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ADAPTIVE SYNERGETIC CONTROLLER FOR TAIL-SITTER VTOL AIRCRAFT

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Abstract

The Tail-Sitter is a unique and innovative configuration that combines the vertical take-off and landing (VTOL) abilities of a helicopter with the speed and efficiency of a fixed-wing aircraft, providing a suggested solution for various civil and military applications. This work performs on synergetic control theory based on adaptive control strategy to overcome the influence of gust wind which Tail-Sitter VTOL aircraft are exposed to; this control algorithm is formed based on given model parameters. Conversely, in practice Tail-Sitter VTOL aircraft systems have some inherent parametric uncertainties and thus an Adaptive Synergetic Control (ASC) strategy is suggested and combined for a Tail-Sitter VTOL aircraft exposed to perturbation in its parameters. Based on Lyapunov stability analysis, an ASC scheme was performed under wind gust effect on the system coefficients. The adaptive control strategy was established to confirm a stable controlled system. This controller handles the problem of suppressing the effect of gusty winds experienced by the Tail-Sitter VTOL, and a gusty wind control scenario is performed and simulated. The ASC strategy showed efficient performance via computer simulation by used MATLAB environment where adaptive and classical Synergetic Control (SC) were compared. Moreover, ASC is compared to Model Reference Adaptive Control (MRAC) which is designed in literature to prove its efficiency.

Keywords: Adaptive control, Model reference control, Synergetic control, VTOL-UAV.

1. Introduction

The world has recently witnessed many developments in various activities, including aircraft, where Unmanned Aerial Vehicles (UAVs) have been widely used in many applications. By using this type of aircraft, many civil and military tasks have been facilitated, such as inspecting building infrastructure and remote photography. It is used to monitor traffic and reach places that are difficult for humans to reach, and other applications.

In addition, this type of aircraft has the ability to manoeuvre, fly for long periods, and switch between different flight modes depending on the mission [1]. This aircraft is considered the developed generation, as it has the characteristics of a helicopter in vertical take-off and landing, has the characteristics of an aircraft of fixed-wing in forward flight, and also has the ability to operate uniquely and flexibly [2]. Moreover, these drones cost less than some standard drones [3]. One of the exchangeable aircraft constructions is the Tail-sitter vehicle, which can be described by approving the straight up airframe behaviour while landing and taking off in cruising, as do classical airplanes [4].

Designing an effective control technique for tail sitter aircraft is challenging due to the complex flight dynamics, particularly during hover mode [5]. As a result, various research projects have concentrated on creating control solutions for tail-sitter aircraft. For example, Jacson MO Barth proposed a control system for stabilizing the Darko model airplane under strong gusts [6]. Zhou et al. [7] developed a model predictive control system for a VTOL tail-sitter UAV that uses sequential linearization during vertical take-off, descent, and soaring. This architecture was validated using an estimated state-space model, which was improved via feedback combination and predicted perturbation modifications.

Huang et al. [8] devised a reliable control approach based on adaptive sliding mode control. Jacob et al. [9] compared a Sliding Mode Control (SMC) mechanism to a Proportional-Integral-Derivative (PID) controller, demonstrating SMC's resilience. Similarly, Husain et al. [10] introduced an Integral Sliding Mode Control (ISMC) mechanism and demonstrated its better efficiency over classic SMC. Al-Qassar et al. [11] proposed a super-twisting sliding mode control strategy for parameter tweaking, which was optimized using the grey-wolf method.

Furthermore, He et al. [12] proposed an adaptive fault-tolerant control system for hybrid VTOL-UAVs, which addresses actuator faults and model uncertainties in fixed-wing mode. Ajel et al. [13] provided a model reference adaptive control approach, whereas Dalwadi et al. [14] proposed a nonlinear observer-based backstepping control strategy to improve system stability under parameter fluctuations and external perturbations. Zhou et al. [15] proposed a recurrent neural network and showed that it produces smoother output signals than nonlinear control schemes. Finally, Mhmood [16] proposed an optimal, robust deadbeat control strategy for regulating roll angle in horizontally launching and landing tail-sitter vehicles.

