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STABILIZATION OF SINGLE-AXIS PROPELLER-POWERED SYSTEM FOR AIRCRAFT APPLICATIONS BASED ON OPTIMAL ADAPTIVE CONTROL DESIGN

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Abstract

This study presents the design of Adaptive Super-Twisting Sliding Mode Control (ASTSMC) for single-axis propeller-driven aircraft to solve the chattering problem in classical sliding mode control and to address the finite-time convergence of system trajectories to their corresponding equilibrium states. The asymptotic stability of the system controlled by STSMC has been proved based on Lyapunov theorem. To cope the uncertainties in system parameters, an adaptive STSMC has been proposed and the adaptive laws is developed accordingly to estimate the uncertain parameters such as to guarantee the asymptotic stability of the closed-loop system. For further improvement of STAMC and adaptive STSMC, this study has suggested Particle Swarm Optimization (PSO) to tune the design parameters of proposed controllers. With this modern optimization technique, the tedious try-and-error procedure in setting the design parameters has been avoided and optimal performances of controllers have been obtained. The effectiveness of the proposed optimal controllers is verified using computer simulations based on MATLAB/ Simulink software package.

Keywords: Adaptive super-twisting control, Aircraft application, Propeller-driven system, Particle swarm optimization (PSO), Super-twisting sliding mode controller.

1. Introduction

The propeller-driven system is a simplified plant model which represents unmanned autonomous vehicle. This simple system is commonly used in academic purposes for teaching of system dynamics or education of control topics in mechanical and mechatronics engineering. There are different types of applications based on propeller-driven systems such as special aircrafts, measurement applications, coupled pendulum applications, Schuler tuning methods, entertainment purposes, etc. This system consists of motorized propeller at the end of a pendulum rod, which produces a thrust force that can lift the pendulum up and down. This concept establishes the essence in developing aircrafts like quadcopters, helicopters and take-off and landing aircrafts [1-3].

The control of this system is important to show how one can control the behaviours of propeller position such as the stability, rise time, and overshoots by adjusting the applied voltage [3]. The following literature reviews the most related works for control and application of propeller-driven systems.

Taskin [1] has proposed a fuzzy Proportional Integral Derivative (PID) controller for angular positioning of driven suspended pendulum system. The proposed controller consists of a conventional PID controller and fuzzy logic inference to tune the gains of classical controller. A comparison study in performance has been established between the conventional PID controller and the proposed controller in the presence of disturbance. Based on numerical simulation, it has been shown that the performance of the proposed controller outperforms the conventional one in terms of tracking behaviour.

Mohammadbagheri and Yaghoobi [2] have proposed PID control design to control the angular position of the driven suspended pendulum. The proposed controller has been designed to enhance the transient and steady-state characteristics of angular position. The elements of the PID controller have been set based on the try-and-error procedure and computer simulation based on MATLAB/Simulink has been used to verify the effectiveness of the proposed controller.

Job and Jose [3] have presented the design of Linear Quadratic Regulator (LQR), conventional PID controller, and PID-based LQR controller for position control of nonlinear aero-pendulum system. The computer simulation has been used to investigate the performances of proposed controllers and to conduct a comparison study between the proposed controllers. The simulated results showed that the LQR controller outperforms other controllers in terms of transient characteristics of the controlled system.

Enikov and Campa [4] conducted a low-cost hands-on experiment useful for undergraduate mechatronics and control courses. The experiment is based on a light rod with a DC motor attached at its end. The motor works to drive a propeller which permits the rod to swing up and down. The controller is developed inside real-time windows target software within Matlab/Simulink and the commanded signal is send to the pendulum environment via a USB port using a virtual RS-232 port. Different controllers can be implemented such as conventional or modern controllers.

Kizmaz et al. [5] have presented control design based on sliding mode control methodology to robustly control the angular position of suspended pendulum system (SPS). The model of SPS has been approximated using input-output practical measurements. The sliding mode controller has been designed and coded using MATLAB/Simulink programming format. Also, the real-time implementation of sliding mode controlled SPS is performed using LabVIEW software. The robust controller has been verified for different reference inputs using both simulated and experimental results.

Huba et al. [6] presented an embedded control design based on the propeller pendulum system. This work established a framework to motivate students for "experimental learning" or for system identification or model development and knowledge needed in modern control theory based on experimental measurements. The design of the embedded controlled system was dedicated to measuring the angular position and velocity of suspended pendulum driven by impeller.

Gültekin and Taşcıoğlu [7] designed an experimental control setup for suspended pendulum actuated by two motorized propellers. The control design based on feedback linearization and discrete PD controller could successfully position the pendulum at any desired angular position including the upright unstable position. The performance of the controlled system based on single and differential thrusts has been assessed and verified using computer simulation and real-time implementation.

Yoon [8] has conducted real-time implementation to address the stabilization problem in one-dimensional impeller-actuated pendulum. The suspended pendulum model has been linearized and transfer function has been derived. The work focused on the validation of the linearized model experimentally. In spite that the experimental results showed the validity of the simple pendulum model, the hardware setup encountered some problems due to large noise in measuring sensors.

Raju et al. [9] proposed a Quadratic Dynamic Matrix Control (QDMC) method to control a driven pendulum system. The model has been linearized and transfer function has been derived. The control strategy assumes that there is a limitation in the control signal and accordingly the prediction and control horizons are specified. Based on numerical simulation, it has shown that the proposed control scheme could guarantee the stability of controlled system and result in simple tuning technique.

