Robust Super-Twisting Sliding-Mode Controller for Launch Vehicle

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Abstract— **Attitude control of launch vehicle in atmospheric phase is a challenging problem which involves ensuring stability for a time-varying plant with minimal tracking error and effective wind disturbance rejection. This paper deals with design of a robust controller for attitude control in atmospheric phase with slosh and flexibility dynamics included. Standard linearized time-slice based model is adopted as baseline model for control design. A robust super twisting sliding mode controller is designed to handle the uncertainties in plant model and achieve the desired response. Super-twisting sliding mode control law is derived for an attitude tracking problem of the launch vehicle. Performance is augmented by using the saturation function instead of signum function in the controller. Robustness of the proposed controller algorithm is validated in presence of liquid engine slosh, structure flexibility and the wind disturbance. Stability validations and time domain responses presented in the paper reinforces the ruggedness of the proposed controller.**

Keywords— ***Launch Vehicle Control, Robust Control, Sliding Mode Control, Super-Twisting Sliding-Mode Control, Launch Vehicle flexibility, Liquid Engine Sloshing***

I. INTRODUCTION

Launch vehicle control is a challenging problem owing to the complexity in terms of time varying flexibility dynamics, sloshing in liquid engines along with aerodynamic disturbances. Attitude control is a critical aspect of launch vehicle operation, ensuring that the vehicle upholds the desired orientation throughout its flight. Accurate attitude regulation is not only to cater for aerodynamic load on vehicle but also essential for achieving precise trajectory tracking and successful payload deployment. Stabilizing an inherently unstable launch vehicle (vehicle with positive aerodynamic disturbance moment coefficient) subjected to aero disturbances and structural and flexibility effects makes attitude control problem more challenging. A robust control design ensures precise orientation tracking despite external disturbances, structural flexibility and internal couplings such as fuel slosh. Ineffective control may lead to mission failure or excessive guidance correction that results in payload penalty. Traditionally, launch vehicles have employed classical gain-scheduled control strategies, where gains are designed for a linearized plant at specific points (time-sliced approach) over the flight envelope. Designed gains are adjusted or interpolated along the flight envelope. In general, design based on linearized plant and gain-scheduling along the trajectory is an effective approach in this field. However, various conventional as well as modern approaches are available in the literature.

Conventional proportional integral and derivative (PID) controllers with appropriate filters for flexibility and slosh dynamics is also a viable solution cited in the literature. PID based approach further augmented with various load relief algorithms during high dynamic pressure regime of the ascent flight [1, 2]. In [3], Active Disturbance Rejection Control(ADRC) based continuous-time predictive controller is designed wherein wind disturbance is estimated by Generalized Extended State Observer (GESO). Adaptive methodology based controllers are also cited in literature, as given in [4] where Lyapunov based adaptive PD and PID controller in Model Reference Adaptive Control (MRAC) technique for a highly unstable launch vehicle is designed. It provides better performance than conventional gain scheduling approach in terms of tracking error.

One important aspect of launch vehicle control is the utmost ruirement of robustness, due to uncertainty in terms of disturbances, un-modelled dynamics and parameter perturbations. Induced angle of attack in response to the winds and other disturbances like separation disturbances must be controlled specifically in the region where dynamic pressure is high.

Higher order controllers are also implemented as explained in [5], wherein a robust H_∞ based controller is designed for the attitude control. Transfer function of the simplified model (neglecting component due to wind) is considered for the automatic weight selection algorithm of the H_∞ Controller and its robustness is analyzed. Similarly, an H_∞ controller is designed and compared with classical controller in [6].

In field of robust control, variable structure control i.e. Sliding Mode Control (SMC) is also an effective tool to design a robust controller. SMC techniques have gained attention as it is highly robust as providing strong resistance to model uncertainties, parameter changes and external disturbances. It drives the system's trajectory onto a predefined sliding surface, wherein the system behavior remains unaffected by these imperfections once it reaches the sliding mode. Sliding mode in the context of control system was introduced by Utkin [7], since then it is successfully applied to a wide range of systems, including robotics, automotive control, and aerospace applications [8-10]. Among these, the Super-Twisting Sliding Mode Control (STSMC) algorithm, a second-order SMC method, offers notable advantages including finite-time convergence and reduced chattering without ruiring measurement of the derivative of the sliding variable. These features make it particularly suitable for aerospace systems, where maintaining smooth and reliable control is essential.In view of the above, variable structure based approach i.e. sliding mode is a suitable candidate for the launch vehicle control due to its inherent robustness.

