Hybrid fuzzy and sliding mode control for motorised space tether spin-up when coupled with axial oscillation

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Abstract. A hybrid fuzzy sliding mode controller is applied to the control of motorised tether spin-up coupled with an axial oscillation phenomenon. A six degree of freedom dynamic model of a motorised momentum exchange tether is used as a basis for interplanetary payload exchange. The tether comprises a symmetrical double payload configuration, with an outrigger counter inertia and massive central facility. It is shown that including axial elasticity permits an enhanced level of performance prediction accuracy and a useful departure from the usual rigid body representations, particularly for accurate payload positioning at strategic points. A special simulation program has been devised in $MATLAB$ and $MATHEMATICA$ for a given initial condition data case.

1. Introduction

Space tethers can be used for orbit raising, lowering, and maintenance, and in principle can also be used for interplanetary propulsion of appropriate payloads. There are two distinct types of space tether; the mechanical 'momentum exchange' system in which orbital energy is used to manipulate payload mass advantageously, and the electrodynamic 'ED' tether which uses the geomagnetic field in conjunction with a conductive tether core and an on-board plasma generator. The ED tether can perform either as a gigantic motor or as a dynamo in order either to raise or lower payload altitude. In this case the momentum exchange variant is considered, albeit with additional energy provided by an exciting motor. The application of momentum exchange tethers to space vehicle propulsion from Low Earth Orbit (LEO) has been explored in considerable depth during the last a few decades, with many ingenious designs exploiting the principle of momentum transfer. The motorised momentum exchange tether (MMET) was first proposed by Cartmell [1]. The modelling and conceptual design were developed further, in particular MMET modelling as a rigid body, Ziegler and Cartmell [2]; MMET modelling with axial elasticity, Chen and Cartmell [3]. The conceptual schematic of the MMET system is shown in Figure 1 (A-braided propulsion tether tube; B-braided outrigger tether tube; C-launcher mass, rotor; D-launcher mass, stator; E/F-outrigger mass; G/H-payload mass), in which it is excited by a motor and uses angular generalised co-ordinates to represent spin and tilt, together with an angular co-ordinate for circular orbital motion. Another angular co-ordinate defines backspin of the propulsion motor's stator components. The payload masses (H and G in Figure 1) are fitted to each end of the tether sub-span (A in Figure 1), and the system orbits a source of gravity in space, in this case the Earth. The use of a tether means that all parts of the system have the same angular velocity as the overall centre of mass (COM, C and D in Figure 1). As implied in Figures 1 and 2, the symmetrical double-ended motorized spinning tether can be applied as an orbital transfer system in order to exploit momentum exchange for propelling and transferring payloads.

Variable structure control (VSC) with sliding mode control was introduced in the early 1950s by Emelyanov and was published in the 1960s [4], and further developments were proposed by several researchers [5][6]. Sliding mode control (SMC) has been recognized as a robust and efficient control method for complex high order nonlinear dynamical systems. The major advantage of sliding mode control is its low sensitivity to a system's parameter changes under various uncertainty conditions, and the fact that it can be used to decouple system motion into independent partial components of lower dimension, which reduces the complexity of the system control and feedback design. A major drawback of traditional SMC is chattering, which is generally disadvantageous within control systems.

It has been well recognized that fuzzy logic controllers (FLC) can be effective and robust for various applications, and conventionally the FLC rule-base is based on practical human experience, however the linguistic expression of the FLC rule-base can sometimes make it difficult to guarantee the stability and robustness of the control system. In recent years, a lot of literature has been generated in the area of fuzzy sliding mode control (FSMC) and has covered the chattering phenomenon. When FLC is involved in designing a FSMC based controller, this can be harnessed to help to avoid the chattering problem. The feature of the smooth control action of fuzzy logic can be helpful for overcoming the disadvantages of chattering. This is why it can be useful to merge FLC with SMC to create the FSMC [7][8][9][10][11][12]. A hybrid fuzzy sliding mode control method is applied here to the tether for sub-span length changing in order to provide spin-up control of the MMET system.

