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SECOND ORDER SLIDING MODE CONTROLLERS OF MICROPOSITIONING STAGE PIEZOELECTRIC ACTUATOR WITH COLMAN-HODGDON MODEL PARAMETERS

AMOR OUNISSI[1], AZEDDINE KADDOURI[2], MOHAMMED SALAH AGGOUN[1], RACHID ABDESSEMED[1]

Keywords: **Colman-Hodgdon model, Identification particle swarm optimization (PSO) approach, Second order sliding mode controllers (SOSMC), Piezo-positioning mechanism.**

This paper presents the second order sliding mode controller (SOSMC) of a micro positioning stage piezoelectric model actuator (PEA), where the C-H model parameters are adopted to describe the hysteresis behavior and identified through particle swarm optimization. In this technique two control algorithms are developed. The first one is the so-called twisting algorithm (TA). The control appears explicitly in the second surface derivative, and in a discontinuous control action that ensures a sliding regime mode. The second one, the super twisting algorithms (STA) has been developed and analyzed for systems. The use of both algorithms gives a significant reduction in chattering as compared to the standard sliding mode control. It is shown that the STA case offers better performances than TA. Simulation results are presented to demonstrate the advantage of SOSMC over SMC.

1. INTRODUCTION

Dynamic modelling is an important step in the development and control of dynamic systems. In fact, the model allows the engineer to analyse the possibilities of the system and its behaviour under various conditions. Moreover, dynamic models are very popular in the design of piezo-actuated stage control for several purposes and are more widely used in modern precision because of displacement resolution, stiffness, frequency response, power density and efficient tracking systems, such as super resolution microscopy, semiconductor manufacturing, medical engineering, biotechnology, plant engineering, surface metrology, or in astronomy and diamond tuning machines [1–3]. However, their performances are still limited by the exhibit hysteresis behavior, which severely limits the system precision. The hysteresis phenomenon in piezo actuated stage actuators is the main non-linear form that makes the development of PEA actuator applications complex [4,5]. The model presented in [6] can be very useful in the calculation of hysteresis energy losses. In [7], the hysteresis model based on Jiles-Atherton theory was developed and validated. The parameters of the C-H model have been identified using the Artificial Intelligence Technique (AIT). The evolutionary algorithm of artificial efficiency was chosen for its simplicity, flexibility, efficiency, and the fact that it has already shown good performance in the treatment of complex optimization problems. The model developed in this paper is based on the position according to the applied voltage. We will develop a mathematical model to describe the dynamic movement of the mechanisms piezo actuated stage. The modeling and identification of the hysteresis nonlinearity in the PEAs can enhance the control performance. The C-H model is employed to describe the hysteresis phenomenon. This model, characterized by a set of six parameters, can be identified by particle swarm optimization (PSO). Due to the presence of structured uncertainties caused by model imprecision of link parameters and disturbances in control PEA, the sliding mode controller (SMC) theory has been widely used to control nonlinear dynamic systems, especially the Piezo-actuated stage. The SMC methods have been widely used in the industrial applications [8, 9]. However, the main disadvantage of the classical SMC is the chattering problem that adversely affects the performance of many dynamical systems. Chattering often results in poor system performances and actuator degradation with time. Several methods have been proposed to overcome the difficulties. In [10], authors propose to include the boundary layer; the sign function can be replaced in small areas of the surface by a saturation, sigmoid, hyperbolic and hysteresis functions. In [11], a standard technique consists in replacing the switching element by a high gain. In [12], the authors propose an adaptive proportional-integral (PI) based sliding mode control (APISMC) design for nano positioning of piezoelectric actuators. A Bouc-Wen model for hysteresis is employed. In [13,14], the placement of a asymptotic observer sliding mode is implemented to eliminate the chattering due to the discontinuity of the control law. In [15,16], authors propose the application of discrete time SMC. In [17], the authors design the ideal sliding mode algorithms for any order. However, the implementation of these algorithms may present some difficulties due to some singularities in the time derivatives of the sliding variable. In practice, it is impossible to change the control infinitely fast because of the time delay for control computations and physical limitations of switching devices. Another approach is to use a higher-order sliding mode concept introduced in [18, 19]. In [20], the authors consider a smooth dynamic system with an output function S of class S^{r-1} closed by static or dynamic discontinuous feedback. In [21], the authors propose a continuous finite time control scheme using a new form of terminal sliding mode (TSM), combined with a sliding mode disturbance observer (SMDO) applied for nano positioning piezoelectric actuator. Several higher order sliding mode controllers has been recently introduced in several fields such as in mechanics [22, 23], electrical machines [24], and robotics [25]. In this paper, second order sliding mode control algorithms have been

