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Synergetic control of micro positioning stage piezoelectric actuator

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ABSTRACT

The work carried out in this article essentially relates to the application of a synergetic control to the piezoelectric positioning mechanism or piezoelectric actuator (PEA). A LuGre model has been followed, capturing the most physical phenomena, in order to be able to follow the most realistic and representative model possible. From this model, which is then identified by particle swarm optimization (PSO), we apply the synergetic control technique, which is a very efficient control method that allows demonstrating the good functioning of the stability of nonlinear system in closed loop. The simulation results have been compared to those obtained when using sliding mode to confer the best performance in terms of tracking error and minimization of oscillations.

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1. INTRODUCTION

Piezoelectric actuators for positioning of the stacks type are increasingly present in a very large number of industrial processes affecting manufacturing, microscopic [1]–[4], medicine [5], [6], robotics [7], [8], and defence [9]. In reality, these systems this characterize by their reduced size, and low energy cost, and the good dynamic performance of the actuators are appreciated [10]–[14] The brake on their use and their development is the fact that the nonlinear phenomena (hysteresis, creep, vibration, and thermal drift) [15]. Which characterize their functioning and the specific requirements of their control circuits make the control of these systems difficult [16]. Indeed, modelling and control are essential to achieve the objectives of high precision movement [17].

It is often very difficult to faithfully represent a mechanism and to know all the variables involved [18]. Consequently, the law of control, which will be associated with it, must be robust in order to overcome some nonlinearity or identification errors [19]. Control by sliding mode makes it possible to respond to this problem, this robustness will be determined at the performance level [20]. The Sliding mode control is a special case of variable structure control, very known for its insensitivity to variations in internal and external parameters, its stability, its simplicity and these very low response times [21]. The sliding mode has become interesting and attractive [22]. It is considered as the simplest approaches for the control of nonlinear systems having an imprecise model [23]. Indeed, the discontinuity of the input induces vibrations of high-frequencies undesirable in practice [24]. In addition, the sliding surface defined in the formalism reduces the order of the closed-loop system, which does not in some cases make it possible to impose a stabilization mode on the system [25]. In order to remedy these drawbacks, a new control algorithm is proposed, called synergetic control, which has been recently studied to further improve control performance. In recent years, considerable efforts have been made to improve the dynamic stability of positioning systems, which are very complex, non-linear [26]. Two control approaches are used to stabilize a PEA system, such as variable structure control (CSV) and synergetic control.

2. METHOD

2.1. Modeling and identification of LuGre parameters

The experimental configuration used for the identification of the LuGre model on the piezo actuator positioning mechanism is validated in [27].

2.2. Nonlinear systems control

Consider the nonlinear systems described by (1):

$$\dot{x} = A.x + B.u$$
$$y = C.x \tag{1}$$

$x \in R^n, x = (x_1, x_2, \ldots, x_n)$ is the state vector of dimension n $A \in R^n$ and $B \in R^{m.n}$, $u \in R^m$, $u = (u_1, u_2, \ldots, u_m)$, is the state vector control of dimension m. The procedure for conception the system control (1) is carried out in two stages.

2.3. Designation of a manifold according to the desired performance

Synthesize a surface S (x, t) such that all the trajectories of the system obey a behavior desire for pursuit, regulation and stability; the switching surface associated with the control system with variable structure, is called hyperplane of the surface function.

$$M = \{x: \sigma = S(x) = 0, S(x) \in R^m\} \text{ [28]} \tag{2}$$

Where $S(x)$ hyperplane of the surface function.

2.4. Designation of the controller using the relation $S(x).\dot{S}(x) \leq 0$, which directs the trajectories of the system towards the manifold

The variable structure control (CSV) is by nature a non-linear control. The main characteristic of systems with variable structure consists of a control law based on the switching of functions of state variables, used to create a variety or hyper sliding surface. The purpose of this control is to force the dynamics of the system to match that defined by the hyper surface equation. When the state is maintained on this hyper surface, the system is in a sliding regime. An equivalent control vector u_{eq} is defined as being the ideal sliding regime equations. We are interested in the computation of the equivalent control and subsequently in the computation of the attractive control of the system defined in (3).