The STSMC is a recent sliding mode control strategy, and it is characterized by the following features [10-16]:

- It reduces the chattering effect as compared to classical SMC.
- It enables the system trajectories to reach the equilibrium in finite time. In other words, the STSMC is capable of setting both the sliding variable and its time derivative to zero value in finite time.
- Rather than other SMC schemes, the STSMC does not require the knowledge of state derivatives in its design, but only needs the sliding variable - output variable- and hence this leads to a simple control law with less computation effort.
- No singularity and exact convergence have been detected with the application of STSMC.

According to the above features, the STSMC has been adopted to angular position control of the suspended pendulum. However, in the presence of uncertainty and unknown parameters, an adaptation mechanism in the STSMC scheme is required to estimate the uncertain system parameters such as to cope and eliminate their adverse effects on the stability of the controlled system. Therefore, adaptive STSMC has been presented to address the problem of uncertainty existence.

Previous studies have shown that the design parameters of developed STSMC and adaptive STSMC have an impact on their performances [17, 18]. To avoid the tedious and non-optimal try-and-error procedure in tuning the design parameters, which fails to find the optimal performance of controllers (STSMC and adaptive STSMC), a modern optimization technique is used instead to tune these design parameters. The present work suggested Particle Swarm Optimization (PSO) technique for optimal adjustment of these parameters. The PSO was firstly introduced in 1995 by Kennedy and it is inspired by the social behaviour of organisms [19]. This optimization technique was widely used in control and optimization applications due to efficiency of computation, fast convergence and it capable to reach global solutions [19-22]. In the literature, other modern optimization techniques based on behaviours of other animals like monkeys, whales, bees, bats, spiders, wolves and cuckoos are applied for optimization in many control applications [23-30].

This study proposed three versions of control design based on sliding mode control theory, which are SMC, STMC, and ASTMC. The stability analysis of controlled system is established for each proposed controller. A comparison study has been established to investigate the effectiveness of proposed controllers. In addition, to better enhance the performances of the proposed controllers, the PSO algorithm is developed for tuning the designed parameters of these controllers. The following points highlight the contributions of the present work:

- Design of control law based on SMC and STSMC for position control of propeller-powered system.
- Design of control and adaptive laws based on ASTSMC for position control of propeller-powered system in the presence of uncertainty in system parameters.
- Proof of asymptotic stability for propeller-powered system controlled by the proposed controllers SMC, STMC, and ASTMC based on Lyapunov stability analysis such that all error trajectories converge to zero equilibrium points.
- Design of PSO algorithm to optimally tune the design parameters of proposed controllers to improve the dynamic performance of system controlled by optimal SMC, STSMC and ASTSMC.
- Reduction of chattering effect resulting from classical SMC by proposing STSMC strategy.

2. Mathematic Model of Single-axis Propeller Driven Aircraft

Figure 1 shows the schematic diagram of the propeller-powered system. As indicated in the Fig. 1, the suspended pendulum is attached with motorized propeller at the end of the arm. The suspended pendulum is controlled by actuating the input voltage of the DC electric motor. In Fig. 1, there is the control signal of the propeller DC motor is u. To get the stability of the system, then we can obtain the first and the second derivative of the angle of the suspended pendulum $\dot{\theta}$ and $\ddot{\theta}$ [4, 5].

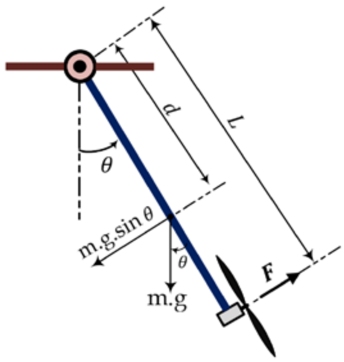


Fig. 1. Schematic diagram of single-axis propeller-driven system.

The mathematical model of the propeller-suspended system is obtained as follows [5]:

$$J\ddot{\theta} + C\,\dot{\theta} + m\,d\,g.sin(\theta) = T + \varphi(t) \tag{1}$$

where θ is the angle of the pendulum, *J* is the inertia of moment, *C* viscous damping coefficient, *m* is the weight of propeller assembly, *g* is the acceleration of gravity, *d* is the distance from suspending point to the mass center, *L* represents the length of the pendulum arm, *T* is the thrust provided by DC motor, and φ represents the disturbances. The relationship between the control input signal u and the thrust generated from the motor can be given by

$$T = k_m u \tag{2}$$

Therefore, Eq. 1 can be written as below:

$$\ddot{\theta} + C\dot{\theta} + m\,d\,g\,sin(\theta) = k_m\,u + \varphi(t) \tag{3}$$

Now, from the above equations the transfer function of the suspended pendulum can be written as follows:

$$\ddot{\theta} = \frac{k_m\,u + \varphi(t) - C\,\dot{\theta} - m\,d\,g\,sin(\theta)}{J} \tag{4}$$

3. Design of Super-Twisting Sliding Mode Control of Propeller-driven System

In this section, the control law has been developed based on STSMC. This control law will conduct the error trajectory from initial condition to reach a sliding surface and it will enforce the trajectory to be held on the sliding surface until it finally settles at the equilibrium point.