STSMC is used in [11] to deal with slosh dynamics of launch vehicle whereas in the present study, flexibility dynamics and wind disturbance are also added to the vehicle model. Further, work is extended by deriving generalized STSMC for attitude tracking problem. Sign function of STSMC is updated with saturation function as explained in [9].

In present study, a detailed model of launch vehicle consisting of flexibility, slosh, and actuator is considered. Here, simulation study mainly focuses on the application of the STSMC algorithm to a linear model of a launch vehicle, which incorporates structural flexibility and propellant slosh dynamics, two effects known to significantly influence vehicle behavior during ascent. To evaluate the robustness and performance of the proposed control scheme, a representative wind disturbance profile is introduced, consisting of an initial ramp input (shear), followed by a gust, and finally a constant wind phase. This profile simulates realistic environmental conditions encountered during launch and allows for a comprehensive assessment of the control algorithm's disturbance rejection capability.

Simulation results demonstrate that the STSMC provides effective attitude stabilization and disturbance attenuation under the defined conditions. The findings highlight the suitability of the super-twisting approach for launch vehicle control, offering a robust and high-performance alternative to conventional gain-scheduled or PID-based controllers, especially in scenarios where vehicle flexibility, sloshing , parametric uncertainties and disturbances play a significant role.

II. Mathematical model

Mathematical model of the launch vehicle is considered as given in [1], [6], [11]. Dynamics of an unstable launch vehicle in longitudinal plane is explained by means of mathematical model given by (1).

Linearized motion of the launch vehicle in pitch plane can be written as

$$\begin{aligned} \ddot{z} &= -\frac{T_T-D}{m}\theta - \frac{L_\alpha}{m}\alpha + \frac{T_c}{m}\delta \\ \ddot{\theta} &= \mu_\alpha \alpha + \mu_c \delta \end{aligned} \quad (1)$$

where $\alpha = \theta + \frac{\dot{z}}{V} + \alpha_w$. z is normal displacement of the vehicle in Z_I axis. D is drag, m is mass of vehicle, θ is attitude angle of the vehicle relative to inertial frame. V is forward velocity of the vehicle and α_w is the gust angle of attack of the vehicle. T_T is defined as total thrust of the vehicle given by $T_T = T_c + T_s$; where T_s is non-swivelled thrust.

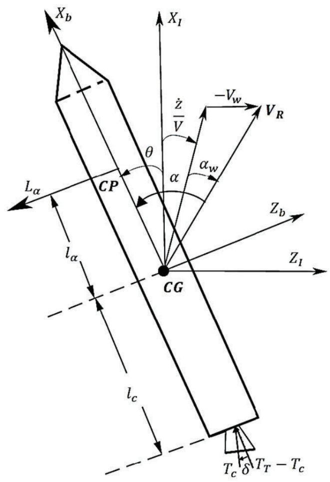

Fig. 1. Launch vehicle geometry in longitudinal direction.

A. Slosh and Flexibility Dynamics

Mathematical Model is further augmented with linear model of slosh and flexibility dynamics. Simple pendulum model of slosh is considered as explained in [1], [11].

$$\ddot{\Gamma}_p = \frac{1}{L_p}\left[-\frac{\Sigma F_Z}{m_0} + \frac{(l_p - L_p)}{I}\Sigma M_y - \dot{U}_0 \Gamma_p\right] \quad (2)$$

forces and moments of slosh phenomenon can be expressed as

$$\begin{aligned} \Sigma F_z &= T_c\delta - L_\alpha \alpha + m_p \dot{U}_0 \Gamma_p \\ \Sigma M_y &= T_c l_c \delta + L_\alpha l_\alpha \alpha - m_p l_p \dot{U}_0 \Gamma_p \end{aligned} \quad (3)$$

where, L_p is the length of the pendulum considered for the slosh dynamics, l_p represents distance of the hinge point from the origin of the body axis of the system, Γ_p is slosh angle, m_0 is the vehicle mass without the slosh mass. I is the moment of inertia, $\dot{U}_0$ is forward acceleration and m_p is mass of the pendulum.