These works add to the developing field of control approaches for tail-sitter UAVs, each tackling a distinct difficulty in flight dynamics, resilience, and adaptability. Like mainly systems which are exposed to external disturbance, an aircraft requires a robust control mechanism that can handle the external influences and model uncertainties. Some classical controllers are suitable for tracking but are unable to resist external influences on the aircraft. Thus, this system requests a robust control mechanism to overcome parameters uncertainties and external influences [17, 18]. Robust control has been applied in the literature like SMC and ISMC, which can resist external influences, these mechanisms have chattering problem, therefore needs approximation to resist this problem [19-29].

In this work, classical and Adaptive Synergetic control (SC and ASC) strategies were presented to control Tail-Sitter VTOL aircraft. In adaptive control methods, the parameters of a system in real time are regulated to provide a desired level of dynamic performance when the system is subjected to unknown and changing (varying with time) parameters. Moreover, ASC and SC were chosen due to their ability to steer the system's states to track an invariant manifold. This manifold is designed according to the desired control specifications in the presence of parametric uncertainties and external influences [30-35]. Moreover, SC strategy does not cause chattering problem [36-39]. ASC ensures stability even under external perturbations. The main contributions of this work are summarized as the follows:

- Adaptive synergetic controller is designed and compared to synergetic control law for a Tail-Sitter VTOL aircraft.
- Synergetic control and adaptive synergetic control performances are compared to some types of SMC.
- Minimization of control effort and mitigate the chattering effect.

The rest of the paper is organized as: A tail sitter VTOL aircraft model is explained in section two, and the control strategy based on classical synergetic control and adaptive mechanism in section three. while the computer simulation results performed to test the efficiency of the suggested control strategy are existing in section four. In section five, the concluded and future work are highlighted.

2. Mathematical model of Tail-Sitter VTOL Aircraft

The Tail-Sitter VTOL aircraft mathematical model is established in this part. Two main assumptions are created in developing the mathematical model.

Assumption 1: The aircraft is assumed to work in a minor local region. This will support the system mathematical equation of flat earth [13].

Assumption 2: both elevators and blade masses have been ignored [13].

The position, the moments and the forces for Fig. 1 are defined as follows [10]:

$$\dot{P} = L(e)v \tag{1}$$

$$\dot{\Theta} = G(e)\Omega \tag{2}$$

$$m\dot{v} = -\Omega \times V + f \tag{3}$$

$$J\dot{\Omega} = -\Omega \times J\Omega + \tau \tag{4}$$

where $L(e)$ transforms from airframe to the fixed inertial coordinate used the transformation matrix [10, 13]:

$$\begin{bmatrix} C_\theta C_w & S_\varphi S_\theta C_w - C_\varphi S_w & C_\varphi C_\theta C_w + S_\varphi S_w \\ C_\theta S_w & S_\varphi S_\theta S_w + C_\varphi C_w & C_\varphi S_\theta S_w - S_\varphi C_w \\ -S_\theta & C_\theta S_\varphi & C_\theta C_\varphi \end{bmatrix}$$

where, C_a and S_a indicate $Cos(a)$ and $Sin(a)$, respectively. The parameter p represents the mass of the centre positions of the rigid body which denoted by $p = [p_n \quad p_e \quad p_d]^T$. The variable e: denotes the quaternion of the current attitude that expressed by the vector $e = [e_0 \quad e_1 \quad e_2 \quad e_3]^T$ which is described by $e = e_1 i + e_2 j + e_3 k$.

The VTOL aircraft's coordination in the n-frame is given as by $\Theta = [\varphi \quad \theta \quad w]^T$, where φ, θ, and w are the roll, pitch, and yaw angles, respectively. The Euler angles are utilized in aerodynamic modelling. The angular velocity in the b-frame remains constant and is represented by $\Omega = [P \quad Q \quad L]$. The vector F depicts the system's mass center and the external forces operating on it. The angular velocity transformation matrix, $G(e)$, is represented as follows [10, 13]:

$$G(e) = \begin{bmatrix} 1 & t_\theta S_\varphi & t_\theta C_\varphi \\ 0 & C_\varphi & -S_\varphi \\ 0 & S_\varphi / C_\theta & C_\varphi / C_\theta \end{bmatrix} \tag{5}$$

where t_θ represents $tan(a)$. The torque vector $\tau = [\tau_1 \quad \tau_2 \quad \tau_3]^T$ contains the torque elements applied to the mass center of VTOL aircraft in the body frame. The inertia matrix of the flying aircraft J is defined as follow [10, 13].