The first step in the design is to define the error between the desired angle θ_d and the actual angle θ and as follow:

$$e_\theta = \theta_d - \theta \tag{5}$$

Then, the sliding surface must be defined. For the second-order system of the suspended pendulum, the sliding surface is defined by

$$s_\theta = \dot{e}_\theta + c_1 e_\theta \tag{6}$$

where $c_1 > 0$. The time derivative of s_θ is given by

$$\dot{s}_\theta = \ddot{e}_\theta + c_1\,\dot{e}_\theta = \ddot{\theta}_d - \ddot{\theta} + c_1\,\dot{e}_\theta \tag{7}$$

Using Eq. 4, Eq.7 becomes

$$\dot{s}_\theta = \ddot{\theta}_d - \left(k_m\,u + \varphi(t) - C\dot{\theta} - m.d.g.sin(\theta)\right)/J + c_1\dot{e}_\theta \tag{8}$$

To ensure $\dot{s}_\theta = 0$, the control law *u* can be proposed to be

$$u = (J/k_m)\left(u_{eq} + u_{sw}\right) \tag{9}$$

where u_{eq} is the continuous part of control law, called as the equivalent control law, and it is found by setting $\dot{s}_\theta = 0$ and assuming the presence of equivalent part only; that is,

$$u_{eq} = \ddot{\theta}_d + \frac{C}{J}\dot{\theta} + \frac{d\,g\,m}{J}\sin(\theta) + c_1\dot{e}_\theta \tag{10}$$

while u_{sw} is the switching element of control law, which is responsible for confining the trajectory to slide on the sliding surface [12, 15]. The control law consists of an integral part with the positive scaling function k_1 and $sgn(.)$ function as below:

$$u_{sw} = k_1\sqrt{|s_\theta|}\,sgn(s_\theta) + k_2\int sgn\,(s_\theta)\,dt \tag{11}$$

$$u = \left(\frac{J}{k_m}\right)\left(\ddot{\theta}_d + \frac{C}{J}\dot{\theta} + \frac{d\,g\,m_l}{J}\sin(\theta) + c_1\dot{e}_\theta + k_1\sqrt{|s_\theta|}\,sgn(s_\theta) + k_2\int sgn\,(s_\theta)\,dt\right) \tag{12}$$

where, k_1 and k_2 are positive real design parameters. Substituting the control law of Eq.12 into Eq.8 to have

$$\dot{s}_\theta = -k_1\sqrt{|s_\theta|}\,sgn(s_\theta) - k_2\int sgn(s_\theta)\,dt + \varphi(t) \tag{13}$$

To discuss the stability of the pendulum system controlled by STSMC, the Lyapunov function can be expressed in terms of the sliding surface as follows,

$$\mathrm{V}\,(s_\theta) = \frac{1}{2}s_\theta^2 \tag{14}$$

The time derivative of this function is given by:

$$\dot{V} = s_\theta\left(-k_1\sqrt{|s_\theta|}\,sgn(s_\theta) - k_2\int sgn(s_\theta)\,dt + \varphi(t)\right) \tag{15}$$

Using the mathematical fact $sgn(s_\theta)\,s_\theta = |s_\theta|$, the stability condition can be established based on the following inequality

$$\dot{V} \le -k_1\sqrt{|s_\theta|}\,|s_\theta| - |s_\theta|\int k_2\,dt + |\varphi(t)\,s_\theta| \tag{16}$$

The term $|\varphi(t)\,s_\theta|$ can be written in terms of integration

$$|\varphi(t)\,s_\theta| = |s_\theta|\int|\dot{\varphi}(t)|\,dt \tag{17}$$

Adding an integral part, Eq.16 becomes

$$\dot{V} \leq -k_1\sqrt{|s_\theta|}\,|s_\theta| - |s_\theta|\int k_2\,dt + |s_\theta|\int \dot{\varphi}(t)\,dt \tag{18}$$

$$\dot{V} \leq -k_1\sqrt{|s_\theta|}\,|s_\theta| - |s_\theta|\left(\int k_2\,dt - \int \delta_1\,dt\right) \tag{19}$$

Remark: According to Eq. 19, the stability of the propeller-driven system based on STSMC is ensured if k_2 is chosen such that $k_2 \geq \delta_1 \geq |\dot{\varphi}(t)|$.

4. Adaptive Super-Twisting Sliding Mode Control of Propeller-powered System

The control law developed based on classical super-twisting sliding mode control cannot cope the case of controlled system subjected to uncertainty in parameters. Therefore, the adaptive version of STSMC is used instead to solve the control problem and to cope with such variation in parameters by developing adaptive law, which is responsible for estimating the uncertain parameters to compensate and reduce its changing effect. Strictly speaking, the adaptive controller could ensure the asymptotic stability of the controlled propeller-based system in the presence of unknown and uncertain parameters [10-15]. In what follows, the control and adaptive laws are developed based on stability analysis.

The first step in the design of adaptive sliding mode control is to assign the estimation error $\tilde{\varphi}(t)$ of the uncertain load to be the difference between estimation value $\hat{\varphi}(t)$ and the actual value $\varphi(t)$ of actual load, i.e.,

$$\tilde{\varphi}(t) = \hat{\varphi}(t) - \varphi(t) \tag{20}$$

Using Eq.20, Eq.4 becomes

$$\ddot{\theta} = \frac{k_m\,u + \hat{\varphi}(t) - \tilde{\varphi}(t) - C\dot{\theta} - m_l dgsin(\theta)}{J} \tag{21}$$

The sliding surface which is used to force the system to track the desired angle is defined as:

$$s_\theta = \dot{e}_\theta + c_2 e_\theta \tag{22}$$

where $c_2 > 0$, and the time derivative of s is given by

$$\dot{s}_\theta = \ddot{\theta}_d + \frac{-k_m u - \hat{\varphi}(t) + \tilde{\varphi}(t) + C\dot{\theta} + m_l dgsin(\theta)}{J} + c_1\dot{e}_\theta \tag{23}$$