Similarly, uation for the flexibility can be expressed in terms of generalized coordinate q.

$$\ddot{q} = -\frac{T_c \Phi_T}{m_q}\delta - 2 * \zeta_q \omega_q \dot{q} - \omega_q^2 q \quad (4)$$

where m_q is generalized mass of bending mode, Φ_T represents modal displacement, ω is fruency and ζ_q is damping of first bending mode. q represents generalized coordinate for first bending mode. Bending modes are generally normalized at thrust location so here Φ_T is considered as unity [1]. Engine dynamics is not considered in

(4). (1) can be augmented further with the slosh and flexibility dynamics as

$$\ddot{\theta} = \mu_\alpha \alpha - \mu_p \Gamma_p + \mu_q q + \mu_c \delta; \quad (5)$$

where slosh angle dynamics given as

$$\ddot{\Gamma}_p = \frac{1}{L_p} \left[(l_p - L_p)\mu_c - \frac{T_c}{m_0} \right] \delta + \frac{1}{L_p} \left[\frac{L_\alpha}{m_0} + (l_p - L_p)\mu_\alpha \right] \theta - \frac{1}{L_p} \left[\left(1 + \frac{m_p}{m_0}\right) \dot{U}_0 + (l_p - L_P)\mu_p \right] \Gamma_p \quad (6)$$

Here, aerodynamic, thrust and sloshing coefficients are defined as

$$\mu_\alpha = \frac{L_\alpha l_\alpha}{I}, \mu_c = \frac{T_c l_c}{I}, \mu_p = \frac{m_p l_P \dot{U}_0}{I},$$
$$\mu_q = -\frac{T_c}{I_{yy}} (l_c \sigma_T + \Phi_T)$$

where Φ_T represents modal displacement and σ_T is slope of first bending mode at thrust location. μ_q is flexibility coefficient.

B. State Space uation

In state space uation derivation, α is replace by $\alpha = (\theta + \frac{\dot{z}}{V} + \alpha_w)$. State space uation is derived by using (1) to (6). State vector is given by

$$x_p = [\theta, \dot{\theta}, \dot{z}, q, \dot{q}, \tau_p, \dot{\tau}_p, \delta_a, \dot{\delta}_a]^T.$$

State-space uation with defined state vector can be written as

$$\dot{x}_p = A_p x_p + B_p u + B_d d$$
$$y_p = C_p x_p$$
$$y_m = C_m x_p \quad (7)$$

where matrices are defined as

$$A_p = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \mu_\alpha & 0 & \frac{\mu_\alpha}{V} & \mu_q & 0 & -\mu_p & 0 & \mu_c & 0 \\ b_1 & 0 & -\frac{L_\alpha}{mV} & 0 & 0 & 0 & 0 & \frac{T_c}{m} & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\omega_q^2 & -2\zeta_q\omega_q & 0 & 0 & -\frac{T_c\Phi_T}{m_q} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ b_2 & 0 & 0 & 0 & 0 & b_3 & 0 & b_4 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\omega_a^2 & -2\zeta_a\omega_a \end{bmatrix}$$

$$B_p = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \omega_a^2 \end{bmatrix}^T$$

$$C_p = [1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0];;$$

$$C_m = \begin{bmatrix} 1 & 0 & 0 & \sigma_q & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & \sigma_q & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix};$$

$$B_d = \begin{bmatrix} 0 & \mu_\alpha & -\frac{L_\alpha}{m} & 0\ 0\ 0\ 0\ 0\ 0 \end{bmatrix}^T$$

Here, u is control input i.e. commanded deflection δ_c and disturbance d is wind induced angle of attack α_w. y_p is output i.e. attitude angle of vehicle relative to inertial frame. y_m is measured output vector consists of attitude and rate with flexibility component and $\dot{z}$ (normal velocity of the vehicle in ZI axis) . Coefficients of matrix A defined as $b_1 = -\frac{T_T - D + L_\alpha}{m}$, $b_2 = \frac{1}{L_p}\left[\frac{L_\alpha}{m_0} + (l_p - L_p)\mu_\alpha\right]$, $b_3 = -\frac{1}{L_p}\left[\left(1 + \frac{m_p}{m_0}\right)\dot{U}_0 + (l_p - L_p)\mu_p\right]$, $b_4 = \frac{1}{L_p}\left[(l_p - L_p)\mu_c - \frac{T_c}{m_0}\right]$. Here, in C_m matrix, effect of vehicle flexibility in attitude and rate measurement by the sensor is considered. σ_q represents bending mode slope at sensor location.