$$u = u_{eq} + u_n \tag{3}$$

Where u_n is the switching control, u_{eq} is the equivalent control yielded from $\dot{S} = 0$. u_{eq} is defined by (4) and (5) [29].

$$u_{eq} = -(S(x).B(x))^{-1}S(x).A(x) \tag{4}$$

$$u_n = -\eta.(S(x).B(x))^{-1}\frac{S(x)}{|S(x)|} \tag{5}$$

The following variable structure sliding mode controller in (6).

$$u = -(S(x).B(x))^{-1}S(x).A(x) - \eta.(S(x).B(x))^{-1}\frac{S(x)}{|S(x)|} \tag{6}$$

2.5. Synergetic control

Synergetic control is fairly close to control by sliding mode in the direction where the system is forced to evolve according to a dynamic chosen by the designer. It differs from it in the fact that the synergetic control is always continuous and uses a macro-variable, which can be a function of two or more variables of state of the system [30].

$$\psi_s = \psi_s(x_1, x_2, \ldots, x_n) s = 1,2, \ldots m \tag{7}$$

ψ_s: represents the invariant manifolds
m: the number of invariant manifolds

Each manifold presents a new constraint on the system in its state space by reducing its order by one, and forcing it to converge to the desired state. Consequently, the command will force the system to operate on the intersection of the manifolds (ψ_s =0) [31]. The fixation of the dynamic evolution of macro-variables (7) towards manifolds (ψ_s =0) is given by the following functional in (8).

$$T.\psi + \psi + 0T \geq 0 \tag{8}$$

T : is a conception parameter defining the convergence speed toward the manifold
The expression of the manifold derivative is given by (9).

$$\begin{aligned} \dot{S} &= \frac{d\ \ S(x)}{d\ \ x}.\dot{x} \\ &= \frac{d\ \ S(x)}{d\ \ x}(A.x + B.) \end{aligned} \tag{9}$$

We replace (9) in (8) we obtain (10).

$$T.S(A.x + B\ u) + S = 0 \tag{10}$$

From (10), we deduce the control law (11).

$$u_n = -(T.SB)^{-1}(T\ SA. + S) \tag{11}$$

From (11), we can see that the control depends 0not only on the state variables of the system, but also on the macro-variable and on the control parameter T . In other words, the designer can choose the characteristics of the controller by choosing an appropriate macro-variable and a specific control parameter.

2.6. Application of the synergetic control to the PEA

The dynamic of the movement of PEA is [32].

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \frac{k_e u}{M} - \frac{1}{M}\left[\sigma_0 g(x_2)\frac{x_2}{|x_2|} + (D + \sigma_2)x_2 + \sigma_3 x_1 + F_l\right] \end{cases} \tag{12}$$

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = k_0.u - h(t) - k_1.x_2 - k_2 x_1 + F_l \end{cases} \tag{13}$$

With $k_0 = \frac{k_e}{M}$,$k_1 = \frac{D+\sigma_2}{k_e}$,$k_2 = \frac{\sigma_3}{k_e}$, and $h(t) = \frac{1}{k_e}\left[\sigma_0.g(x_2)\frac{x_2}{|x_2|} + F_L\right]$ $k_0, k_1, k_2, and\ h(t)$ are unknown and bounded parameters, just as$h(t)$ is unknown and bounded by k_3. The objective of synergetic control is to force the system to follow a reference signal. We want to maintain $\psi = 0$, i.e. The system is confined to it and that we are tending towards the origin of the plane of phase. The macro-variable is chosen as (13).

$$\begin{cases} \psi = k_4.e_1 + e_2\ \ k_4 \geq 0 \\ \dot{\psi} = k_4.\dot{e}_1 + \dot{e}_2 \end{cases} \tag{14}$$

The desired dynamic evolution of the macro-variables given by (8), and the (14) we get:

$$\begin{aligned} e_1 = x_{ref} - x, and \quad e_2 = \dot{e}_1 = \dot{x}_{ref} - x \quad &\Leftrightarrow \quad e_2 = x_{ref} - x \\ = x_{ref} - k_0.u + h(t) + k_1.x_2 + k_2 x_1 + F_l& \end{aligned} \tag{15}$$

Finally, replaces (8) in (15), the control law can be described as (16).

$$u_n = k_0(x_{ref} - k_0.u + h(t) + k_1.x_2 + k_2 x_1 + F_l + \frac{\psi}{T} + k_4 e_2) \tag{16}$$

The advantage of the synergetic control is that it is linear which drives the trajectory of the system towards the manifold $S(x) = 0$, once on the manifold; the dynamics of the system is a reduced order. The values of k_4, T, are adjusted to have the desired performances: the speed of the response without overshoot, the reduction of the amplitude of the oscillations and the reduction of the static error.