[1] LEB Research Laboratory, Department of Electrical Engineering University of Mustapha enboulaid, Batna 2, 05000, Algeria
E-mail: ounissi_omar@yahoo.fr, rachid.abdessemed @gmail.com, mohammedsalahaggoune@yahoo.com
[2] GRETER Research Group, Department of Electrical Engineering University of Moncton, Moncton, NB, Canada, E-mail: Azeddine.kaddouri@umoncton.ca

successfully used in practice for trajectory and position tracking such as the twisting algorithms [26, 27], and the super twisting algorithms [28]. In [29], uses the principle of higher order sliding mode observers (super twisting) to focus on the state observation of a serial multicell converter. The super twisting algorithm is designed to perform a second order sliding mode control using only the surface information *S*. The convergence of this algorithm is governed by rotations around the origin of the phase plane (also called twisting). The efficiency of the presented methodologies will be demonstrated by simulation studies.

2. MODELING AND IDENTIFICATION OF THE PIEZOELECTRIC ACTUATOR (PEA)

In the C-H model, Coleman and Hodgdon consider rate-independent hysteresis in soft ferromagnetic materials [30]. A first-order nonlinear differential equation presents the relationship between magnetic flux *B* and magnetic field *H* [31]. Magnetic flux *B* is replaced by position *x* and the magnetic field by the input voltage *U*. The dynamic model of the entire micro positioning system with Colman-Hodgdon hysteresis model includes a symmetric and asymmetrical hysteresis and can be established as follows:

$$x(U) = \begin{cases} c_{16} + (c_{11} - c_{12}\mathrm{e}^{-c_{13VR}})\,U - \\ c_{14}(1 - \dfrac{2e^{-c_{15U}}}{e^{-c_{15VM}} + e^{-c_{15Vm}}})\ \mathrm{for}\,\mathrm{d}U \geq 0 \\ c_{16} + (c_{11} - c_{12}\mathrm{e}^{-c_{13VR}})\,U + \\ c_{14}(1 - \dfrac{2e^{c15U}}{e^{c_{15VM}} + e^{c_{15Vm}}})\ \text{for } \mathrm{d}U < 0 \end{cases} \quad (1)$$

The six parameters (c_{11}, c_{12}, c_{13}, c_{14}, c_{15} and c_{16}) are constants to be determined, V_{M} and V_{m} are the maximum and minimum input voltages. The voltage range is $V_{\mathrm{R}} = V_{\mathrm{M}} - V_{\mathrm{m}}$. The feasibility and effectiveness of these experimental research studies on a piezoelectric stage are provided to demonstrate the performance of the modeling and identification strategy when applying a sinusoidal input signal. Based on the relation between the input voltage and the output displacement, the parameters of the system are identified by applying the PSO. The whole processes are carried out by the MATLAB identification Toolbox from Math Works. The six parameters (c_{11}, c_{12}, c_{13}, c_{14}, c_{15} and c_{16}) of the system model with C-H hysteresis can be identified simultaneously. The parameters values are shown in Table 1.