III. CONTROL LAW DESIGN

In the present section STSMC control law for the system given by (7) is derived. Ideal actuator dynamics are assumed along with nominal plant characteristics for control law derivation. Flexibility, slosh and actuator dynamics are modelled in simulation studies provided in section(5) to demonstrate the performance of proposed control law. Vehicle dynamics given by (5) can be written as

$$\ddot{\theta} = \mu_\alpha \left(\theta + \frac{\dot{z}}{V} + \alpha_w\right) - \mu_p \tau_p + \mu_q q + \mu_c \delta_c \quad (8)$$

Rewriting (8) and following procedure given in [9], [12] as

$$\ddot{\theta} = f_x + f_d + gu \quad (9)$$

where $f_x = \mu_\alpha\theta + \mu_\alpha\frac{\dot{z}}{V} - \mu_p\tau_p + \mu_q q$, $f_d = \mu_\alpha\alpha_w$ is wind disturbance, $g = \mu_c$ is control moment coefficient of vehicle, and u is nozzle deflection command δ_c. Now, sliding mode surface can be defined in such a way that its relative degree with respect to control input is one [13].

$$S = (\dot{\theta}_c - \dot{\theta}) + \lambda(\theta_c - \theta) = \dot{e} + \lambda e \quad (10)$$

Here, θ_c and $\dot{\theta}_c$ are desired attitude and rate respectively and e is tracking error. Sliding surface S reaching towards zero ensures stable attitude dynamics of the vehicle for a positive $\lambda > 0$. Super-twisting sliding mode controller can be designed for launch vehicle dynamics (defined by (9)) as

$$u = \frac{1}{g}(-f_x - f_d - u_1) \quad (11)$$
$$u_1 = -K_1|S|^{\frac{1}{2}}sign(S) + \nu$$
$$\dot{\nu} = -K_2 sign(S)$$

Here, K_1, K_2 are control gains satisfying, $K_1 > 0$, $K_2 > 0$. Control law given by (11) can be written as

$$u = \frac{1}{\mu_c}\Big(-\mu_\alpha\theta - \mu_\alpha\frac{\dot{z}}{V} + \mu_p\tau_p - \mu_q q - \mu_\alpha\alpha_w + K_1|S|^{\frac{1}{2}}sign(S) - \nu\Big) \quad (12)$$

If the information of disturbance α_w and dynamics of slosh and flexibility are not available then nominal control law can be redesigned as,

$$u = \frac{1}{\mu_c}\left(-\mu_\alpha\theta - \mu_\alpha\frac{\dot{z}}{V} + K_1|S|^{\frac{1}{2}}sign(S) - \nu\right) \quad (13)$$

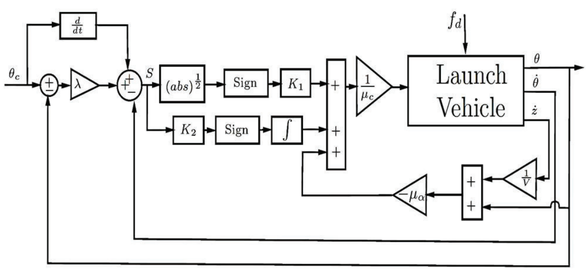

Fig. 2. Schematic block diagram of control law given by (13)

In control law given by (13), term $(\lambda|S|^{\frac{1}{2}}sign(S))$ drives sliding surface to zero, and $-\nu$ compensates for total disturbance similar to integral effect of PID controller. These two terms are critical in providing robustness in the absence of information regarding wind-gust angle , flexibility and slosh dynamics. It also provides robustness against parametric uncertainties in launch vehicle like dispersion in control-moment coefficient , aerodynamic disturbance coefficient etc. Present study mainly focuses on robustness property of super twisting algorithm towards wind disturbance, flexibility and slosh dynamics. Super-twisting sliding mode is a continuous control law wherein high fruency switching is circumvented by means of integration of sign of sliding surface as given in (11).

Control law give by (13) is designated as SMC1. In order to incorporate tracking error dynamics in the control design [10], control-law is derived by means of sliding surface dynamics of (10).

$$\dot{S} = (\ddot{\theta}_c + \lambda\dot{\theta}_c) - (\ddot{\theta} + \lambda\dot{\theta})$$
$$\dot{S} = K_{\theta_c} - f_x - f_d - gu - \lambda\dot{\theta} \quad (14)$$

where $K_{\theta_c} = (\ddot{\theta}_c + \lambda\dot{\theta}_c)$ term is due to commanded attitude dynamics and f_x, f_d and g are defined in (9). Resulting control law derived from dynamics of (14) is augmented with K_{θ_c} and $\lambda\dot{\theta}$ terms and given as

$$u = \frac{1}{\mu_c}\left(K_{\theta_c} - \mu_\alpha\theta - \lambda\dot{\theta} - \mu_\alpha\frac{\dot{z}}{V} + K_1|S|^{\frac{1}{2}}sign(S) - \nu\right) \quad (15)$$

Control law given by (15) is designated as SMC2, as generalized version of SMC1 and can be used either in attitude tracking or regulation problem.