As mentioned earlier, the control law of SMC consisting of two elements: equivalent part and switching part. One can follow the same analysis as in case of SMC to deduce the control law.

$$u = \left(\frac{J}{k_m}\right)\left(\ddot{\theta}_d + \frac{C}{J}\dot{\theta} + \frac{d.g.m}{J}\sin(\theta) - \frac{\hat{\varphi}(t)}{J} + c_1\dot{e}_\theta + k_3\sqrt{|s_\theta|}\,sgn(s_\theta) + k_4\int sgn\,(s_\theta)\,dt\right) \tag{24}$$

Substituting Eq. 24 into Eq. 23 to have:

$$\dot{s}_\theta = \frac{\tilde{\varphi}(t)}{J} - k_3\sqrt{|s_\theta|}\,sgn(s_\theta) - k_4\int sgn(s_\theta)\,dt \tag{25}$$

The Lyapunov function has been chosen to be expressed in terms of sliding variable and load estimation error,

$$V = \frac{1}{2}\left(s_\theta^2 + \frac{1}{n}\tilde{\varphi}^2(t)\right) \tag{26}$$

Taking the time derivative of Eq. 26 gives

$$\dot{V} = s_\theta\, \dot{s}_\theta + \frac{1}{n}\dot{\tilde{\varphi}}(t)\, \tilde{\varphi}(t) \tag{27}$$

Assuming stationary value of actual load, then

$$\dot{\tilde{\varphi}}(t) = \dot{\hat{\varphi}}(t) \tag{28}$$

Using Eq. 28, Eq. 27 can be written as

$$\dot{V} = \left(\frac{\tilde{\varphi}(t)}{J} - k_3\sqrt{|s_\theta|}\, sgn(s_\theta) - k_4 \int sgn(s_\theta)\, dt\right) s_\theta + \frac{1}{n}\dot{\hat{\varphi}}(t)\, \tilde{\varphi}(t) \tag{29}$$

In order to guarantee $\dot{V} < 0$, one has to assume the following

$$\frac{1}{J}\tilde{\varphi}(t)\, s_\theta + \frac{1}{n}\dot{\hat{\varphi}}(t)\, \tilde{\varphi}(t) = 0 \tag{30}$$

According to Eq. 30, the adaptive law can be deduced

$$\dot{\hat{\varphi}}(t) = -\frac{n}{J}\, s_\theta \tag{31}$$

Then, $\dot{V}$ equation reduces to

$$\dot{V} = -k_3\sqrt{|s_\theta|}\, |s_\theta| - |s_\theta| \int k_4\, dt \tag{32}$$

with $k_3, k_4 > 0$, then the negative definite condition is satisfied, and the adaptive controller can guarantee an asymptotic convergence of both sliding trajectory and estimation error to their corresponding equilibrium points. The schematic diagram of adaptive super-twisting control strategy for angular position control of propeller-suspended system is shown in Fig. 2.

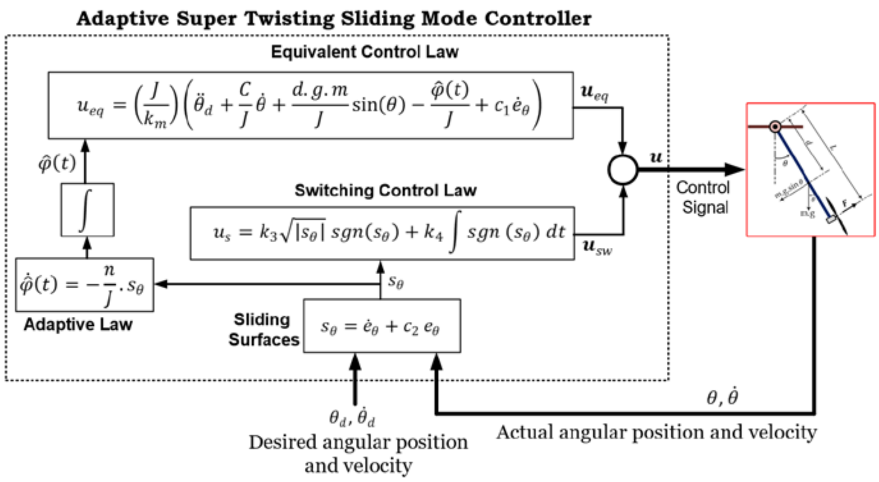


Fig.2 Adaptive scheme of super-twisting sliding mode controller for propeller-suspended aircraft system.

5. Optimization of Control Performance based on PSO

To get the best control performance of SMC, STSMC and ASTSMC controllers, their design parameters must be tuned to satisfy specified dynamic performances of controlled systems. The try-and-error procedure was the traditional method for tuning these design parameters to give satisfactory performance. However, this classical and tedious method cannot find the optimal dynamic performance of controlled system and takes long time to reach satisfactory response.

Therefore, the PSO algorithm has been developed to tune and obtain the optimal values of these design parameters which lead to have optimal performance of the proposed controllers. In the case of SMC, the design parameters are (c_3 and k_5), while the design parameters for STSMC are (c_1, k_1 and k_2) and those for the ASTSMC are (c_2, k_3, k_4 and n).