Table 1

Identification parameters for the C-H model

Parameters	Value	Unit
c_{11}	2.0488 e–05	$(\mu\mathrm{mV})^{-1}$
c_{12}	0.02021	$(\mu\mathrm{mV})^{-1}$
c_{13}	81.7942	V^{-1}
c_{14}	0.002728	$(\mu\mathrm{mV})^{-1}$
c_{15}	–0.22371	V^{-1}
c_{16}	0.00097159	$(\mu\mathrm{mV})^{-1}$

3. EXPERIMENTAL SETUP

To verify the feasibility of the C-H model used for PEA modeling and the effectiveness of the identification method, the used experimental setup of the system is driven by the controller (model 610. SOX Physik Instrument Company) to provide a voltage between 0 –100 V to control the piezoelectric actuator (P-611.1S model of the PI Company). The piezoelectric actuator is equipped with a SGS sensor. Its signal is processed by a module (E-801.10 model of the PI company), and the capture card is used to acquire data. From the obtained parameters, the experimental results of the hysteresis response and the simulated results for a frequency of 1 Hz illustrated on Fig. 2. Figure 2 shows the experimental and simulation result when a 3.5 V sinusoidal input voltage of frequency of 1 Hz is applied to the CH model using the parameters of Table 1. The obtained plot shows a concordance between the experimental data and the simulation

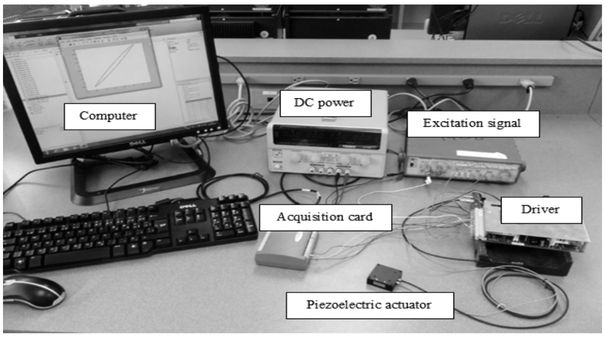

Fig. 1 – Experimental setup [33].

results of the identified CH model. The displacement of the piezoelectric actuator falls in the range of 115 to 192.2 μm.

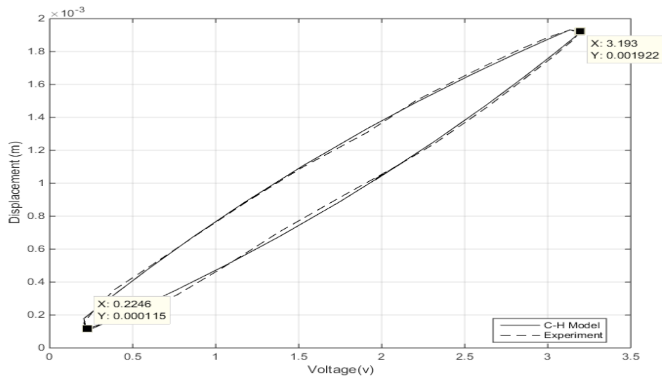

Fig. 2 – Experimental and PSO-based C-H model hysteresis with an input voltage of 1 Hz.

4. SLIDING MODE CONTROLLER

The sliding mode is a special mode of the system variable structure. It is characterized by a choice of a function and a logic switching. This configuration can switch at any time between the two states to combine the useful properties of each of these structures. The output tracking problems are addressed as follows.

$$\mathrm{d}x = f(x) + \mathrm{g}(x)U\,. \quad (2)$$

When the variable structure control system operates in sliding mode, the switching function satisfies the conditions cited by [34]. The first step in the sliding mode control design is to define a sliding surface, which renders the dynamic system stable when the system lies on the sliding surface, *i.e.* $S = 0$. The aim is to drive the states of the system into the set S defined by