IV. Stability Analysis

Close loop stability is analyzed by means of Lyapunov function, from (14)

$$\dot{S} = \ddot{e} + \lambda\dot{e} = \left(\ddot{\theta}_c - \ddot{\theta}\right) + \lambda(\dot{\theta}_c - \dot{\theta}) \quad (16)$$

Substituting $\ddot{\theta}$ from (9), with assumption that only nominal value of f_x, and f_d, i.e. f_{x0}, and f_{d0}, respectively are known. Here, $f_{x0} = \mu_\alpha\theta + \mu_\alpha\frac{\dot{z}}{V}$ and $f_{d0} = 0$ as no information of wind disturbance is available to controller.In general, exact information regarding dynamics and disturbances are not known. One can also asses impact of parametric uncertainty by using these nominal values. Now, sliding surface dynamics can derived from (9) and (15) as

$$\dot{S} = -f_x + f_{x0} - f_d - K_1|S|^{\frac{1}{2}}sign(S) + \nu$$
$$\dot{S} = \bar{d} - K_1|S|^{\frac{1}{2}}sign(S) + \nu \quad (17)$$

where $\bar{d} = -f_x + f_{x0} - f_d$ represents total disturbance need to be compensated by the controller. Rewriting sliding mode dynamics in compact form as given in [14]

$$\dot{S} = -K_1|S|^{\frac{1}{2}}sign(S) + \bar{\nu} \quad (18)$$

$\bar{\nu}$ is defined as $\bar{\nu} = \bar{d} + \nu$.
Now defining Lyapunov function Z as

$$Z = \Psi^{\mathrm{T}}\ P\ \Psi \quad (19)$$

and state vector Ψ given by

$$\Psi = \begin{bmatrix} |S|^{\frac{1}{2}}sign(S) \\ \bar{\nu} \end{bmatrix}$$

Here P is a symmetric metric with $P > 0$. Derivative of state vector Ψ can be written in matrix form, by defining $\frac{d}{dt}\left(|S|^{\frac{1}{2}}sign(S)\right) = \frac{1}{2\sqrt{|S|}} * (-K_1|S|^{\frac{1}{2}}sign(S) + \bar{\nu})$ by means of (18). Derivative of state vector is defined $\forall s$, except at $S = 0$ due to the discontinuity of sign function at zero.

$$\dot{\Psi} = |S|^{-\frac{1}{2}} A_v\, \Psi \quad (20)$$

Here

$$A_v = A_{v0} + \Delta A_v$$

$$A_{v0} = \begin{bmatrix} \frac{-K_1}{2} & \frac{1}{2} \\ -K_2 & 0 \end{bmatrix}, \Delta A_v = \begin{bmatrix} 0 & 0 \\ \dot{\bar{d}}\ sign(S) & 0 \end{bmatrix}$$

Rewriting ΔA_v matrix in terms of maximum disturbance bound $\dot{\bar{d}}_{max}$ such that f_v is always ≥ 1

$$\Delta A_v = C_v\, f_v\, e_v$$

where

$$C_v = \begin{bmatrix} 0 \\ 1 \end{bmatrix}_{2\times1},\ f_v = \left(\frac{\dot{\bar{d}}}{\dot{\bar{d}}_{max}}\right), e_v = \begin{bmatrix} \dot{\bar{d}}_{max}sign(S) & 0 \end{bmatrix}_{1\times2}$$

Now derivative of Lyapunov function is obtained as

$$\dot{Z} = |S|^{-\frac{1}{2}}\,\Psi^T({A_v}^T P + PA_v)\Psi$$
$$\dot{Z} = |S|^{-\frac{1}{2}}\,\Psi^T\{(A_{v0} + C_v\, f_v\, e_v)^T P$$
$$+P(A_{v0} + C_v\, f_v\, e_v)\}\Psi \quad (21)$$

Now from Lyapunov theorem defining ${A_v}^T P + PA_v = -Q$

$$\dot{Z} = -|S|^{-\frac{1}{2}}\,\Psi^T(Q)\Psi \quad (22)$$

Here, gains of super-twisting controller are chosen such that A_{v0} is Hurwitz, and existence of $P > 0$ for $Q > 0$ ensures the stability of dynamics given by (20). Reader may refer to [14] for finite time convergence analysis.