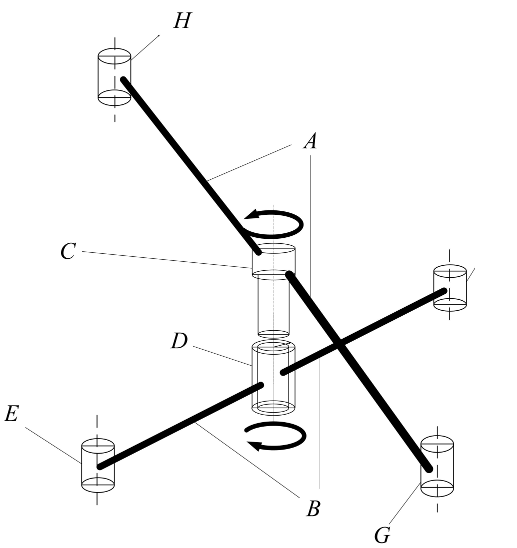

Figure 1. Conceptual Schematic of the Motorised Momentum Exchange Tether

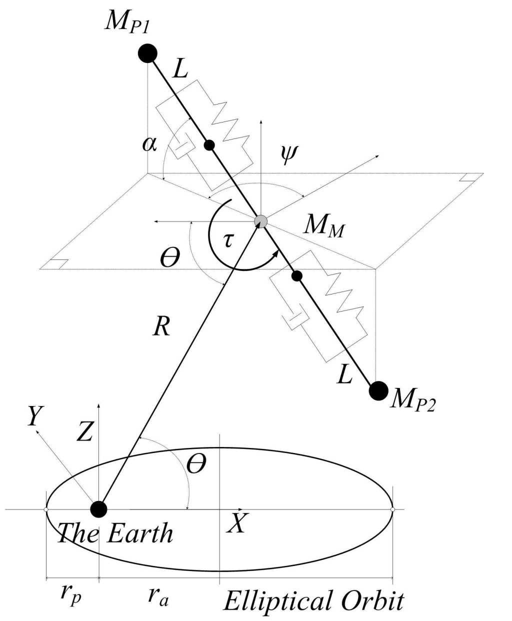

Figure 2. Modelling of the axially elastic MMET

2. Six degree of freedom MMET Model

A six degree of freedom non-planar tether model, which includes an axial elasticity coordinate and a solid rolling coordinate, is proposed for the MMET system in Figure 2. This discretised MMET system comprises a symmetrical and cylindrical double payload configuration, a cylindrical motor facility, and two axially flexible tubular tether sub-spans. In the discretised non-planar tether model, environmental effects such as solar radiation, residual aerodynamic drag in low Earth orbit and electrodynamic forces, that may also influence the modelling, are reasonally assumed to be negligible in this context. The motor consists of a central rotor, which is attached to the propulsion tethers, and a stator which locates the rotor by means of a suitable bearing. The power supplies, control systems, and communication equipment are assumed to be fitted within and surrounding the stator assembly in a practical installation. The stator also provides the necessary reaction that is required for the rotor to spin-up in a friction free environment. The motor torque acts about the motor drive axis, and it is assumed that the motor drive axis will stay normal to the spin plane of the propulsive tethers and payloads.