$$S = \mu_1 e + \mathrm{d}e + \mu_2 \int_0^t e(t)\,\mathrm{d}t \,, \tag{3}$$

where the tracking error is identified as

$$e = x_{\mathrm{ref}} - x \,. \tag{4}$$

The parameters μ_1 and μ_2 are positive and determine the dynamics of the sliding surface, and x_{ref} represents the reference trajectory. Therefore, in the sliding surface, $S = 0$, $e = 0$, $\mathrm{d}e = 0$ and are an asymptotically stable equilibrium. The sliding mode control is expressed by

$$U = U_{\mathrm{SW}} + U_{\mathrm{eq}} \,, \tag{5}$$

where U_{SW} is the switching control, U_{eq} is the equivalent control yielded from $\mathrm{d}\,\mathrm{S} = 0$.The switching control is expressed by :

$$U_{\mathrm{SW}} = \varepsilon.\mathrm{sign}\ S(t) \,, \tag{6}$$

where ε is a positive constant.

The control objective is to make the sliding dynamics in (1) stable despite the bounded uncertainty and external disturbance. To evaluate the stability of the closed loop, we can consider Lyapunov function:

$$v(x) = \frac{1}{2} S^2(x) \,. \tag{7}$$

Time differentiation of equation (18), gives

$$\mathrm{d}v = S.\,\mathrm{d}S = -\varepsilon\left|\mathrm{d}S\right| - k_1 S^2 \le 0 \,. \tag{8}$$

Therefore, the system is stable, and the convergence of the sliding mode is guaranteed.

4.1. PEA SLIDING MODE CONTROL AND SIMULATION RESULTS

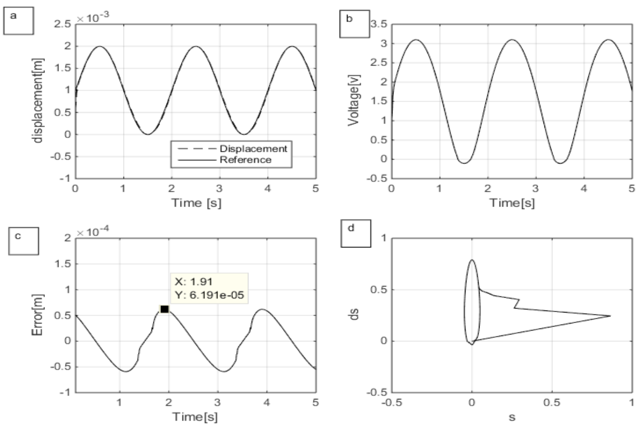

Fig. 4 –Simulation results of sliding mode controller system for periodic sinusoidal command with conditions at 10 μm, 0.5 Hz: (a) tracking response; (b) control effort; c) tracking error d) the phase plane (S.dS).

Once the system has been modelled and identified as accurately as possible, we simulated the PEA for a sinusoidal reference of amplitude of 10 μm with a frequency of 0.5 Hz. The curves (a, b, c, d) of Fig. 4 represent the tracking displacement, the tracking error, the control voltage, and the phase plane ($S.\,\mathrm{d}\,\mathrm{S}$) respectively.

The results show the efficiency and performance of the sliding mode control and a good reference tracking. This pursuit is carried out by minimizing the tracking error on the one hand, and the trajectory in the phase plane sliding in the vicinity of the sliding surface to the origin while ensuring the stability of the system on the other hand.

5. SECOND ORDER SLIDING MODE CONTROLLER

The higher order sliding modes have been introduced to overcome the problem of chattering while keeping the convergence properties in finite time and robustness of control by conventional sliding mode. The objective is to establish a sliding regime of order two with respect to S_2 by imposing on the state trajectories $f(x,t)$ and $g(x,t)$ to evolve on the set S_2 during a finite time. $S_2 = \{x : S = \mathrm{d}S = 0\}$ [35].