V. Simulations

Simulations with actuator dynamics, wind disturbance profile, bending and slosh dynamics are carried out to showcase the efficacy of proposed algorithm in launch vehicle control. Sliding surface is selected as $\dot{e} + 2e$ to fulfill settling time ruirement of 2 sec for attitude dynamics . Super-twisting gains $K_1 = 0.6708$ and $K_2 = 0.11$ are designed as per [13, 14] and then tuned iteratively based on simulation results. Performance comparison of SMC1 controller with signum (Sign) and saturation (Sat) function is carried out. It is found that, super-twisting controller reduces chattering, and can be further reduced by saturation function with appropriate error band e_{lim}. Comparison with both the functions are shown in Fig(3).

Signum (Sign) function of the controller is replaced with saturation function defined as [9].

$$sat(S) = \begin{cases} 1 & S > e_{lim} \\ \frac{S}{e_{lim}} & |S| \geq e_{lim} \\ -1 & S > e_{lim} \end{cases} \tag{23}$$

In present simulation e_{lim} is taken as 0.1 deg. Simulation results with actuator dynamics of 6Hz and damping of 0.7, 1 flexible mode with fruency 3Hz and damping of 0.01 is considered. Slosh and other parameters of launch vehicle are given in the Table(1). Initial conditions of launch vehicle considered as zero except initial position of 1 deg and rate of 2deg/sec. Commanded attitude and rates are taken as zero.

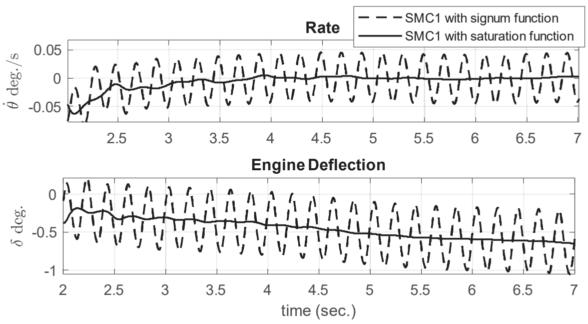

Fig. 3. Comparative study for signum and saturation function in super-twisting sliding mode control

TABLE I: Launch vehicle parameters

parameter	value
l_c: control arm	21 m
T: thrust	$6.4 \times 10^5 N$
I_{yy}: moment of inertia	$4 \times 10^6 kg - m^2$
m_o : vehicle mass without slosh	50580 kg
m_p : pendulum mass	2500 kg
$\dot{U}_0$:forward acceleration	12 m/s^2
μ_c: control moment coefficient	3.36 sec^{-2}
L_p: pendulum length	2.73 m
l_p: hinge point to CG	5.56 m
σ_q: bending mode slope at sensor location	-0.0127 rad/m
σ_T: bending mode slope at thrust location	0.015 rad/m
l_α: aero moment arm	15 m
L_α: Lift coefficient	3.2267×10^5 N/rad
V: forward velocity of vehicle	170 m/s
μ_q: bending mode coefficient	-0.2104 sec^{-2}
m_q : generalized mass of bending mode	4000 kg
ω_a: actuator frequency	37.6991 rad/s
ζ_a: actuator damping	0.7
ζ_q: bending mode damping	0.01
ω_q: bending mode frequency	18.8496 rad/s
μ_p: slosh mode coefficient	0.0417 sec^{-2}

Comparative study between SMC1 controller given by (13) and SMC2 controller given by (15) is carried out for the attitude regulation problem.

In simulation, a typical wind profile is selected to test robustness of SMC controller. Till 8 sec a ramp wind profile followed by a wind gust and then constant wind is considered. In Fig.(4) , profile of wind disturbance is given. As response to wind disturbance , angle of attack α profile of launch vehicle is shown. Initial overshoots in α and attitude θ is higher in SMC1. SMC2 output is smoother as compare to SMC1 as shown in steady state rate in Fig(5). Performance of SMC2 is better even in regulation problem because of additional term $\lambda\dot{\theta}$ in the control law.

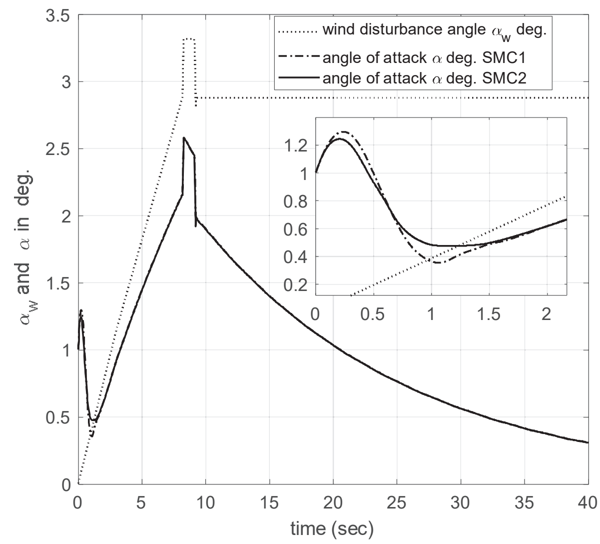

Fig. 4. Wind disturbance angle α_w and angle of attack α of the vehicle

States related to flexibility, slosh and actuator are plotted in Fig(6). 3Hz bending fruency of considered mode is visible in plot of generalized coordinate q.