$$J = \begin{bmatrix} J_x & J_{xy} & J_{xz} \\ J_{yx} & J_y & J_{yz} \\ J_{zx} & J_{zy} & J_z \end{bmatrix} \tag{6}$$

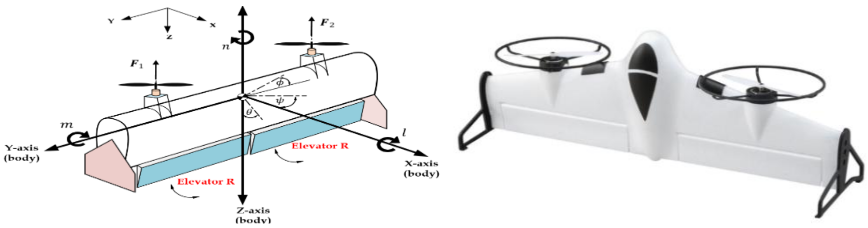

Fig. 1. The tail-sitter and flight dynamics UAV respectively [13].

The transformation of tail-sitter VTOL aircraft is achieved by the inertia matrix and its inverse as the following [13]:

$$J = \begin{bmatrix} J_x & 0 & 0 \\ 0 & J_y & 0 \\ 0 & 0 & J_z \end{bmatrix} \qquad J^{-1} = \begin{bmatrix} 1/J_x & 0 & 0 \\ 0 & 1/J_y & 0 \\ 0 & 0 & 1/J_z \end{bmatrix} \tag{7}$$

The matrix G in equation (2) transforms the angular velocity elements, resulting from Euler rotations, from the body frame to the inertial frame [10]. Consequently, the kinematic Eq. (2) can be represented in this way:

$$\dot{\varphi} = tan(\theta)\left(QSin(\theta) + LCos(\varphi)\right) + P \tag{8}$$

$$\dot{\theta} = QCos(\varphi) - LSin(\varphi) \tag{9}$$

$$\dot{w} = \frac{Q\,Sin(\theta) + L\,Cos(\varphi)}{Cos(\theta)} \tag{10}$$

Rewrite the expression of Eq. (4) by utilizing the torque vector $\tau = [\tau_1 \quad \tau_2 \quad \tau_3]^T$ and the inertia matrix taken by Eq. (6) resulting the follows [10, 13]

$$\dot{P} = (J_y - J_z)\frac{QL}{J_x} + \frac{\tau_1}{J_x} \tag{11}$$

$$\dot{Q} = (J_z - J_x)\frac{PL}{J_y} + \frac{\tau_2}{J_y} \tag{12}$$

$$\dot{L} = (J_x - J_y)\frac{PQ}{J_z} + \frac{\tau_3}{J_z} \tag{13}$$

To obtain the roll dynamic, assume that pitch rates and the yaw are zero ($Q = P = 0$) as presented in Fig. 2. As a result of this assumption and depending on Eq. (6) and Eq. (9) the rotational dynamics was expressed the roll angle with the next second order mathematical expression [10, 13]:

$$\ddot{\varphi} = \frac{\tau_1}{J_x} \tag{14}$$

The exerted torque τ_1 able to determine as follows:

$$\tau_1 = f.d - C_l\,\dot{\varphi} \tag{15}$$

where f denotes the difference force of the forces due to right and left rotor as $f = F_1 - F_2$. The d expression denoted the distance between reach rotor and the mass center. The expression $C_l\dot{\varphi}$ is the drag force, that signifies the aerodynamic moment that operates to resist the rolling moment with the damping constant C_l.

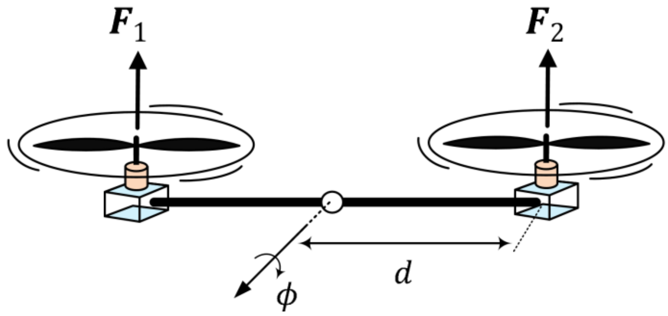

Fig. 2. The roll dynamics conformation [13].