In this paper, we will describe the different steps for the implementation of the control based on the twisting and super twisting algorithm of the nonlinear system of order two. The control will be applied to constrain the output of the system y to follow a reference trajectory and that the tracking error converges to zero in the presence of uncertainty and disturbances. To increase accuracy, decrease convergence time and simplify calculations, the canonical form of the nonlinear system presented by equation (1) can be written in the following form.

$$\begin{cases} \mathrm{d}x_1 = x_2 \\ \mathrm{d}x_2 = f(x) + g(x)U \,. \\ y = x_1 \end{cases} \tag{9}$$

5.1. TWISTING ALGORITHM CONTROLLERS

This is done by a command acting on the second derivative of the sliding variable, which can generally be written as:

$$\begin{aligned} \mathrm{d}S^2(\mathrm{x}) &= \mathrm{d}f(\mathrm{x}) + \mathrm{d}\ g(x)U + g(x)\ \mathrm{d}U \\ &\quad + \mu_1 \mathrm{d}e + \mathrm{d}e^2 + \mu_2 e \\ &= f_1(x,t) + g_1(x,t)U. \end{aligned} \tag{10}$$

$\mathrm{d}U$ becomes the control which is of order two and U is considered as an additional state of the system. $f_1(x,t)$ and $g_1(x,t)$ are nonlinear functions not well known but limited. To achieve second-order sliding mode algorithms, it is necessary to verify the following hypothesis:

- The uncertain functions $f_1(x,t)$, $g_1(x,t)$ are bounded;
- There are four following positive constants S_0, C_0, k_{M} and k_{m} such as in a neighbourhood $\left|f_1(x,t)\right| < S_0$, the following inequalities are verified: $\left|S(x,t)\right| < \mathrm{S}_0$ and

$$0 < k_{\mathrm{m}} \le g_1(x,t) \le k_{\mathrm{M}} \,. \tag{11}$$

The hypothesis enunciated above implies that the second derivative of the switching function is uniformly bounded. By respecting the already defined conditions, we can write that any solution relating to the equation (18) satisfies the following differential inclusion [36]

$$\mathrm{d}^{\,2}S \in \left[-C_0\,,\,C_0\right] + \left[k_{\mathrm{m}}, k_{\mathrm{M}}\right]U \,. \tag{12}$$

The control law using the twisting algorithm is given by [22]

$$U = -r_1 \mathrm{sign}(S(x) - r_2 \mathrm{sign}(\mathrm{d}\ S(x)) \,, \tag{13}$$

with $r_2 > r_1 > 0$.

Under the conditions described by inequalities (22), the trajectory of the differential system (9) converges at the equilibrium point $S = \mathrm{d}S = 0$ in a finite time under the following conditions:

$$(r_1 + r_2)k_m - C_0 > (r_1 - r_2).k_M + C_0 \qquad (14)$$
$$(r_1 + r_2)k_M > C_0).$$

The homogeneity of this control law is obvious, because its expression does not depend on the value of S or $\mathrm{d}\,S$, but only on their sign which does not vary by multiplying them by $k > 0$.

The Lyapunov function can be chosen as:

$$v_1 = \frac{1}{2}\alpha_1 S^2 + \frac{1}{2}\mathrm{d}\,S^2 . \qquad (15)$$

Differentiating (15) gives

$$\begin{aligned} \mathrm{d}v_1 &= \alpha_1 S\,\mathrm{d}S + S\,\mathrm{d}S^2 \\ &= \alpha_1 S\,\mathrm{d}S + \mathrm{d}S\,(f_1(x,t) + g_1(x,t)\,U). \end{aligned} \qquad (16)$$

By imposing $\mathrm{d}S^2 = 0$, the equivalent control can be expressed as

$$U_{eq} = -\frac{g(x)}{f(x)} . \qquad (17)$$

$$U_{SW} = \frac{1}{g(\mathrm{x})}(-r_1\mathrm{sign}(S(x) - r_2\mathrm{sign}(\mathrm{d}\,S(\mathrm{x}))) . \qquad (18)$$