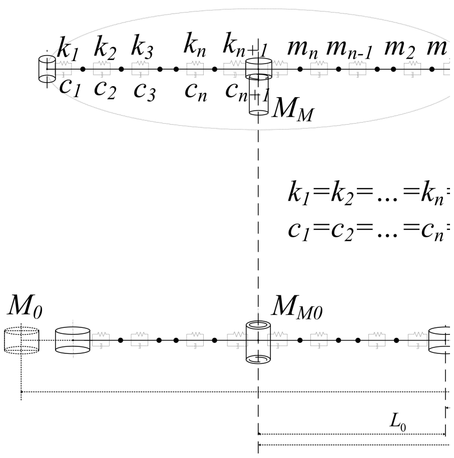

Figure 3. Modelling of the axial elastic for motorised momentum exchange tether

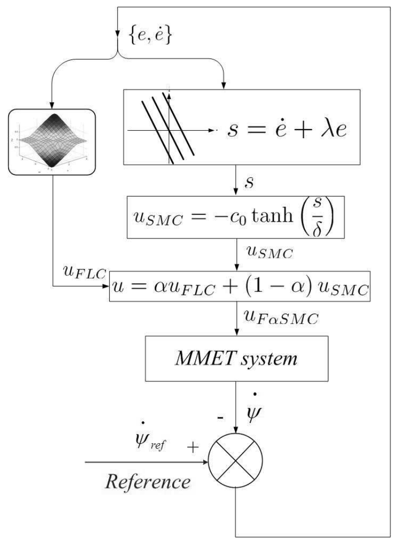

Figure 4. Hybrid fuzzy and sliding-mode control flow diagram

The elasticity of the tether system is considered to be distributed symmetrically along each tether sub-span. The tether and the motor are connected by a series of discrete spring-damper groups as shown in Figure 3. When the tether moves out of the orbital plane, the motor drive axis remains orthogonal to the spin plane, meanwhile the motor torque will act about the principal axis through its centre of mass. The length of the discretised MMET from payload to COM is given by $L(t) = L_0 + L_x(t)$, where the time variant length $L(t)$ of the tether is the sum of the static length, L_0, and the elastic length, $L_x(t)$, of the discretised tether. There are six generalised coordinates in this model, in the form of four rotational coordinates (ψ, θ, α, γ) and two translational coordinates (L_x, R). Coordinate ψ defines the spin-up performance of the MMET system and is the in-plane pitch angle. This denotes the angle from the x_0 axis to the projection of the tether onto the orbit plane. θ is the circular orbit angular position, effectively the true anomaly. α is the out-of-plane angle, from the projection of the tether onto the orbit plane to the tether, and is always within a plane normal to the orbit plane. γ is the rolling angle, which lies between the torque-plane and the tether-spin-plane. R is the distance from the Earth to the MMET COM, and L_x is the axial elastic length. Lagrange's equations are used to obtain the dynamical equations of motion based on the six generalised coordinates [3]. Lateral vibrations are included in this study because terrestrial and in-space deployment tests have shown that centripetal stiffening and gravity gradient effects in oscillating (librating) and spinning tethers, and just gravity gradient stabilisation in hanging tethers, provide very useful lateral rigidisation of otherwise flexible tethers, irrespective of whether they are single line designs or highly redundant multi-line structures. On that basis the predominant elastic effect is in axial stretch, and to some extent in torsion along the length. In this paper we solely consider the axially elastic effect and neglect any relatively small lateral oscillations, or torsional effects. Axial stretch is particularly important as even an extension of 0.1% will generate an axial displacement of the payload of 50 m when using a tether with a typically pragmatic sub-span length of 50 km. This would obviously have a very serious consequence for payload collection and delivery accuracy.

3. Hybrid Control - FαSMC

The chattering phenomenon is an acknowledged drawback of sliding mode control, and is usually caused by unmodelled system dynamics. In traditional SMC design, a sign function is conventionally applied but this can also lead to chattering in practice. Therefore a special boundary layer around the sliding surface is introduced to solve the chattering problem [5][6]. To make the necessary enhancement to the FSMC method, a hybrid control law is introduced here to combine fuzzy logic control with a soft continuous switching hyperbolic tangent control law, which is named FαSMC and given in equation 1. The flow diagram of the FαSMC approach is given in Figure 4. The hybrid control effects of FLC and SMC are combined in equation 1, where α is a proportionality factor, included to balance the weight of the fuzzy logic control to that of the hyperbolic tangent sliding mode control. Clearly, $\alpha = 0$ represents hyperbolic tangent control, and $\alpha = 1$ represents fuzzy logic control, $\alpha \in [0,1]$.

$$u_{F\alpha SMC} = \alpha u_{FLC} + (1 - \alpha)\, u_{SMC} \tag{1}$$

3.1. Fuzzy Logic Controller Design

Fuzzy control provides a convenient method for constructing nonlinear controllers via the use of heuristic information. An operator can act as a human-in-the-loop controller so that an appropriate fuzzy control implementation can provide a human-experience based representation, and an implementation of the ideas that a human could have about how to achieve high-performance control [13][14]. The structure of the FLC for the MMET system is shown in Figure 5, in which the FLC flow diagram is characterized by a set of linguistic description rules based on conceptual expertise which arises from typical human situational experience. The 'If-Then' rule base is then applied to describe the experts' knowledge, the 2-in-1-out FLC rule-base for the spin-up of the 6DOF MMET system is given in Figure 6. Figure 6 is the FLC rule-base cloud for the 2-in-1-out FLC, which came from previous experience gained from observing for the tether length changes during angular velocity control. Briefly, the main linguistic control rules are: [1] when the angular velocity decreases, the length tether increases; Conversely, when the angular velocity increases,the tether length decreases. [2] When the angular acceleration increases, the tether length increase can reduce the error between the velocity and the reference velocity; otherwise, when the angular acceleration decreases, the tether length decreases as well. The full rule-base is given in Figure 6 as a rule-base 3D plot, which defines the relationship between the two inputs of Error (E) and Change in Error (EC), with one output of the Fuzzified Length (FL).