The particles, which contitute the elements of PSO algorithm, navigate around the solution (search) space by updating their velocities according to their own positions and the positions of other particles (searching experience). Each particle in the population has to update its position and velocity at every iteration and this task will obey the optimal performance creterion or a cost function, which has to be minimized or maximized to reach the global optimal solution. In our design, the Integral Time Absolute Error (ITAE) has been chosen as the fitness function that used to evaluate the particles at every iteration within the PSO algorithm for all controllers [31, 32],

$$f = ITAE = \int_0^T t\,|e|\,dt \tag{33}$$

The velocity of each particle is updated according to the following equation [33]:

$$V_i^{k+1} = w.V_i^k + C_1 \cdot rand \cdot \left(p_{best} - X_i^k\right) + C_2 \cdot rand \cdot \left(g_{best} - X_i^k\right) \tag{34}$$

where, C_1 denotes the personal acceleration coefficient and C_2 is the social acceleration coefficient, and w is the inertial coefficient. The variable p_{best} represnts the location of best fitness function reached by a particular particle, g_{best} represents the location with the best fitness among all the visited locations of all the particles.The position of each particle is updated by:

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{35}$$

where X_i^k and X_i^{k+1} represent the current and updated position vectors of particles, respectively, while V_i^{k+1} denotes the updated velocity vector. In the present work, the setting of parameters for PSO algorithms are listed in Table 1. The choice of these parameters is based on try-and-error procedure via many trials of simulation to ensure stable, efficient and low computational effort algorithm.

This study can be extended for future work to include other optimization techniques to conduct a comparison study with the present PSO algorithm such as Genetic algorithm, social spider optimization, etc. [26, 28, 31, 34]. Also, other control techniques such as RISE-control, model predictive control, passivity-based control, active disturbance rejection control, optimal control, backstepping control, and nonlinear PD control can be designed to for this application [35-41].

Table 1. The list of parameters used in the PSO algorithm.

Parameter description	Value
The population size (swarm size)	30
Coefficient of personal acceleration, C_1	2
Coefficient of social acceleration, C_2	2
The number of algorithm iterations	100
The inertia coefficient, *w*	1.4

6. Computer Simulation

The numerical values Impeller-Suspended Pendulum system are listed in Table 2. The numerical simulation has been implemented within MATLAB software and the programme has been coded inside m-file. The Runge Kutta (4th order) method has been used to solve the differential equations encountered in computer simulation. To get high-performance quality, the PSO algorithm has been utilized to tune the design parameters of SMC, STSMC, and ASTSMC to have better dynamic performance. Figures 3, 4 and 5 show the behaviour of cost function with respect to iteration for controlled propeller-suspended system based on SMC, STSMC, and ASTSMC, respectively.

Table 2. The numerical values of parameters for pendulum system [5].

Parameter description of pendulum system	Value
Weight of pendulum, *m*	0.36 kg
Distance from suspending point to center of mass, *d*	0.03 m
Inertia moment *J*	0.0106 kg m^2
Acceleration of gravity, *g*	9.81 m/s^2
Viscous damping coefficient, *c*	0.0076 Nms/rad
Motor constant, k_m	0.0296

Table 3 gives the set of design parameters are based on the PSO technique for the Impeller-Suspended Pendulum system controlled by SMC, STSMC, and ASTSMC. The initial values of variables θ, $\dot{\theta}$ and $\hat{\varphi}$, which are used to initialize the simulation for the adaptive and conventional super-twisting sliding mode controllers and sliding mode controller, were set as follows: $[\theta(0), \dot{\theta}(0), \hat{\varphi}(0)]^T = [0, 0, 0.01]^T$.

Table 3. The optimal setting of design parameters based on PSO technique.

Controller	Optimal Values	
	Coefficient	Value
SMC	c_3	9.9379
	k_5	37.1658
STSMC	c_2	6.8089
	k_1	4.9999
	k_2	3.7992
ASTSMC	c_2	18.0941
	k_3	47.4657
	k_4	17.1689
	n	0.0009

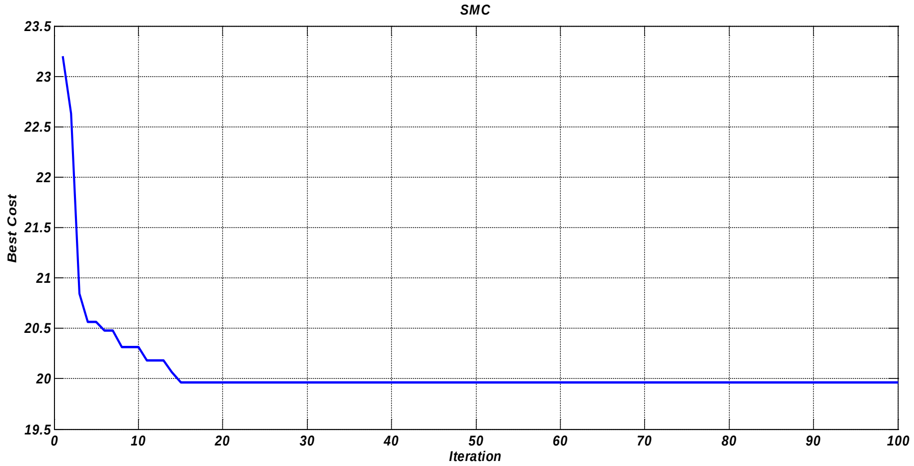


Fig. 3. Cost function behaviour for SMC.