The total control is defined by:

$$U = U_{eq} + U_{sw} . \qquad (19)$$

By replacing (17), (18) in (16), the result is simplified as:

$$\begin{aligned} \mathrm{d}v_1 &= \alpha_1 S\,\mathrm{d}S + S\,\mathrm{d}S^2 \\ &= \alpha_1 S\,\mathrm{d}S + \mathrm{d}S\,(f_1(x,t) + g_1(x,t) . \\ &\quad (-\frac{g(x)}{f(x)} + \frac{1}{g(x)}(-r_1\mathrm{sign}(S - r_2\mathrm{sign}(\mathrm{d}\,S)) \\ &= \mathrm{dS}\,(\alpha_1 S - r_1\mathrm{sign}(S - r_2\mathrm{sign}(\mathrm{d}\,S)) \qquad (20) \\ &= \mathrm{d}S\,\mathrm{sign}(\mathrm{d}\,S)(\alpha_1 S - \mathrm{sign}(\mathrm{d}\,S) - r_1\mathrm{sign}(S - r_2) \\ &= \left|\mathrm{d}S\right|((\alpha_1\left|S\right| - r_1\left|S\right|\mathrm{sign}(S\mathrm{d}S) - r_2) \\ &= \left|\mathrm{d}S\right|((\alpha_1 - r_1)\left|S\right| - r_2) \le 0. \end{aligned}$$

The system is stable if $(\alpha_1 - r_1) < 0$. The block diagram of the proposed control is shown in Fig. 5.

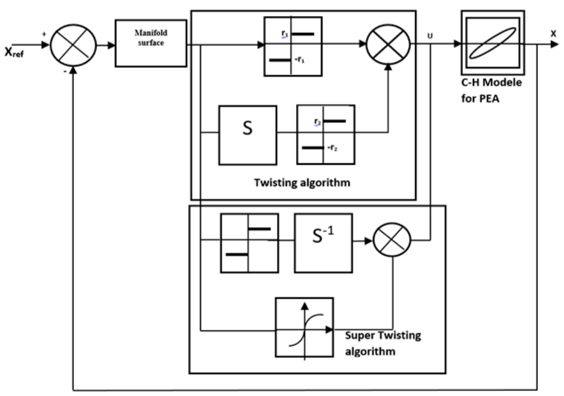

Fig. 5 – The block diagram of second order sliding mode controller for PEA.

5.2. INTERPRETATION AND DISCUSSION OF SIMULATION RESULTS

The control by sliding mode of order two led us to the results shown on Fig. 6 (a, b, c, d). We used the twisting algorithm with a sinusoidal reference of amplitude 10 μm of frequency 0.5 Hz. It can be seen from the results that the trajectory tracking is achieved, and the control signal is continuous. The magnitude of the tracking error is of the order of $3.864\mathrm{e}^{-5}$ m. The trajectory of the system in the phase plane revolves around the origin.

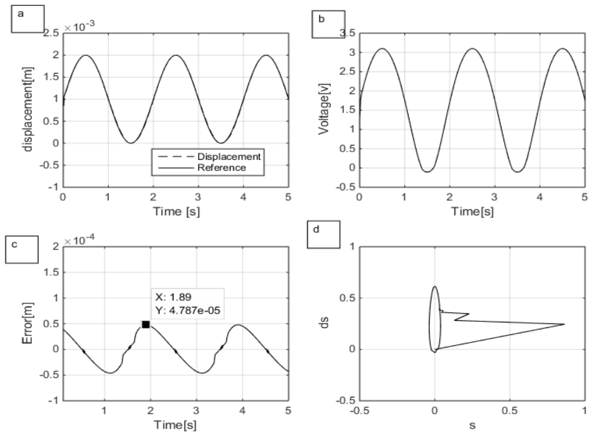

Fig. 6 – Results of simulation of the second sliding mode with twisting algorithm tracking response for a sinusoidal reference of 10 μm amplitude signal and at a frequency of 0.5 Hz; a) tracking displacement; b) tracking error; c) control voltage; d) the phase plane S.dS.