Fuzzification is the process of decomposing the system inputs into fuzzy sets, that is, it is used to map variables from practical space to fuzzy space. The process of fuzzification allows the system inputs and outputs to be expressed in linguistic terms so that rules can be applied in

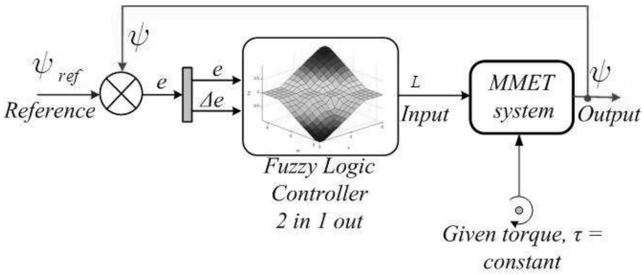

Figure 5. FLC flow diagram

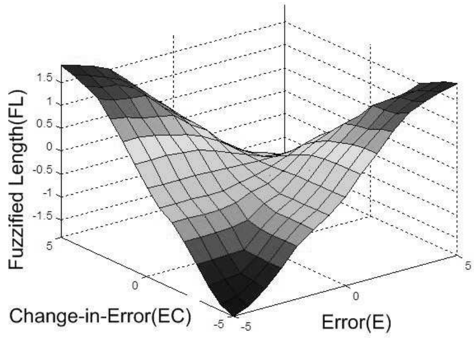

Figure 6. 2-in-1-out FLC rule-base 3D plot

a simple manner to express the complicated system. In the FLC for the MMET system, there are nine elements in the fuzzy sets for two inputs of E and EC, and one output of FL. These are: $< NB, NM, NS, NZS, ZE, PZS, PS, PM, PB >$. The Fuzzy Inference System (FIS) uses Mamdani-type inference [15] for the 2-in-1-out FLC. Defuzzification is the opposite process of fuzzification and is used to map variables from fuzzy space to practical space. A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value between 0 and 1. The MF for the MMET system is the symmetric Gaussian function. The inputs of E and EC are interpreted from this fuzzy set, and the degree of membership is interpreted.

3.2. Soft Switching Sliding Mode Control Design

The objective is to consider the non-linear tether system as the controlled plant, and therefore defined by the general state-space equation $\dot{x} = f\,(x, u, t)$, where $x \in R^n$ is the state vector, n is the order of the non-linear system, $u \in R^m$ is the input vector, and m is the number of inputs. $s(e, t)$ is the sliding surface of the hyperplane, which is given below and shown in Figure 7, where λ is a positive constant that defines the slope of the sliding surface. In the MMET system, we let n = 2 given that as it is a second-order system in which s defines the position and velocity errors.

$$s\,(e, t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e \tag{2}$$

$$s = \dot{e} + \lambda e \tag{3}$$

From equations 2 and 3, the second-order tracking problem is now replaced by a first-order stabilization problem in which the scalar s is kept at zero by means of a governing condition [8]. This is obtained from use of the Lyapunov stability theorem, given in equation 4, and stating that the origin is a globally asymptotically stable equilibrium point for the control system. This equation is positive definite and its time derivative is given in inequality 5 , to satisfy the negative definite condition, that the system should satisfy the inequality 5.

$$V\,(s) = \frac{1}{2}s^2 \tag{4}$$

$$\dot{V}(s) = s\dot{s} < 0 \tag{5}$$

A soft switching control law is introduced [9] for the major sliding surface switching activity in equation 6, where c_0 is an assumed positive damping ratio for the switching control law. This law needs to be chosen in such a way that the existence and the reachability of the sliding-mode are both guaranteed, noting that δ is an asssumed positive constant which defines the thickness of the sliding mode boundary layer [10].

