \frac{dh_{11}(q_2)}{dq_2}\dot{q}_2\dot{q}_1 + \frac{dh_{12}(q_2)}{dq_2}\dot{q}_2^2 + b_1(q); \tag{3}$$

$$G_2(q,\dot{q}) = \frac{dh_{21}(q_2)}{dq_2}\dot{q}_1\dot{q}_2 + \frac{dh_{22}(q_2)}{dq_2}\dot{q}_2^2 + b_2(q), \tag{4}$$

where $b_1(q) = \frac{\partial V(q)}{\partial q_1}$ and $b_2(q) = \frac{\partial V(q)}{\partial q_2}$.

Thus, the system can be presented as the following state representation [19]:

$$\begin{cases} \dot{x}_1 = x_2; \\ \dot{x}_2 = f_1(x) + g_1(x)U + d(t); \\ \dot{x}_3 = x_4; \\ \dot{x}_4 = f_2(x) + g_2(x)U + d(t), \end{cases} \tag{5}$$

where $d(t)$ is the vector of extern disturbances; $f_1(x)$, $g_1(x)$, $f_2(x)$, $g_2(x)$ are the nonlinear functions.

We suppose that system in (5) is bounded input bounded output and all state variables signals are measurable.

First order sliding mode control procedure (FOSMC). SMC strategy is a very powerful nonlinear tool that has been widely employed by researchers [25, 26]. It has been also applied for nonlinear and complex mechanical systems.

In this work, we will apply this controller to the mechanical system presented in (5), the objective is to construct a control law which simultaneously leads errors e_1 and e_2 converge to zero, such that: $e_1 = x_1 - x_{1d}$, $e_3 = x_3 - x_{3d}$, x_{1d}, x_{3d} are desired values [9, 17].

The first sliding surface is chosen as:

$$s_1 = \sigma_1 e_1 + e_2 . \tag{6}$$

The second sliding surface is chosen as:

$$s_2 = \sigma_2 e_3 + s_1 . \tag{7}$$

The third and the last sliding surface is given by:

$$s_3 = \sigma_3 e_4 + s_2 . \tag{8}$$

Lyapunov functions $V_1 - V_3$ are defined as:

$$V_1 = \frac{1}{2}s_1^2 = \frac{1}{2}\sigma_1^2 e_1^2 + \sigma_1 e_1 e_2 + \frac{1}{2}e_2^2 , \tag{9}$$

for V_1 to be greater than 0, it must be $\sigma_1 e_1 e_2 > 0$.

$$V_2 = \frac{1}{2}s_2^2 = \frac{1}{2}\sigma_2^2 e_3^2 + \sigma_2 e_3 s_1 + \frac{1}{2}s_1^2 , \tag{10}$$

for V_2 to be greater than 0, it must be $\sigma_2 e_3 s_1 > 0$, so we have:

$$\frac{1}{2}s_1^2 < \frac{1}{2}s_2^2 \Rightarrow 0 \le V_1 \le V_2 ;$$

$$V_3 = \frac{1}{2}s_3^2 = \frac{1}{2}\sigma_3^2 e_4^2 + \sigma_3 e_4 s_2 + \frac{1}{2}s_2^2 , \tag{11}$$

for V_2 to be greater than 0, it must be $\sigma_3 e_4 s_2 > 0$, so:

$$\frac{1}{2}s_2^2 < \frac{1}{2}s_3^2 \Rightarrow 0 \le V_1 \le V_2 \le V_3 .$$

where σ_i, $i = \{1, 2, 3\}$ are the positive constants chosen such that: $\sigma_1 e_1 e_2 > 0$, $\sigma_2 e_3 s_1 > 0$, $\sigma_3 e_4 s_2 > 0$.

From the derivative of (11) we can get the control law of the whole system as follows:

$$\begin{aligned} U = U_{eq} + U_{sw} - \\ - \frac{\sigma_1 x_2 + \sigma_2 x_4 + \sigma_3 f_2 + f_1 - \sigma_1 \dot{x}_{1d} - \ddot{x}_{1d}}{\sigma_3 g_2 + g_1} + \\ + \frac{\sigma_2 \dot{x}_{3d} + \sigma_3 \ddot{x}_{3d} - k\,\mathrm{sign}(s_3)}{\sigma_3 g_2 + g_1}, \end{aligned} \tag{12}$$

where U_{eq} is the equivalent control; U_{sw} is the switching control; k is a positive constant.