Combining the previous two equations and taking into consideration the influence of gust wind ($\zeta(t)$) as external disturbance, the VTOL aircraft model is characterized as [10, 13]:

$$\ddot{\varphi} = F.d - C_l\dot{\varphi} + \zeta(t) \tag{16}$$

Represents the system model in Eq. (16) by state space description with new state variables ($x_1 = \boldsymbol{\varphi}$ and $x_2 = \dot{\boldsymbol{\varphi}}$), and $u = f$. The system with these state variables can be written as the following [10, 13]:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & -a\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}0\\ b\end{bmatrix}u + \begin{bmatrix}0\\ \zeta(t)\end{bmatrix} \tag{17}$$

where $a = C_l/J_x$ and $b = d/J_x$. For control purpose fined errors vector as $e = [e_1 \quad \dot{e}_1]^T$, where $e_1 = x_1 - x_d$ and $\dot{e}_1 = e_2 = x_2 - \dot{x}_d$. where x_r represented desired reference.

3. Control strategy design

Two control strategies have been intended for tracking control problem of roll angle for Tail-Sitter VTOL aircraft. The first control designed based on the classical Synergetic control and secondly, Adaptive Synergetic control which result is guarantees stability [31-35].

3.1. Synergetic Control Design

To design SC must define error between actual x_1 and desired x_d roll angle and error derivative as follows:

$$e_1 = x_1 - x_d$$

$$\dot{e}_1 = x_2 - \dot{x}_d \tag{18}$$

$$\ddot{e}_1 = \dot{x}_2 - \ddot{x}_d = -ax_2 + bu + \zeta - \ddot{x}_d$$

Firstly, define the equation of the Marco variable $s_m(e_1)$ as

$$s_m(e_1) = k_m e_1 + \dot{e}_1 \tag{19}$$

where, k_m is a gain design for synergetic control. Finding the first derivative of Eq. (34) to get

$$\dot{s}_m = k_m \dot{e}_1 + \ddot{e}_1 \tag{20}$$

The $s_m(e_1)$denotes the variable of manifold equation described by Eq. (21)

$$F_m \dot{s}_m(e_1) + s_m(e_1) = 0 \tag{21}$$

Where F_m is positive, and it denotes the converging ratio of $s_m(e_1)$ to manifold with $s_m(e_1) = 0$.

By Substitute Eq. (20) into Eq. (21) the result is

$$F_m(k_m \dot{e}_1 + \ddot{e}_1) + s_m = 0 \tag{22}$$

Using $\ddot{e}_1$ from Eq. (18), one can obtain

$$F_m(k_m \dot{e}_1 + -ax_2 + bu + \zeta - \ddot{x}_d) + s_m = 0 \tag{23}$$

Based on the above equation, the synergetic control law for Tail-Sitter VTOL can be get as

$$u = \frac{1}{b}(-k_m \dot{e}_1 + ax_2 - \zeta + \ddot{x}_d) - \frac{s_m}{F_m}) \tag{24}$$

The candidate positive Lyapunov function is selected in part of micro-variables equation as

$$v = \frac{1}{2}\left(s_m(e_1)\right)^2 \tag{25}$$

Using time derivative of the above Equation:

$$\dot{v} = s_m(e_1)\dot{s}_m(e_1) \tag{26}$$

Substitute $\dot{s}_m\,(e_1)$ from Eq. (21), one can obtain

$$\dot{v} = -\frac{s_m(e_1)^2}{F_m} \tag{27}$$

This shows that the controller of Eq. (24) ensures the stability property of the Tail-Sitter VTOL aircraft system.