5.3. SUPER TWISTING ALGORITHM

This algorithm has been developed for systems with a degree equal to one with respect to the sliding surface. Emelyanov proposed this control law in 1999. The sliding mode control, based on the super-twisting algorithm is a robust variable structure control approach in the form of a combination of two terms: a discontinuous part U_2 and a continuous part U_1 [37]:

$$U = U_1(t) + U_2(t) ,$$
$$U = -k_1\left|S\right|^{0.5}\mathrm{sign}(S) + U_2 + F(t,S) , \qquad (21)$$
$$\mathrm{dU}_2 = -\mathrm{k}_3\,\mathrm{sign(S)} , \qquad (22)$$

where the constants k_1 and k_3 are positive and the sufficient conditions of convergence in finite time of the super twisting algorithm are verified [38]:

Defining a positive Lyapunov function candidate

$$\begin{aligned} v_2 &= 2\,k_2\left|S\right| + \frac{1}{2}U_2^2 + \\ &\quad \frac{1}{2}(k_1\left|S\right|^{0.5}\mathrm{sign}(S) - U_2)^2 , \qquad (23) \\ &= \gamma^{\mathrm{T}} P\,\gamma \end{aligned}$$

where

$$\gamma^{\mathrm{T}} = (k_1\left|S\right|^{0.5}\mathrm{sign}(S)U_2) \quad \text{and}$$

$$P = \frac{1}{2}\begin{pmatrix} 4\,k_2 - k_1^2 & -k_1 \\ -k_1 & 2 \end{pmatrix}.$$

Taking the time derivative of equation (23), results in

$$\mathrm{d}v_2 = -\frac{1}{|S|^{0.5}}\gamma^{\mathrm{T}} Q\,\gamma + \frac{F(t,S)}{|S|^{0.5}} q_1^{\mathrm{T}} \zeta\,, \qquad (24)$$

where $\mathrm{Q} = \dfrac{k_1}{2}\begin{pmatrix} 2\,k_2 - k_1^2 & -\,k_1 \\ -\,k_1 & 1 \end{pmatrix}$,

$$q_1^{\mathrm{T}} = \left[2\,k_2 + \frac{1}{2}k_1^2 \;\; -\frac{1}{2}k_1\right].$$

The function $F(t,S)$ is a function of unknown perturbation and is bounded, defined by a term $|\mathrm{F}(t,S)| \le \delta\, |S|^{0.5}$, $\delta > 0$. Applying the boundedness of the function $F(t,S)$ given by [39]. The equation (24) is simplified to:

$$\mathrm{d}v_2 = -\frac{1}{2.|S|^{0.5}}\gamma^{\mathrm{T}}\widetilde{Q}\,\gamma\;, \qquad (25)$$

where

$$\widetilde{Q} = \begin{pmatrix} 2\,k_2 - k_1^2 - (\dfrac{4\,k_2}{k_1} + k_1)\,\delta & -\,k_1 + 2\,\delta \\ -\,k_1 + 2\delta & 1 \end{pmatrix}.$$

We choose the gains k_1 and k_2 according to the following relations: $k_1 > 2\,\delta$, $k_2 > k_1 \dfrac{5\,\delta\,k_1 + 4\,\delta^2}{2\,(k_1 - 2\,\delta)}$ so $\widetilde{Q}_1 > 0$, which implies that function (25) is negative.

Figure 7 shows a good reference tracking without exceeding the limits of use. It is found that this control eliminates the chattering and ensures the control smoothness, the stabilization of the system and the trajectory continuation.