Stability analysis for the FOSMC procedure. The Lyapunov expression is given by (11), we calculate its derivative as follows:

$$\dot{V}_3 = s_3 \dot{s}_3 = s_3\left(\sigma_3 \dot{e}_4 + \dot{s}_2\right); \tag{13}$$

$$\begin{aligned} \dot{V}_3 = s_3\left(\sigma_3 f_2 + \sigma_3 b_2 U + \sigma_2 x_4 + \sigma_1 x_2 + f_1 + b_1 U\right) - \\ - \sigma_2 \dot{x}_{3d} - \sigma_1 \dot{x}_{1d} - \ddot{x}_{1d} - \sigma_3 \ddot{x}_{1d} + \left(\sigma_3 + 1\right) d. \end{aligned} \tag{14}$$

Substituting the control law (12) in (14), we can get:

$$\dot{V}_3 = -k \operatorname{sign}\left(s_3\right). \tag{15}$$

So:

$$\dot{V}_3 \leq 0 . \tag{16}$$

From (16), we can conclude that the system is stable.

SOSMC procedure. A basic approach to avoid chattering problem is to augment the controlled system dynamics, by adding integrators at the input side, so as to obtain a higher-order system in which the actual control signal and its derivatives explicitly appear. If the discontinuous signal coincides with the highest derivative of the actual plant control, the latter results are continuous with a smoothness degree depending on the considered derivative order. This procedure refers to higher order SMC, as mentioned in [27].

Among the most algorithms which are used in SOSMC we find the TA and the STA. In this work we have chosen to use the STA, because of its simplicity and durability, and in this algorithm the convergence of state variables is faster and more precise, than other techniques. This method has been applied in several fields [28]. In the STA, the system trajectory rotates around the phase plan origin, approaching it in typical way (Fig. 1).

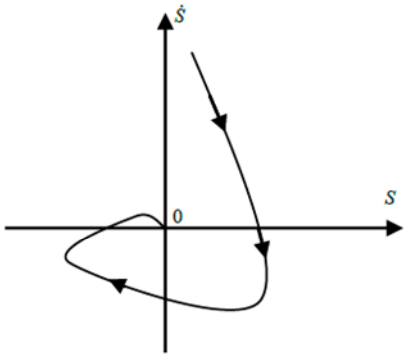

Fig. 1. Super twisting controller trajectory in the phase plane

The control objective is to establish a second order sliding regime with respect to s_3, such as: $s_3 = \dot{s}_3 = 0$. The continuous control law is composed of two terms, the first one is defined by a continuous function of the sliding variable and the second is defined by its discontinuous time derivative.

Since our system is of relative degree equal to 1 with respect to S, which means $\frac{\partial s}{\partial U} \neq 0$, then we have:

$$\dot{s} = \alpha(x,t) + \beta(x,t) U , \tag{18}$$

where α and β are the bounded functions:

$$\alpha(x,t) = f_1 + \sigma_1 \dot{e}_1 - \ddot{x}_{1d} + \sigma_3 f_2 + \sigma_2 \dot{e}_3 - \sigma_3 \ddot{x}_{3d} ; \tag{19}$$

$$\beta(x,t) = g + \sigma_3 g_2 . \tag{20}$$

To state a rigorous control problem, (reach ability of the sliding surface and boundedness of $\ddot{s}$), the following conditions are assumed [29, 30]:

1) Control values are part of the set $\upsilon = \{U : |U| \leq U_M\}$, where $U_M > 1$ is a real constant, moreover the solution of the system is well defined for all t, provided that $U(t)$ is continuous, and $\forall t, U(t) \in \upsilon$.

2) There exists $U_1(t) \in (0, 1)$, such that for any continuous function $U(t)$, $|U(t)| > U_1$, there is t_1, such that $s(t)U(t)>0$ for any $t > t_1$. However the control $U(t) = -U_M \operatorname{sign}(s(t_0))$, where t_0 is the initial value of time, allows to reach the variety $s = 0$ in finite time.