3.2. Adaptive Synergetic Control design

Due to gust wind, the coefficients of a tail-sitter VTOL aircraft are uncertain. For this work, the coefficients a is consider uncertain [35-39]. This can be represented as:

$$\hat{a} = \tilde{a} + a \tag{28}$$

Where $\hat{a}$ is the estimated values coefficient a. The positive Lyapunov function defined as:

$$v = \frac{1}{2}(s_m)^2 + \frac{1}{2}y\tilde{a}^2 \tag{29}$$

where, y represents adaptation law. The result of time derivative of Eq. (29) as follows:

$$\dot{v} = s_m\dot{s}_m + y\tilde{a}\,\dot{\hat{a}} \tag{30}$$

Substituting Eq. (20) into Eq. (30), can be obtain:

$$\dot{v} = s_m(k_m\dot{e}_1 + \ddot{e}_1) + y\tilde{a}\,\dot{\hat{a}} \tag{31}$$

Substituting $\ddot{e}_1$ in above equation, resulting:

$$\dot{v} = s_m(k_m\dot{e}_1 - ax_2 + bu + \zeta - \ddot{x}_d) + y\tilde{a}\,\dot{\hat{a}} \tag{32}$$

The controller u can be designed based on Eq. (24) utilizing the selected estimated values,

$$u = \frac{1}{b}(-k_m\dot{e}_1 + \hat{a}\,x_2 - \zeta + \ddot{x}_d) - \frac{s_m}{F_m}) \tag{33}$$

Using the designed control law which presented in Eq. (33) then Eq. (28), $\dot{v}$ becomes

$$\dot{v} = s_m\left(-ax_2 + \hat{a}\,x_2 - \frac{s_m}{F_m}\right) + y\tilde{a}\,\dot{\hat{a}} \tag{34}$$

$$\dot{v} = s_m\left(\hat{a}\,x_2 - \frac{s_m}{F_m}\right) + y\tilde{a}\,\dot{\hat{a}} \tag{35}$$

$$\dot{v} = -\frac{{s_m}^2}{F_m} + \hat{a}\big(x_2 s_m + y\,\dot{\hat{a}}\big)$$

For $\dot{v} < 0$, consider the following:

$$x_2 s_m + y\,\dot{\hat{a}} = 0 \tag{36}$$

This creates the adaptive synergetic control law:

$$\dot{\hat{a}} = -\frac{x_2}{y}s_m \tag{37}$$

The adaptive law in Eq. (36), ensures that $\dot{v}$ is negative definite, and hence asymptotic stability of the gust wind tail-sitter VTOL aircraft that controlled by ASC is assured.

4. Simulation results and discussion

This part of study existing two scenarios. Firstly, the simulation results of ASC and SC mechanisms applied for tail-sitter VTOL aircraft are existing and discussed. Secondly, the SC and ASC were compared to model reference adaptive control (MRAC) which designed in literature [13]. These simulation results are achieved by MATLAB environment. The "ODE4" solver with fixed-step time were selected. The controller's designed parameters and tail-sitter VTOL aircraft are exhibits in Table 1.

Table 1. Factors of ASC and SC controllers and tail-sitter VTOL aircraft.

Designed Parameters	Value
The damping Coefficient C_l	0.36
Rotor distance from the centre of mass d	0.2 m
The x-axis moment of inertia J_x	0.0144 kg.m^2
Positive gain F_m	9
Gain design for synergetic control k_m	3
The adaptation gain	1

Scenario I: This part exhibits the behaviour of tail-sitter VTOL aircraft exposed to wind disturbance and controlled by ASC and synergetic control strategies. Figure 3 illustrates the gust wind effect, and Fig. 4 indicated the roll angle of tail-sitter VTOL aircraft controlled by ASC and SC.

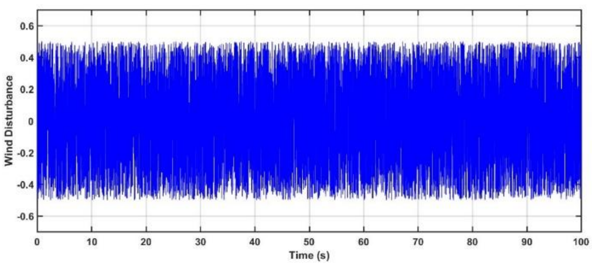

Fig. 3. The wind disturbance.

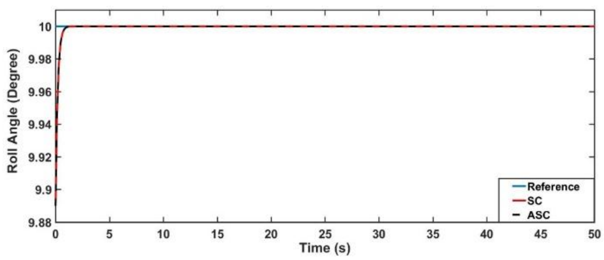

Fig. 4. The roll angle of system controlled by ASC and SC.