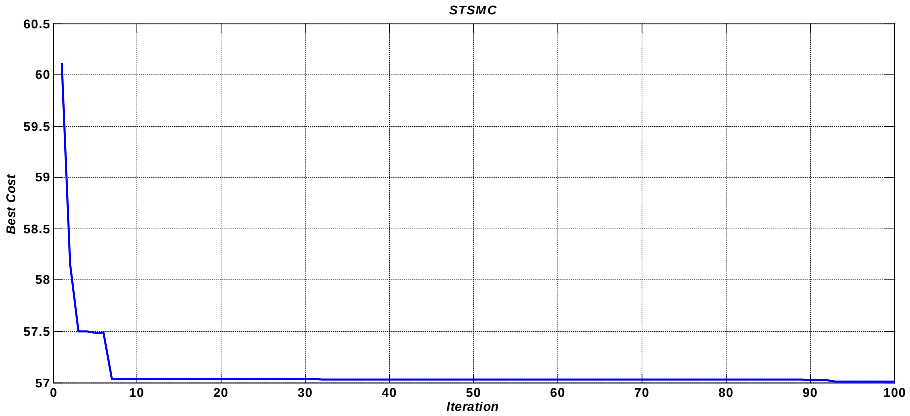


Fig.4. Cost function behaviour for STSMC.

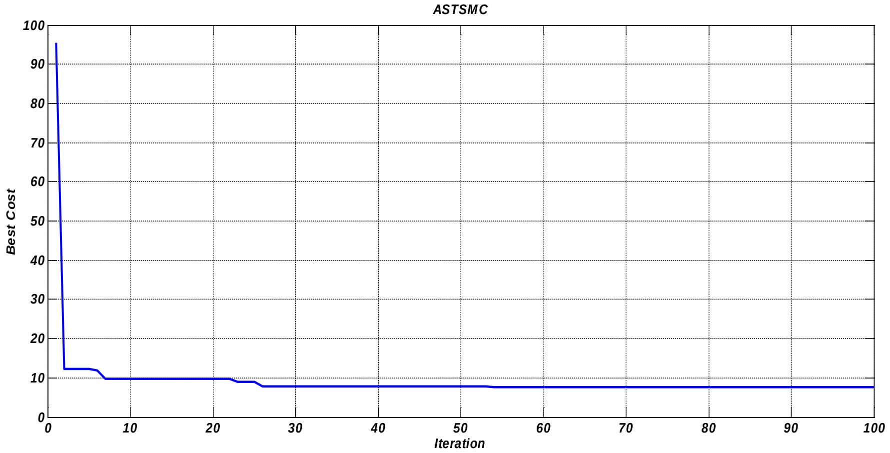
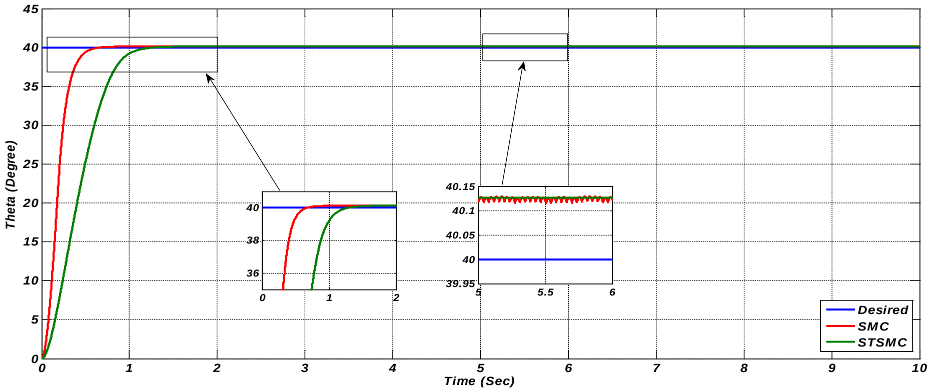


Fig.5. Cost function behaviour for ASTSMC.

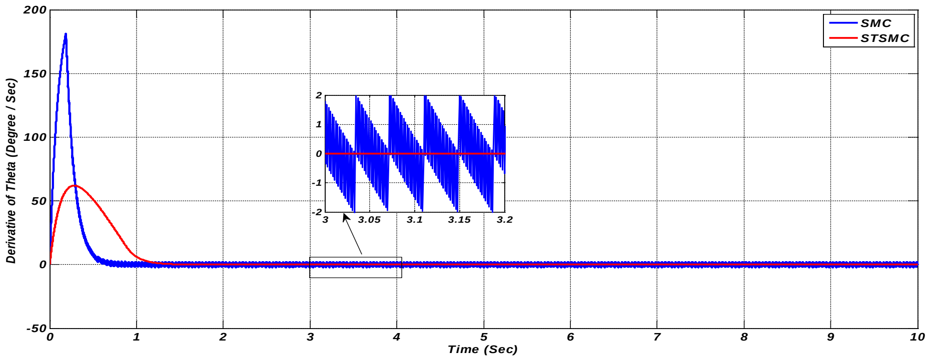
Scenario I: Control without disturbance

In this scenario, the ASTSMC has been discarded due to the absence of external uncertainty. Figure 6 shows the dynamic response of the controlled system based on SMC and STSMC. Figures 6(a) and (b) depicts the responses of angular positions and velocities, respectively, resulting from SMC and STSMC subjected to the same initial condition. The corresponding control signals due to proposed controllers are illustrated in Figs.7 and 8. It is evident from the dynamic responses and control signals that the chattering is considerably reduced by STSMC and this proves the conclusion reached by most works in the literature.

The performance of the super-twisting sliding mode controller (STSMC) and Sliding Mode Controller (SMC) is reported in Table 4. The performance evaluation is based settling time and steady state error. It is evident from Table 4 that the super twisting sliding mode controller has better dynamic characteristics.