3) Let $\dot{s}(x,t,U)$, the derivative with respect to time of the sliding surface $s(x, t)$, there are positive constants $s_0, U_0 < 1, \Gamma_m; \Gamma_M$, such that if $|s(x,t)| < s_0$, so: $0 < \Gamma_m \leq \frac{\partial}{\partial U}\dot{s}(x,t,U) \leq \Gamma_M, \forall U \in \upsilon, x \in X$, and the inequality $|U| > U_0$ leads $sU > 0$.

4) There exists a positive constant ϕ such that in the region $|s(x,t)| < s_0$, the following inequality is satisfied:

$$\left| \frac{\partial}{\partial t}\dot{s}(x,t,U) + \frac{\partial}{\partial x}\dot{s}(x,t,U)\dot{x} \right| \leq \phi .$$

The control law of our system is given by:

$$U = U_{eq} + U_{st} , \tag{21}$$

such that:

$$\begin{aligned} U_{eq} = & \frac{-\left(\sigma_1 x_2 + \sigma_2 x_4 + \sigma_3 f_2 + f_1 - \sigma_1 \dot{x}_{1d}\right)}{\sigma_3 g_2 + g_1} - \\ & - \frac{\left(\sigma_3 \ddot{x}_{3d} - \ddot{x}_{1d} + \sigma_2 \dot{x}_{3d}\right)}{\sigma_3 g_2 + g_1}; \end{aligned} \tag{22}$$

$$U_{st} = -c_1 |s_3|^{\rho} \operatorname{sign}(s_3) - c_2 s_3 + \omega , \tag{23}$$

and

$$\dot{\omega} = -c_3 \operatorname{sign}(\omega) - \varepsilon s_3 , \tag{24}$$

where U_{eq} is the equivalent control; U_{st} is the super twisting control; $c_1 - c_3$ are the positive constants.

Stability analysis for STA. The Lyapunov function candidate is given by:

$$V = \frac{1}{2} s_3^2 + \frac{1}{2\varepsilon}\omega^2 ; \tag{25}$$

$$\dot{V} = s_3 \dot{s}_3 + \frac{1}{\varepsilon}\omega\dot{\omega} ; \tag{26}$$

$$\begin{aligned} \dot{V} = s_3\Big(-c_1 |s_3|^{\rho} \operatorname{sign}(s_3) - c_2 s_3 + \omega\Big) + \\ + \frac{1}{\varepsilon}\omega\left(-c_3 \operatorname{sign}(\omega) - \varepsilon s_3\right); \end{aligned} \tag{27}$$

$$\dot{V} = -c_1 |s_3|^{\rho+1} - c_2 s_3^2 - \frac{c_3}{\varepsilon}|\omega| , \tag{28}$$

such that $-1 < \rho < 0.5$ and $\varepsilon > 0$, therefore $\dot{V} \leq 0$, which guarantees the stability of the system.

Simulation results. The studied controller is applied to a cart-pendulum system as presented in Fig. 2. The objective of the control is the stabilization of this system in its equilibrium points $(x, \theta) = (x, 0)$, which are the linear position of the cart and the upright position of the pendulum. The dynamical model of this system is given by (5) [19], where:

$$f_1(x)=\frac{-\sin\theta\left(mgl\cos\theta-ml^2\dot{\theta}^2\right)}{l\left(M+m\sin^2\theta\right)};$$

$$f_2(x)=\frac{\left((M+m)g-mgl\cos\theta\dot{\theta}^2\right)\sin\theta}{l\left(M+m\sin^2\theta\right)};$$

$$g_1(x)=\frac{l}{l\left(M+m\sin^2\theta\right)};$$

$$g_2(x)=\frac{-\cos\theta}{l\left(M+m\sin^2\theta\right)},$$

where M, m are respectively the masses of the cart and the pendulum; l is the length of the pendulum; U is the controller signal; y is the output vector.

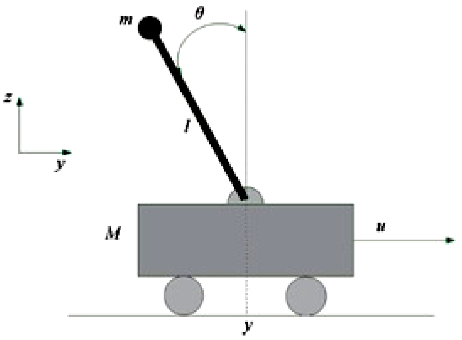

Fig. 2. The cart-pendulum system

Case 1 (without disturbances). Parameters of the system are: l = 0.25 m, M = 2 kg, m = 0.1 kg. The initial conditions of the system are:

$$(x,\dot{x})=(0.2,0),\ (\theta,\dot{\theta})=\left(-\frac{\pi}{6},0\right),$$

and the desired position is chosen as:

$$(x_d,\dot{x}_d)=(0,0)=(\theta_d,\dot{\theta}_d)=(0,0).$$

From the development, we refer x by x_1, and θ by x_3. From Fig. 3, 4 we can see that the system could follow the reference trajectory when using the two controllers – FOSMC and SOSMC. We can also see in Fig. 5 that the sliding surface is stable and converge to 0. Figure 6 shows the control signal; this latter is very smooth when using SOSMC, which presents the advantage of the second controller in reducing or even eliminating the chattering phenomenon.

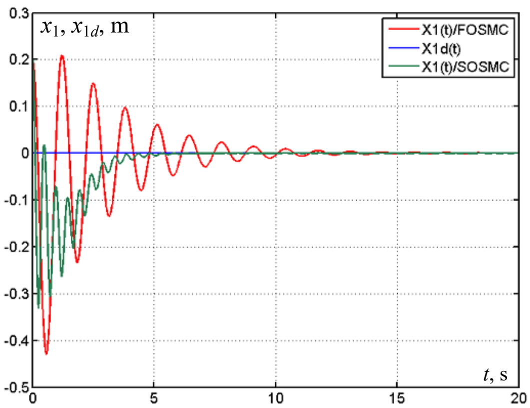

Fig. 3. The output $x_1(t)$ for case 1

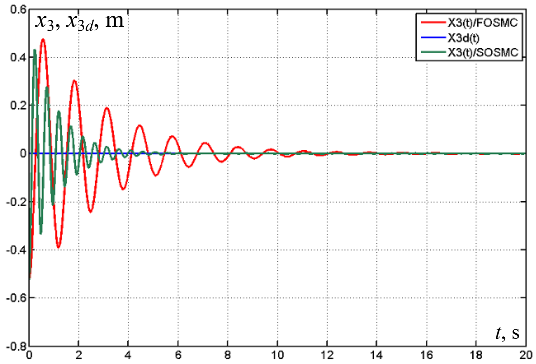

Fig. 4. The output $x_3(t)$ for case 1

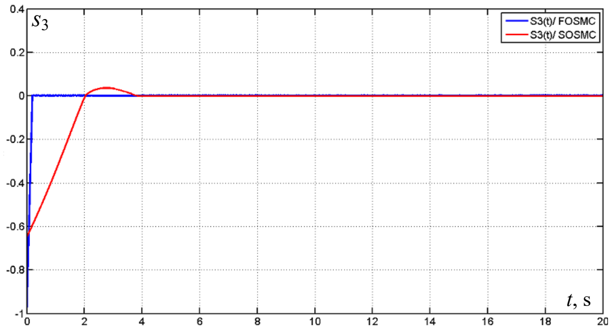

Fig. 5. The sliding surface $s_3(t)$ for case 1

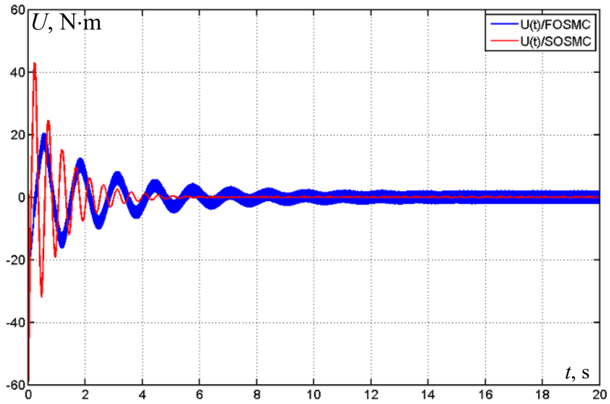

Fig. 6. The control signal $U(t)$ for case 1

Case 2 (with disturbances). In this section, we assume that the system undergoes structured external perturbation, and parameter uncertainties. The parameter uncertainty of the pendulum's mass is Δm = ±0.1 kg, and the perturbation is $d(t)$ = 0.05·randn(1, tf), where $d(t)$ is a Gaussian white noise function of 1 row and tf columns.