The control efforts produced by the classical SC and ASC strategies are denoted in Fig. 5. The control action produced by classical SC was greater than the control action generated by ASC as shown in this figure.

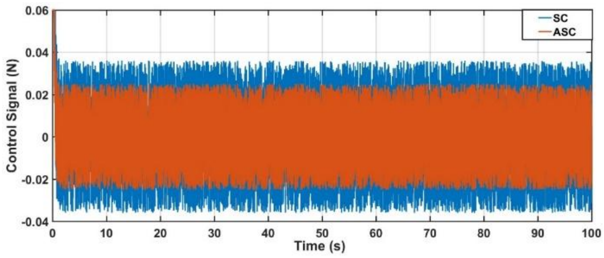

Fig. 5. Control signals (N) created by the SC and ASC.

Figure 6 displays the tracking error (e_1) between the Adaptive and classical synergetic control strategies-controlled tail-sitter VTOL aircraft.

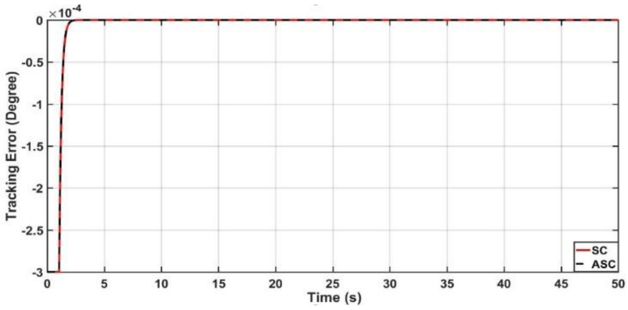

Fig. 6. the Tracking Error of model between the adaptive and classical synergetic control strategies.

Figure 7 demonstrates the uncertainty estimation produced by the adaptive law. The estimate of the coefficient created by the adaptive laws led to bounded estimation of the uncertainty, which yielded a stable controlled tail-sitter VTOL aircraft. This boundedness of coefficient estimation is important otherwise; the estimated coefficient may increase without bounds and this causes instability in the system.

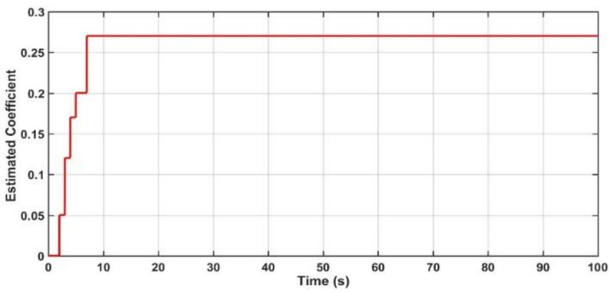

Fig. 7. Estimated coefficient by adaptive law.

Scenario II: This scenario obtainable the results of Model Reference Adaptive Control (MRAC) which designed by Ajel et al. [13], firstly, the roll angle of tail-sitter VTOL aircraft controlled by MRAC was offered in Fig. 8.

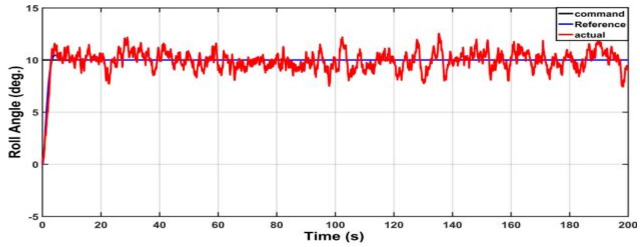

Fig. 8. Performance of the roll angle controlled by MRAC [13].

By observing Figs. 4 and 8, it is clear that ASC and SC are better than the MRAC strategy, as the recommended strategy when it reaches the matter without any fluctuation, while the compared strategy, when it reaches the demand, keeps oscillating around it. But this comes at the expense of access time, as MRAC is faster than ASC. Moreover, ASC and SC are faster than MRAC as the reaching time for MRAC is 2.2 seconds while the access time for ASC is 0.2 seconds and the access time for SC is 0.5 seconds.