(a)



(b)

Fig.6. Dynamic performance of the controlled system-based SMC and STSMC: (a) Angular position (b) Angular velocity.

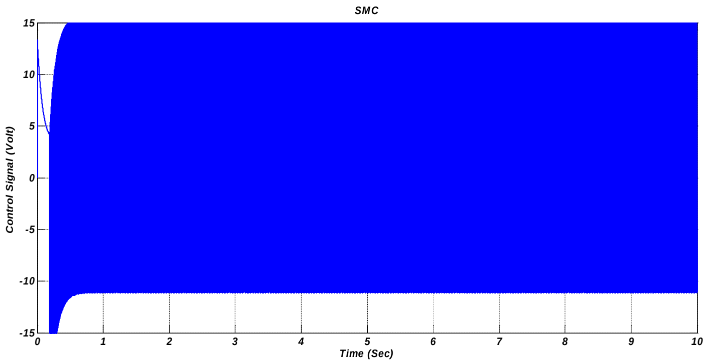


Fig.7. Control signal u-controlled system based on SMC.

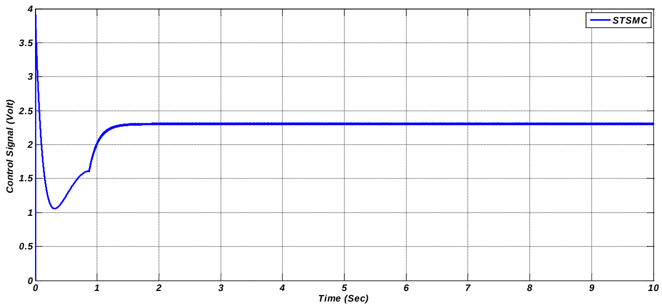


Fig. 8. Control signal u of the controlled system based on STSMC.

Table 4. Transient parameters of the controlled system based on SMC and STSMC.

Controller type	Setting time (s)	Steady state error (degree)	RMSE
STSMC	1.26	0.1	0.1206
SMC	0.88	0.13	0.08097

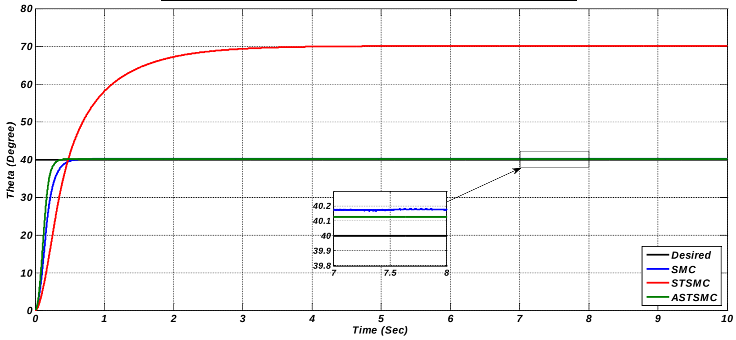
Scenario II: With disturbance

In this scenario, the controllers SMC, STSMC, and ASTSMC have been tested under the presence of external uncertainty represented by $\varphi(t)$. The dynamic performance based on proposed controllers under disturbance application is demonstrated in Fig.9. Figures 9(a) and (b) show the step responses of angular positions and velocities, respectively, based on SMC, STSMC, and ASTSMC. Figure 9 indicates that the STSMC lacks the ability to track the desired trajectory, while the ASTSMC gives better dynamic response compared to other controllers. The behaviour of control signals due to proposed controllers are illustrated in Figs. 10 and 11. It is clear from the control and angular responses that STSMC and ASTSMC have much suppressed the chattering effect in their responses as compared to the noticeable effect of this phenomenon at the responses of SMC.

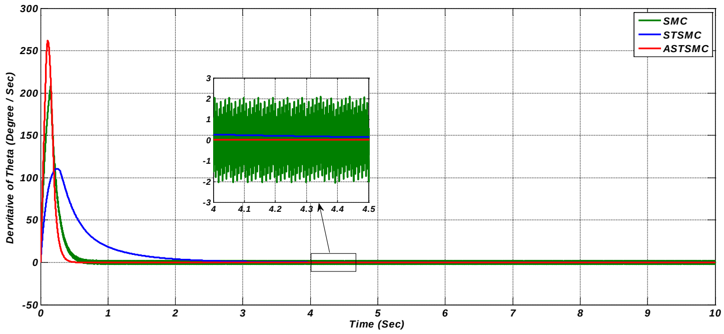
The dynamic performance based on SMC, STSMC, and ASTSMC in the presence of external uncertainty has been numerically evaluated and reported in Table 5. It is clear from Table 5 that the ASTSMC has better robustness characteristics than the other controllers as it could keep the dynamic performance unchanged in the presence of parameter variation.

Table 5. Evaluation of the transient performance of controlled system.

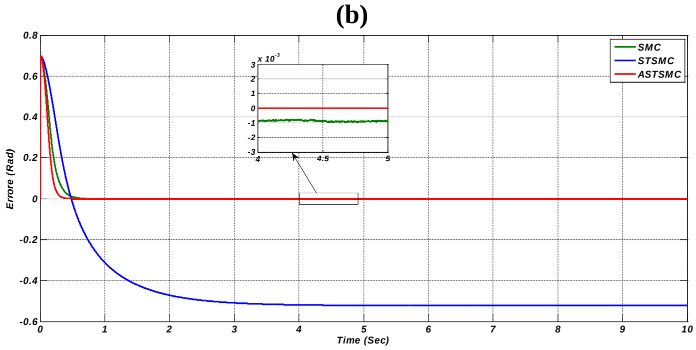
Controller type	Setting time (s)	Steady-state error (degree)	RMSE
ASTSMC	0.44	0.13	0.0682
STSMC	3.64	29.76	0.4929
SMC	0.65	0.18	0.0761



(a)



(b)



(c)

Fig. 9. Dynamic performance of controlled system-based SMC, STSMC and ASTSMC: (a) Angular position, (b) Angular velocity and (c) Error signal.