Additional term $\lambda\dot{\theta}$ added in SMC2 improves performance and reached sliding surface smoothly as shown in Fig (7,8).

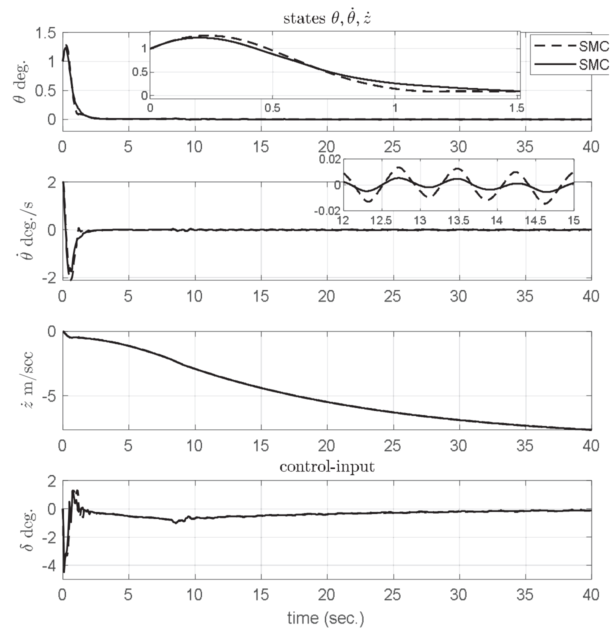

Fig. 5. Attitude, rate, normal velocity and engine deflection of the vehicle

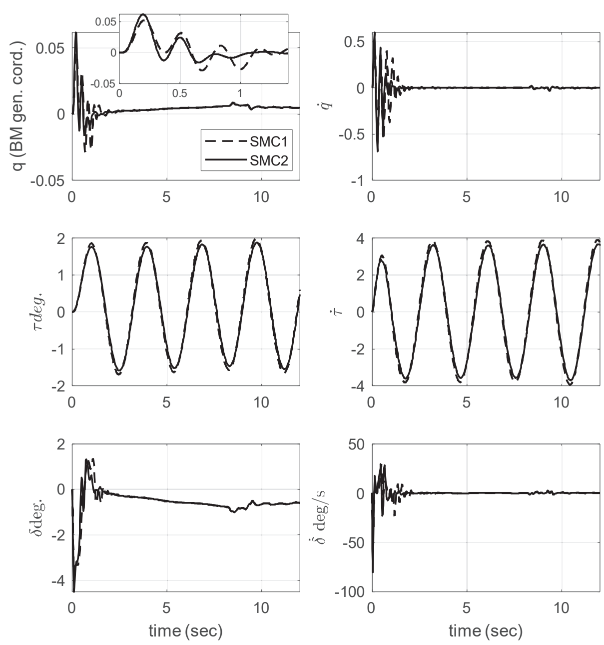

Fig. 6. States related to slosh, flexibility and actuator

VI. Conclusion and Future Scope

In the present study super-twisting sliding mode controller is applied to the launch vehicle with slosh and flexibility dynamics. In presence of wind disturbance vehicle is able to regulate the attitude by means of robust performance of controller. No additional information of slosh and bending mode is used in super-twisting algorithm. Study further can be extended with detailed stability analysis. Wind disturbance observer can be integrated with the proposed algorithm to reduce bounds of uncertainty present in the real scenario. Classical linear control based analysis of super twisting by means of describing function or gain design for super twisting controller of launch vehicle based on classical algorithms can also be a future scope of the study.

References

[1] A. L. Greensite, Analysis and Design of Space Vehicle Flight Control Systems. New York, USA: Spartan Books, 1970.

[2] G. Jee, V. Brinda, V. Lalithambika, and M. Dhekane, "Achieving load relief with minimal change in conventional control law of a launch vehicle," IFAC-PapersOnLine, vol. 49, no. 1, pp. 361–366, 2016, 4th IFAC Conference on Advances in Control and Optimization of DynamicalSystems ACODS 2016.