$$u_{SMC} = -c_0 \tanh\left(\frac{s}{\delta}\right) \tag{6}$$

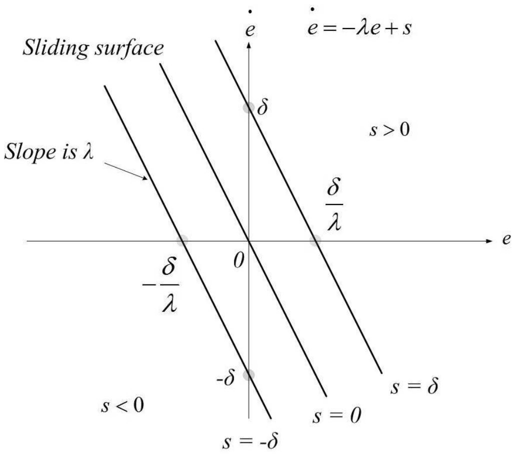

Figure 7. Sliding surface

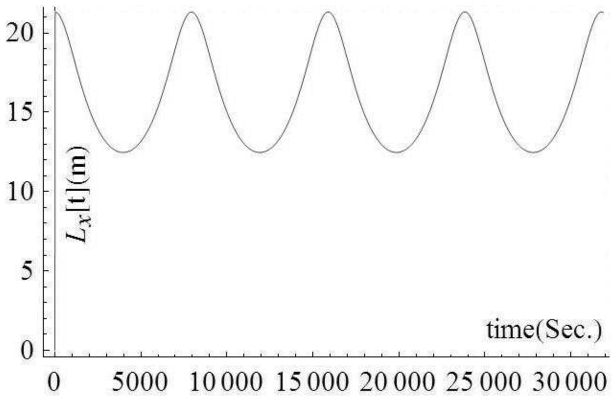

Figure 8. Response of axial displacement of tether sub-span

4. Simulation and Conclusion

Numerical results are obtained using a specially devised co-simulation toolkit of $MATLAB$ and $MATHEMATICA$ functions in an integrated program to provide a new toolbox, known henceforth as $SMATLINK$, which integrates control in $MATLAB/SIMULINK$ with MMET modelling in $MATHEMATICA$. The velocity and acceleration of ψ are selected as error (e) and change-in-error (ec) feedback signals for the 6-DOF MMET spin-up control.

Unless stated otherwise all the results are generated using the following MMET system parameters [3]: the number of mass points $N = 20$, gravitational constant $\mu = 3.9877848 \times 10^{14}$ $m^3 s^{-2}$, propulsion tether payload mass $M_P = 1000\ kg$, mass of motor facility $M_M = 5000\ kg$, static length of propulsion tether $L_0 = 50000\ m$, orbit eccentricity $e = 0.2$, periapsis distance $r_{per} = 6.890 \times 10^6\ m$, apoapsis distance $r_{apo} = 1.0335 \times 10^7\ m$, radius of tether outer and inner tube $r_{Touter} = 0.1\ m$ and $r_{Tinner} = 0.08\ m$, radius of motor facility $r_M = 0.5\ m$, radius of payload $r_P = 0.5\ m$, the undeformed tether tube cross-sectional area $A = 1.13097 \times 10^{-2}$ m^2 , the tether density $\rho = 970\ kg/m^3$, initial angular $\psi_0 = 0\ rad$, initial angular velocity $\dot{\psi}_0 = 0\ rad/s$, motor torque $\tau = 2.5 \times 10^6\ Nm$, damping coefficient $c_i = 2 \times 10^6\ Ns/m$, and stiffness $k_i = 2 \times 10^9\ N/m$.

The hybrid fuzzy sliding mode control system parameters require a judicious choice of the FLC scaling gains, which in this case are taken to be $\{Ke, Kec, Ku\} = \{1.0, 1.0, 21000\}$. The $SMATLINK$ program deals with normalisation of the inputs, so the fuzzification gain factors