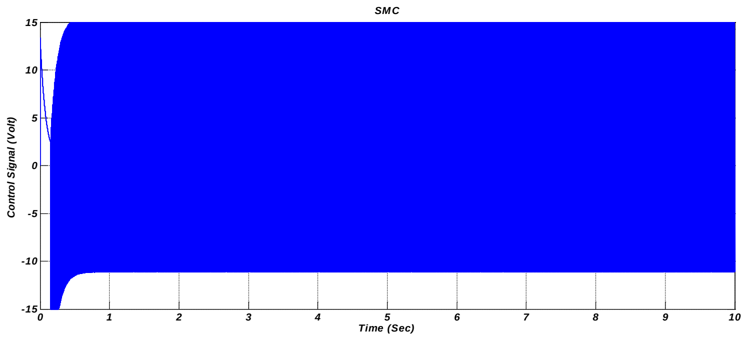


Fig. 10. Control signal u controlled system based on SMC in the presence of disturbance.

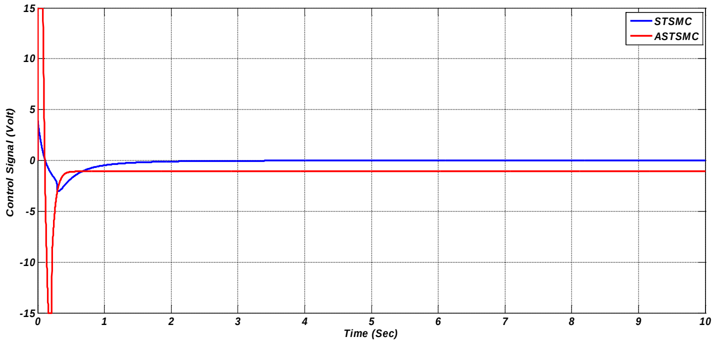


Fig. 11. Control signal u of controlled system based on STSMC and ASTSMC in the presence of disturbance.

Figure 12 shows the estimation behaviours of disturbance $\varphi(t)$ (Nm). It is clear from the Fig. 12 that there is a steady-state estimation error, and the estimation error may not reach zero as time tends to infinity. This can be attributed to the importance given to the zero-convergence of system error over the estimation error in the stability analysis based on the Lyapunov method. However, in spite that the estimation error may not reach zero value, this estimation error remains bounded as indicated in the Fig. 12 . In turn, the bounded steady-state estimation error will prevent the $\varphi(t)$ to grow without bound, which may lead to instability problems.

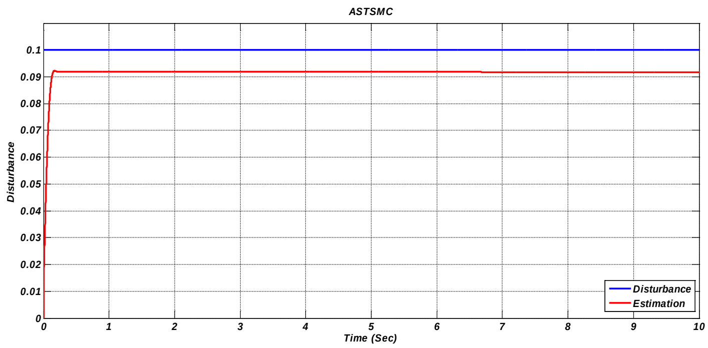


Fig. 12. Disturbance estimation in Nm.

7. Conclusion

This work proposed the design of STSMC and ASTSMC for angular control of propeller-driven system for aircraft application. The stability analysis has been presented for a controlled system based on proposed controllers and the asymptotic convergence of error has been proved. A comparison study has been conducted between SMC, STSMC, and ASTSMC. The simulated results showed that a considerable reduction of chattering in control signals has been achieved by STSMC and ASTSMC as compared to classical SMC. Also, the ASTSMC has been designed to estimate bounded external uncertainty in such a way it could compensate for its effect and guarantee the asymptotic stability of the overall controlled system. Also, it has been shown that the transient characteristics of STSMC are better than SMC in case of no-load exertion, while ASTSMC outperforms the other controllers in case of load consideration.

Nomenclatures

C	Viscous damping coefficient
d	The distance from suspending point to the canter of mass
g	The acceleration of gravity
J	The inertia of moment
m	The weight of pendulum
T	Thrust provided by DC motor
u	Control law
u_{eq}	Equivalent part of control law
u_{sw}	Switching part of control law
$V(.)$	Lypunov function
c_1, k_1, k_2	Design parameters of SMC
c_2, k_3, k_4	Design parameters of ASTSMC

Greek Symbols

θ	The angle of the pendulum
φ	The disturbances
θ_d	Desired angular position
s_θ	Sliding Surface

Abbreviations

DC	Direct Current
PSO	Particle Swarm Optimization
LQR	Linear Quadratic Regulator
PID	Proportional Integral Derivative
SMC	Sliding Mode Control
SPS	Suspended Pendulum System
STSMC	Super Twisting Sliding Mode Control

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