For the purpose of comparison, we also show the error that resulted from the proposed strategy and the compared strategy. Figures 9 and 10, existing e_1 and e_2 resulting from ASC and MRAC respectively.

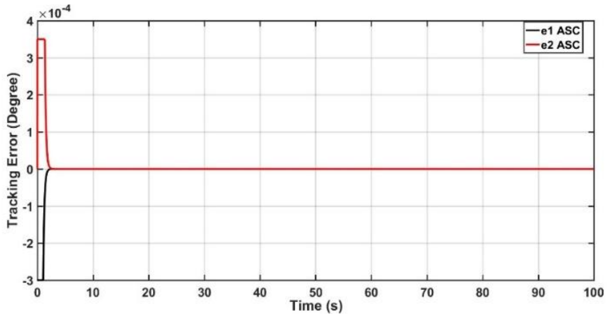

Fig. 9. Tracking errors resulting from ASC.

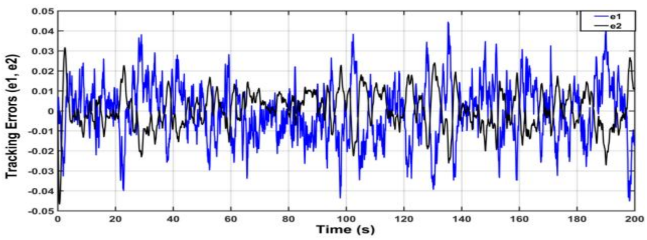

Fig. 10. Tracking errors resulting from MRAC [13].

From observing Figures 9 and 10, the tracking error became near zero when using the ASC strategy, while it fluctuated between (0.04) and (-0.04) when utilizing MRAC. This is what makes ASC better than the compared strategy. Figure 11 demonstration the control action created by the MRAC.

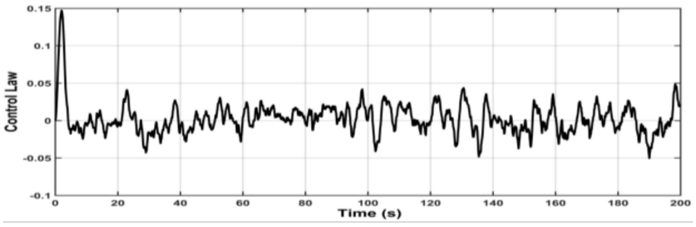

Fig. 11. The control action (N) generated by the MRAC [13].

By comparing Figs. 6 and 11, it was found that the ASC provided the best performance with the least control effort than MRAC, as the value of maximum control action is (0.02), while in the maximum control action is (0.04) given by MRAC.

From the comparison result, it turns out that the performance of proposed strategy is better than MRAC but the response of compered is faster.

The proposed controller can be used as a control framework when compared to other control strategies for VTOL in the future works. In the literature, some types of control schemes may be suggested for the purpose of comparison like nonlinear state-feedback controller, output controller and intelligent controllers [40-57]. Embedded system design based on FPGA board or LabVIEW software, supported by NI interfacing device, can be used to implement the proposed controller in the real-time environment [58-62].

5. Conclusions

This work presents an adaptive control design based on synergetic theory to decrease the influence of wind gust on tail-sitter VTOL aircraft. Based on Lyapunov stability analysis, the controller was designed in order to ensure the stability of the controlled system. Furthermore, the performance of ASC and SC was compared and then the performance of ASC and MRAC was compared to prove the efficiency of the proposed controller. The computer simulations proved that better vibration suppression was gained by applying adaptive synergetic control strategy as compared to SC and MRAC. Moreover, ASC technique resulted achieved a bounded estimate of the tail-sitter VTOL aircraft coefficients. This study can be developed by design Spotted Hyena Optimizer to select optimal gains to ASM control law.

Moreover, able to design Extended State Observer (ESO) to estimate gust wined disturbance. Additionally, can suggest Sliding mode control based on barrier function, this strategy is characterized by generated a smooth and continuous control signal and does not need information about the model uncertainty or disturbances which the system is exposed. Furthermore, A novel Adaptive Integral Sliding Mode Control is proposed, it is calculated without the need to know the perturbation upper bound (only the future state) and reducing chattering amplitude with minimum control effort.

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