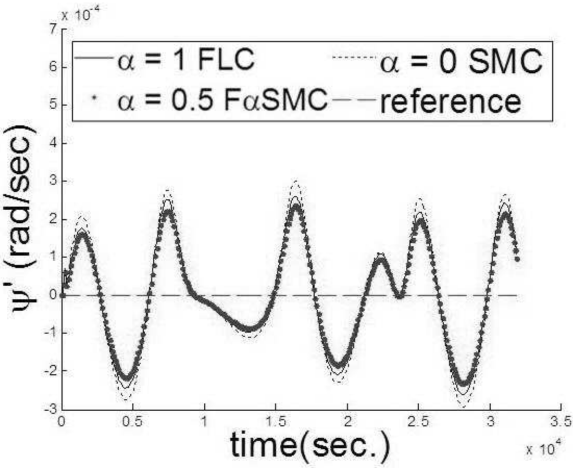

Figure 9. The angular velocity response 6DOF MMET spin-up

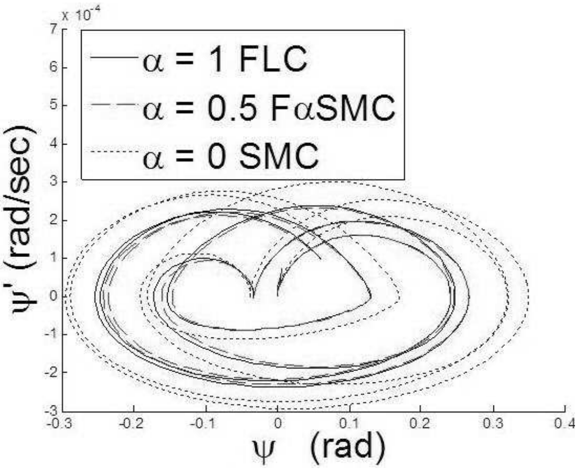

Figure 10. Phase plot for angular response

of Ke, Kec are set to 1.0, and Ku is the defuzzification gain factor which is used to map the FL to the practical tether length range. Similarly, the SMC damping coefficient $c_0 = -3000$ is required to expand the normalised output to a practical tether length. The thickness of the sliding mode boundary layer is given by $\delta = 0.8$, and the slope of the sliding surface $\lambda = 0.0014$. Both data came from previous 6DOF MMET system spin-up simulation results, but without control. In this simulation using the FαSMC, $\alpha = 0.5$ is required to balance the control weight between FLC and SMC. It is easy to switch the controller between SMC and FLC when a proper value of α is selected $(0 < \alpha < 1)$, the hybrid fuzzy sliding-mode controller is generated combining fuzzy logic control with a soft continuous switching hyperbolic tangent control law based on equation (2). All the control methods have an effect on the spin-up of the MMET system from the given initial conditions.

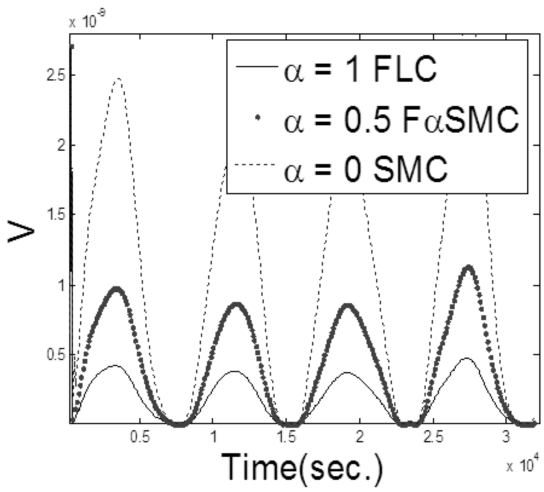

Figure 11. Lyapunov function for the 6DOF MMET system

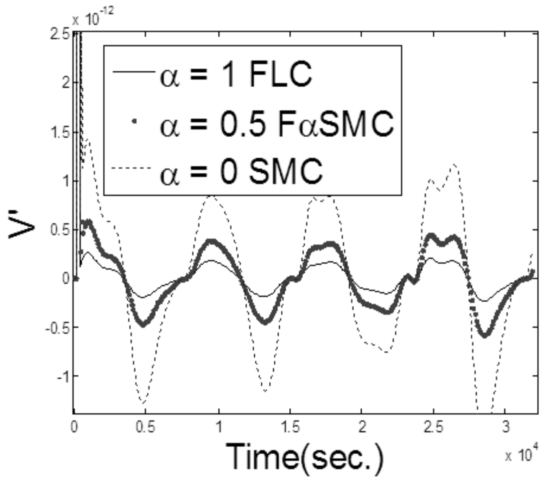

Figure 12. Derivative of Lyapunov function for the 6DOF MMET system

Figure 8 gives the axial elastic behaviour of the MMET in the simulation with the appearance of stable axial oscillation. Figure 9 shows the time responses for the spin-up velocity $\dot{\psi}$ with different values of $\alpha = \{0.0, 0.5, 1.0\}$ for $\{SMC,\ F\alpha SMC,\ FLC\}$ control respectively of the spin-up. The phase plots are shown in Figure 10 as limit cycles whose behaviour for the spin-up coordinate ψ, clearly corroborates interpretations of steady-state. Figures 11 and 12 show the plots for the Lyapunov function and its derivative, which showing that the FαSMC control with different value of α (same as in Figures 9 and 10) for the MMET system satisfies the Lyapunov stability condition in inequality 5.