3. RESULTS AND DISCUSSION

To implement the proposed control system, the P.E.A model is representing the system dynamics. These parameters are identified using experimental data. a sinusoidal reference signal of frequency 1 Hz is applied, Figures 1 and 2, show the displacement and the tracking error of the synergetic control respectively, or the tracking error is approximately + -0.2-micron meter. Figure 3, show the performance of the synergetic control method on the P.E.A with a load (disturbance) of 10 N. the tracking displacement signal follows its reference without overstepping. The system dynamics is stable; the phase plan portrait given in Figure 4 shows a good improvement in the system behavior. The application of synergistic control to the PEA made it possible to highlight its simplicity of design and the superiority of the performances obtained, compared to those obtained with a sliding mode controller. The results show in Figure 5, that the design of the synergetic control to a fast dynamic response, good performance of displacement in pursuit and a strong capacity to overcome the stationary error of the system. Figure 6 represents this comparative study, and the trajectory tracking error tests show the validity of these methods for PEA control. At this level of error, the results of the synergistic command are better than those of t the control by sliding mode.

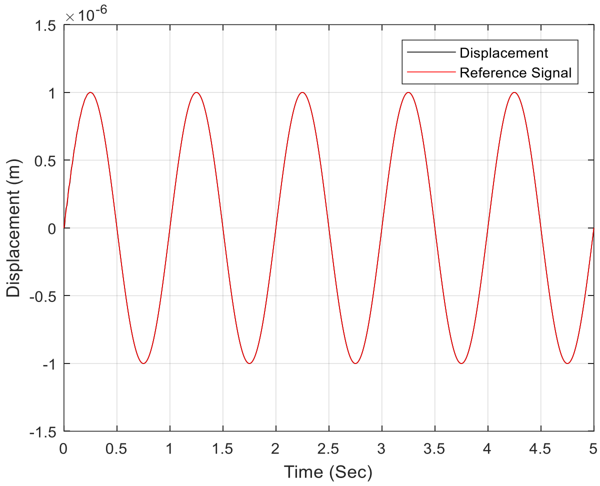

Figure 1. Simulation results of synergetic controller system for periodic sinusoidal control with conditions at 10 µm, 0.5 Hz: tracking response

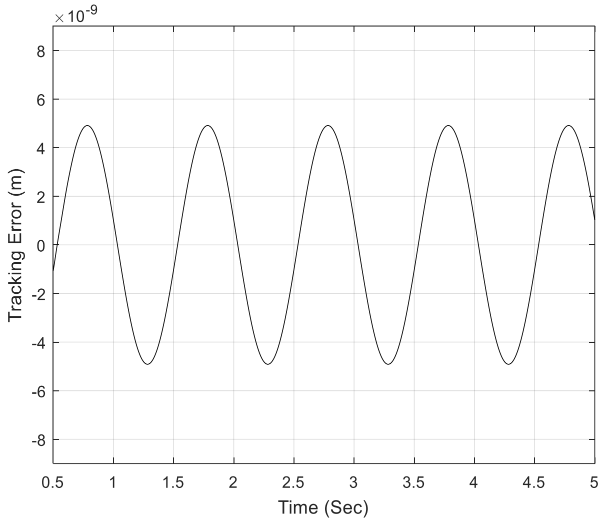

Figure 2. Simulation results of synergetic controller system for periodic sinusoidal control with conditions at 10 µm, 0.5 Hz: tracking error