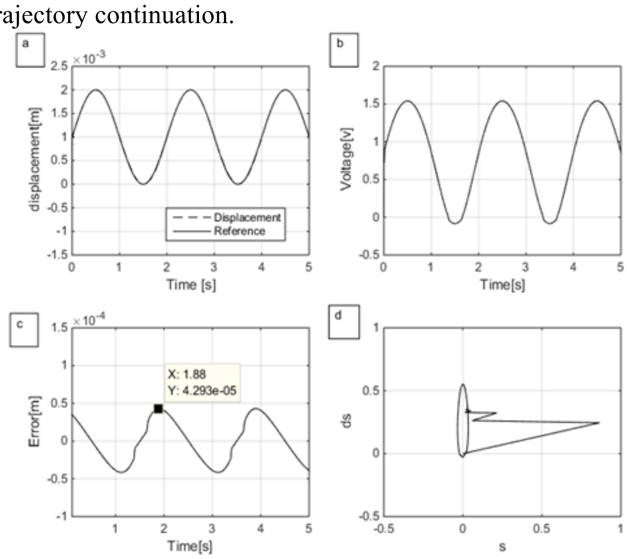

Fig. 7 – Simulation results of super twisting algorithm controller system for periodic sinusoidal command with conditions at 10 μm amplitude signal at a frequency of 0.5 Hz: (a) tracking response; (b) control effort; c) tracking error, d) the phase plane *S*.d*S*.

5.4. COMPARATIVE ANALYSIS

A comparative study between the results obtained by one order (classical) and order two sliding mode controls (twisting algorithm and super twisting algorithm) is carried out through a synthesis showing the differences in the two controls with respect to the error in displacement as described in Fig. 8. Performance response in motion is almost like that of the system based on continuous sliding mode control. A focus on the error variations shows that the system controlled by one order sliding mode suffers from the effect of chattering and poor transient response, steady state response and robustness. However, the performances of the super-twisting algorithm sliding mode controller request information about the derivative of the sliding variable which is the main problem of the implementation of the second order sliding mode control.

Table 2

Tracking error for the two controllers for the frequency variation

Frequency (Hz)	Tracking error (μm) Twisting algorithm	Tracking error (μm) Super twisting algorithm
2	0.0161	0.0149
1	0.899	0.8734
0.5	0.4273	0.4110

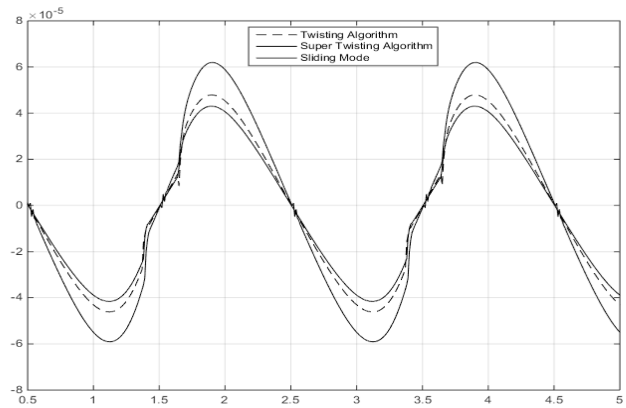

Fig. 8 – Evolution of the tracking error for the three controls.

We performed some additional tests to show the good behavior of the controllers for different operation points. Indeed, the model's nonlinearity (hysteresis) and its parameters are highly sensitive to the input frequency. The table shows that the tracking error for the two controllers stays very small with the frequency variation.

6. **CONCLUSION**

The C-H model that describes the dynamics of the hysteresis effect of the piezo actuator positioning mechanism (PEA) is presented. In practice, it is often very difficult to faithfully represent the piezo actuator positioning mechanism and to know all the variables involved. Therefore, the control law adopted must be robust to compensate some nonlinearities or identification errors. The sliding mode control can be a solution to this problem; however, its robustness will be decreased to the detriment of the performances. Indeed, the discontinuity of the control induces undesirable high frequency vibrations. In addition, the sliding surface defined in the formalism reduces the order of the closed-loop system. To overcome these drawbacks, we suggest a second twisting order sliding mode control or super twisting algorithms which is robust, efficient and easy to implement. To have a better appreciation of the obtained results, a comparative study has been undertaken. By considering the results**.** Finally, we can conclude that the super twisting algorithm control presents better performance and robustness.

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