5. Future work

The work in this paper has shown that including axial elasticity within an MMET model has a significant bearing on overall performance, the parameter settings for the FαSMC need further consideration because the current simulation results come from manual parameter tests. A MMET system with axial and lateral elastic effects could be considered for the further MMET modelling studies. In order to enhance the parameter selection process and validation, some computational intelligence (CI) optimisation tools, such as Genetic Algorithms (GA) and Artificial Neural Networks (ANN), could be applied for parameter selection for the FLC, SMC and FαSMC. This can hopefully give some reference data for the parameter settings. A GA has been used as an optimisation tool for parameter selection of the MMET system payload transfer from LEO to geostationary Earth orbit (GEO), and the GA's optimisation ability has therefore been reasonably demonstrated [16].

References

[1] M. P. Cartmell, (1998), "Generating Velocity Increments by means of a Spinning Motorised Tether", 34th AIAA/ASME/SAE/ASEE Joint propulsion Conference and Exhibit, Cleveland Conference Centre, Cleveland, Ohio, USA, AIAA-98-3739.

[2] S.W. Ziegler,and M. P. Cartmell, (2001), "Using Motorised Tethers for Payload Orbital Transfer", Journal of Spacecraft and Rockets, 38 (6), November / December, pp 904-913.

[3] Y. Chen, M.P. Cartmell, (2007) "Dynamical Modelling of The Motorised Momentum Exchange Tether Incorporating Axial Elastic Effects", Advanced Problems in Mechanics , 20-28 June, Russian Academy of Sciences, St Petersburg, Russia.

[4] S. V. Emelyanov, (1967), "Variable Structure Control Systems(in Russian)", Moscow: Nauka.

[5] Y. Itkis, (1976), "Control Systems of Variable Structure", New York: Wiley

[6] V. A. Utkin, (1978), "Sliding Modes and Their Application in Variable Structure Systems", Moscow: Nauka (in Russian) (also Moscow: Mir, 1978, in English)

[7] John Y. Hung, Weibing Gao, James C. Hung, (1993), "Variable structure control: a survey", IEEE Transactions on Industrial Electronics,pp 2-22.

[8] J.J.E. Slotine, and W.P. Li, (1991), "Applied Nonlinear Control", Prentice-Hall International.

[9] K. C. Ng, Y. Li, D. J. Murray-smith, K. C. Sharman, (1995), "Genetic Algorithm applied to Fuzzy Sliding Mode Controller design", Genetic Algorithms in Engineering Systems: Innovations and Applications, GALESIA. First International Conference on (Conf. Publ. No. 414) 12-14 Sep 1995 Page(s):220 - 225.

[10] J.J. E. Slotine, (1982), "Tracking control of non-linear systems using sliding surfaces with application to robot manipulations", PhD Dissertation, Laboratory for Information and Decision Systems, Massachusetts Institute of Technology.

[11] Brian O'Dell, (1997), "Fuzzy Sliding Mode Control: A Critical Review", Oklahoma State University, Advanced Control Laboratory, Technical Report ACL-97-001.

[12] S. G. Tzafestas ,G. G. Rigatos, (1999), "A Simple Robust Sliding-Mode Fuzzy-Logic Controller of the Diagonal Type", Journal of Intelligent and Robotic Systems, Volume 26, Numbers 3-4 , pp 353-388.

[13] Kevin M. Passino , Stephen Yurkovich, (1998), "Fuzzy Control", Addison Wesley Longman, Menlo Park, CA.

[14] L.A. Zadeh, (1965), "Fuzzy Sets", Information and Control, Volume 8, Number 3, pp. 338–353.

[15] E.H. Mamdani, (1977), "Applications of fuzzy logic to approximate reasoning using linguistic synthesis", IEEE Transactions on Computers, Vol.26, No. 12, pp. 1182-1191.

[16] Y. Chen, M.P. Cartmell, (2007), "Multi-objective optimisation on motorised momentum exchange tether for payload orbital transfer", IEEE Congress on Evolutionary Computation, Publication Date: 25-28 Sept. 2007, pp. 987-993.