The initial conditions of the system are:

$$(x,\dot{x})=(0.1,0),\ (\theta,\dot{\theta})=\left(\frac{\pi}{8},0\right),$$

and the desired position is chosen as:

$$(x_d,\dot{x}_d)=(2,0)=(\theta_d,\dot{\theta}_d)=(0,0).$$

Figure 7 shows the sliding surface, so we can see that it is stable. Figure 8 shows the control signal, it is clear that using SOSMC this signal is smooth than using FOSMC. We see that despite the existence of disturbances and uncertainties, the system was able to follow its reference, but the response of the system is slower when using SOSMC, which is shown in Fig. 9, 10.

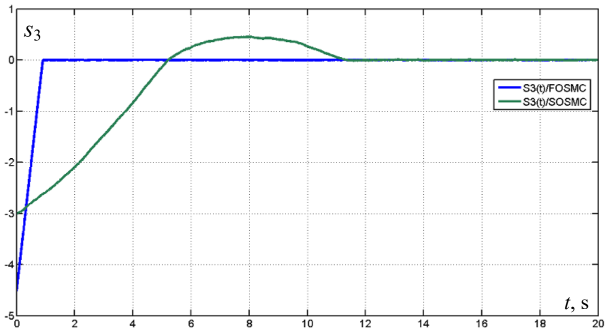

Fig. 7. The sliding surface $s_3(t)$ for case 2

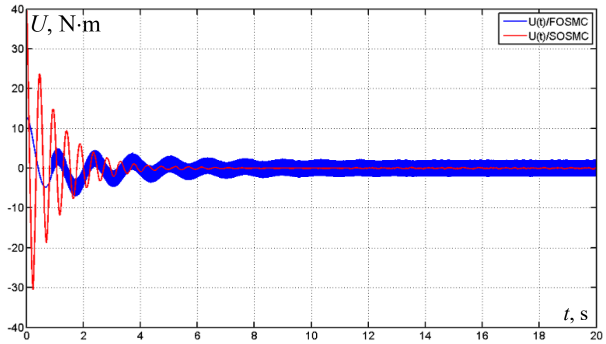

Fig. 8. The control signal $U(t)$ for case 2

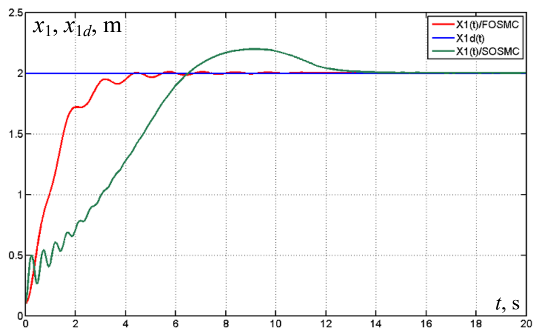

Fig. 9. The output $x_1(t)$ for case 2

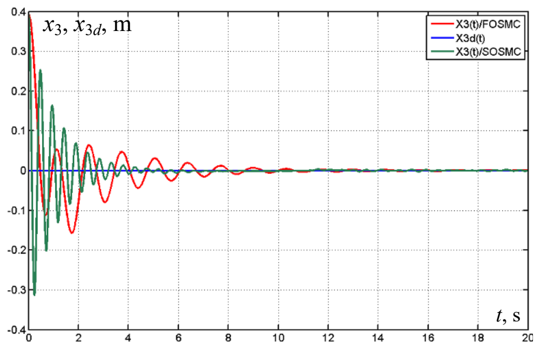

Fig. 10. The output $x_3(t)$ for case 2

Conclusions. In this paper, a SOSMC has been given to stabilize a category of second order SIMO systems which are structured into subsystems.

SOSMC is an extension of the first order SMC, and can preserve the robustness property of this latter. In this work, we had presented the mathematical development of the two controllers, and then we applied them to the system.

The proposed SOSMC controller is effective, it guarantees robustness with good performances, namely the stability and the good precision, which is shown in simulation results, and resolve the problem of chattering encountered in FOSMC that affects the actuators, by shifting the control law discontinuity, to the higher order derivatives of the sliding variable.

As perspectives, we can propose to enhance the performances of the system (such as the response time and the precision) by developing an integral SOSMC controller for this category of systems. Also, it will be more significant, if we resolve the problem considering unstructured uncertainties and perturbations.

Conflict of interest. The authors declare that they have no conflicts of interest.

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