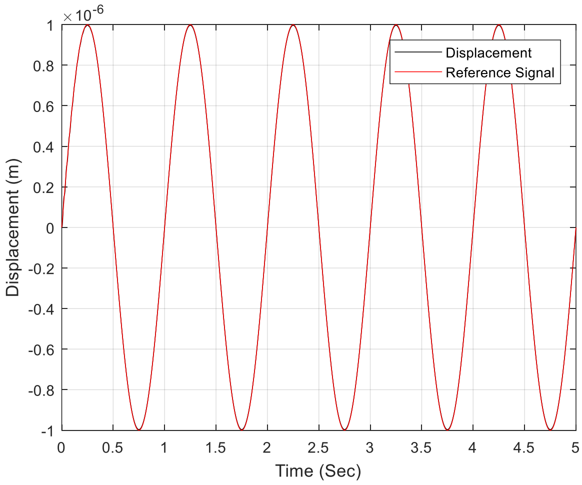

Figure 3. Simulation results of synergetic controller system for periodic sinusoidal control without external load of 10 N with conditions at 10µm, 0.5 Hz: tracking response

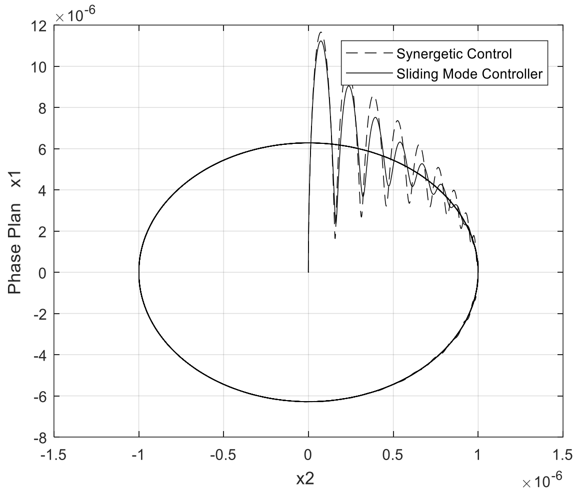

Figure 4. Phase plan

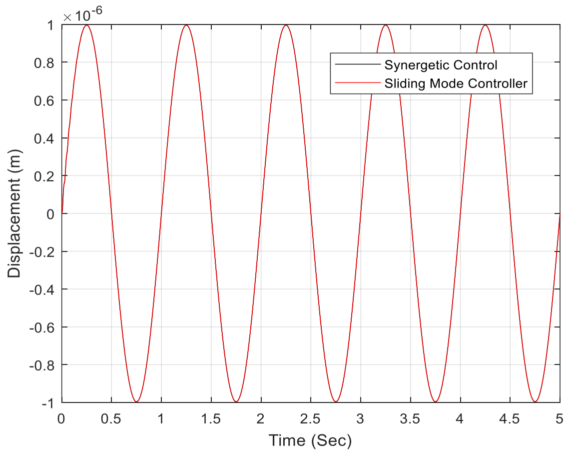

Figure 5. Simulation results of synergetic controller and sliding mode system for periodic sinusoidal control without external load of 10 N with conditions at 10 µm, 0.5 Hz: tracking response

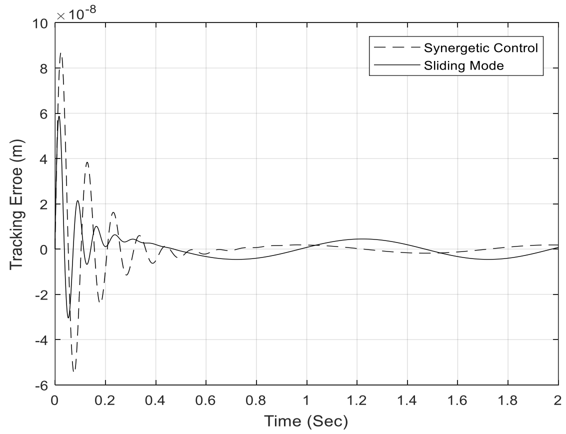

Figure 6. Simulation results of synergetic controller and sliding mode system for periodic sinusoidal control with conditions at 10 µm, 0.5 Hz: tracking error

4. CONCLUSION

In this article, we are interested in applying a synergetic control algorithm to the mechanism positioning piezoelectric P.E.A. This type of control has been sufficiently discussed compared to control by sliding mode. In order to develop this work, we first started by modelling the P.E.A by the LuGre model, to best meet the identification requirements. The model is based on the equation of movement, which takes into consideration (friction and stribeck effect). Then we studied the control by sliding mode and the synergetic control.

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