[3] B. Panchal, U. P. Abhijith, K. Kumar Sharma, S. N, K. CS, A. P. Nair, G. Jee, and S. L, "Continuous-time predictive control based robust attitude control of launch vehicle," in 2025 6th International Conference on Control, Communication and Computing (ICCC), 2025, pp. 1–6

[4] A. P. Nair and N. Selvaganesan, "Lyapunov based pd/pid in model reference adaptive control for satellite launch vehicle systems," vol. 51, pp. 70–77, 2016.

[5] K. E. George, A. Mary, A. M. Varghese, M. Sivadas, A. Mohan, and A. Santhosh, "International conference on advances in computing and communications (icacc) kochi, kakkanad, india," 2021.

[6] V. Garg, R. J. Abraham, A. Antony, and K. K. Sharma, "Design of a robust controller for launch vehicle," vol. 55, no. 1, pp. 8–13, 2022.

[7] V. Utkin, "Variable structure systems with sliding modes," IEEE Transactions on Automatic Control, vol. 22, no. 2, pp. 212–222, 1977.

[8] A. Dixit, A. Kodhanda, M. S. Mahesh, and S. E. Talole, "Active flutter suppression using ude based sliding mode control," pp. 443–447, 2016.

[9] Z. K. Chong Yang, "Application of super twisting guidance law based on extended state observer," Applied Mechanics and Materials, vol. 433-435, pp. 1009–1014, 2013.

[10] S. J. Gambhire, D. R. Kishore, P. S. Londhe, and S. N. Pawar, "Review of sliding mode based control techniques for control system applications," International Journal of Dynamics and Control, 2020.

[11] D. Vinod, A. P. Nair, and L. P. PS, "Nonlinear robust attitude controller for a satellite launch vehicle with fuel slosh dynamics," pp. 1148–1154, 2017.

[12] J. S. Vadim Utkin, Jrgen Guldner, "Sliding mode control in electromechanical systems," CRC Press Taylor and Francis Group, 2009.

[13] R. Sadeghi, S. M. Madani, M. Ataei, M. R. Agha Kashkooli, and S. Ademi, "Super-twisting sliding mode direct power control of a brushless doubly fed induction generator," IEEE Transactions on Industrial Electronics, vol. 65, no. 11, pp. 9147–9156, 2018.

[14] S. M. Nayak, J. Singh, M. Kothari, and S. R. Sahoo, "Robust velocity control of a fixed canard decoupled dual-spin projectile," IEEE Transactions on Aerospace and Electronic Systems, vol. 61, no. 1, pp. 1079–1089, 2025.

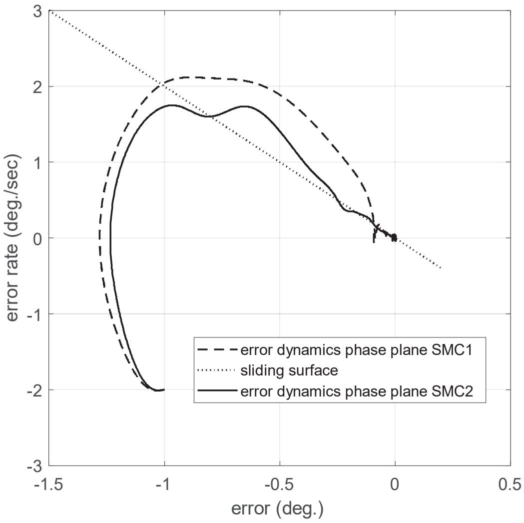

Fig. 7. sliding surface

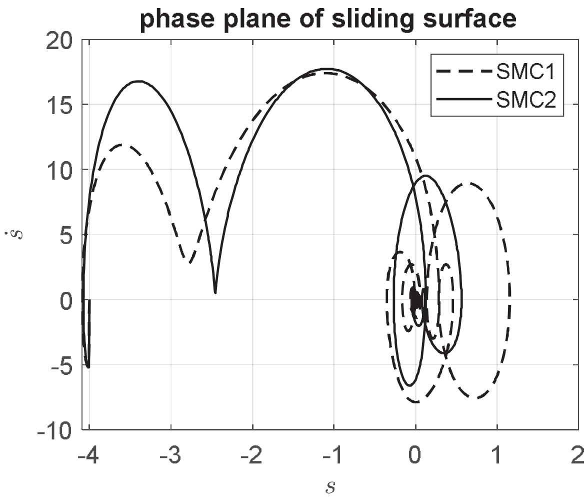

Fig. 8. Phase plane of sliding surface

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