MODEL AND RESULT ANALYSIS OF DRAG SAIL MODULE EARLY TESTING

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MODEL AND RESULT ANALYSIS OF DRAG SAIL MODULE EARLY TESTING

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Abstract—An inverted stepper motor assembly was previously proposed in a design of a satellite deorbiting module incorporating the drag sail method by the authors. Following it, tests were conducted on an embodiment of the module over an adjusted version of a deployment sequence. The results from these tests were compared and reproduced using a numerical model of the stepper motor. A need was identified to produce a model of the tension varying throughout the deployment sequence.. Curve fitting technique was employed to generate from the data obtained during test runs. Moreover, additional results from test runs are discussed in the paper.

Index terms: Curve-fitting, Analytical Model, Motor Drives, Drag Sail, Control System

I. INTRODUCTION

The need and feasibility of a plug and play, scalable drag sail module was overviewed in [1]. Since then, early tests have been done on an early prototype of AirDragMod (ADM) obtaining important data in the process. This prototype had four degrees of freedom. It consists of an embodiment of the deployment mechanism described in [1] with adequate sensors to obtain necessary data needed to iterate the mechanism and derive an analytical model of tension force at the motor drive during the deployment sequence.

The primary components of the system are the rotator, aid masses, and the sail deployment drives. The rotator, controlled by said mechanism, generates the necessary rotation in sync with a pre-defined sequence. The aid masses are released first; due to the sail being connected to these masses at free end, the tension created causes elongation of the sail. The motor units drive the sail, essentially "spewing it out", at a constant rate upto complete extension.

In the setup, the deployment sequence was normalized down to 184 seconds with 120 seconds of sail deployment. The data obtained will be used to develop an active control system for perturbations caused to the system during this deployment. To perform accurate dynamic modeling of the forces at the base of the sail extension (at motor drives), an analytical model is needed. In the paper, the analytical model of tension caused due to centripetal force acting on sail petals is derived with the help of flex sensors at the same in the experimental setup. Additionally, interpolation of angular velocities is performed, the data for which was obtained using IMUs. Additionally, vibration data from the system derived is visualized on a surface plot with the derived model. This helps identify the periods of amplified vibration during the sequence.

II. BACKGROUND

Equation of motion (domain equation) for extended sail petal is [2]

$$\frac{\partial y}{\partial x}\left(\tau(x)\frac{\partial u}{\partial x}\right)+f(x,t)=\rho(x)\frac{\partial^2 u}{\partial t^2} \quad (1)$$

This equation along with its boundary values and initial values forms the initial value boundary problem [2] and can be used to model the motion in Simulink®. $\tau(x)$ in the equation is a function of tension varying with position on the petal. The sail petal can be assumed to be a continuous mass distribution; mass of sail spread over the length of the petal. Figure 1 provides a representation of the location where tension data is recorded. Using Newton's second law and definite integration over a small mass element, $\tau(x)$ can be found to be:

$$\tau(x)=\frac{M}{2L}\omega^2\left(L^2-x^2\right) \quad (2)$$

Here, $\frac{M}{L}$ is the linear mass density; for a sail $7m^2$ the linear mass density for a petal is $6.2756\ gm.m^{-1}$ if material chosen were Aluminized Kapton® Polymer [3]. Here, position x is a function of time; the rate at which motor drive units release the petals. This rate is dependent upon deployment time and sail petal length to be extended. For a $7m^2$ sail, this rate for the 120 second sail release period (for the setup mentioned prior) is $4.124\ cm.s^{-1}$. ω is the angular velocity of the rotator unit. The model of the physical system i.e. the ADM module in Simulink® is shown in Figure 2. This model forms the physical system over which active control is to be achieved.

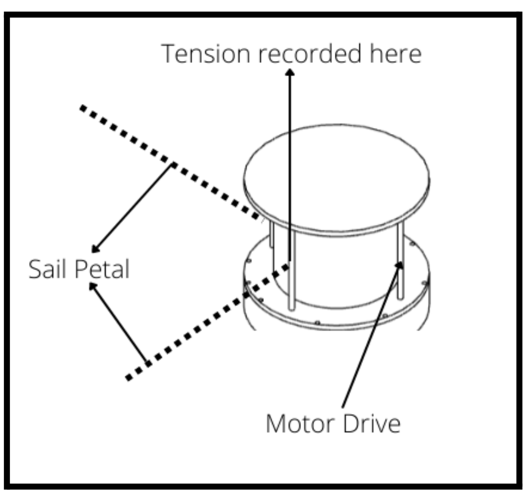

Figure 1: Location of flex sensor recording tension

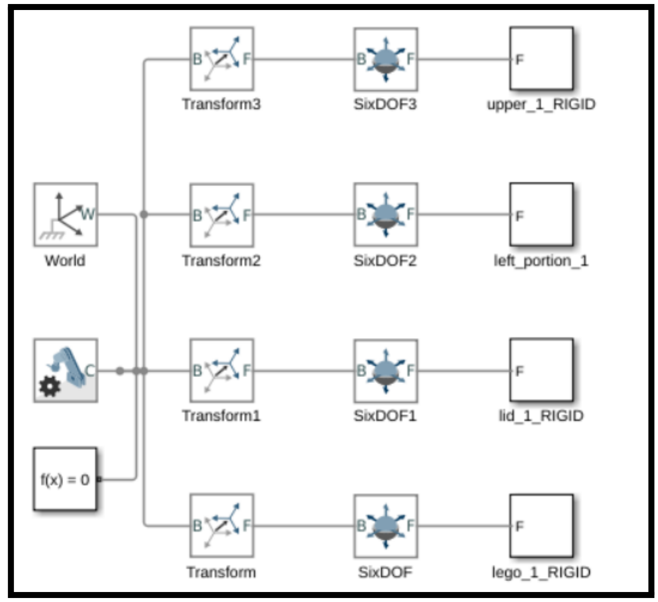

Figure 2: SimScape Physical System Block Diagram

III. NUMERICAL MODEL SETUP

Owing to hardware limitations, the force models do not account for lateral forces on sail petals during deployment, nor are the disturbance models computed in the y-axis of the system as setup was placed on a surface and not in a simulated microgravity environment. The force and acceleration profiles are two dimensional but consistent with the expected three dimensional model. Hence, the current modeling can be extended into three dimensions.

The general setup along with axes are shown in figure 3. Sail placeholders were used in the setup. Testing using actual sail material would yield the lateral force profile. The configuration geometry is novel to the design, however, the number of deployment motor drives can be varied with a minimum of 4. The setup consisted of 4 such motor drives. The release rate was kept as mentioned earlier. The tension data recorded at prototype was at the base of motor drive units during the sail petal release period of the deployment sequence. Theoretically, tension would increase initially, then decrease to attain a constant value. The axes for the setup are shown in Figure 3. Roll axis for the setup is the y-axis; angular velocity is measured around it. Ideally, there should not be any movement in other axes, however, perturbations would be caused and thus need for an active control system.

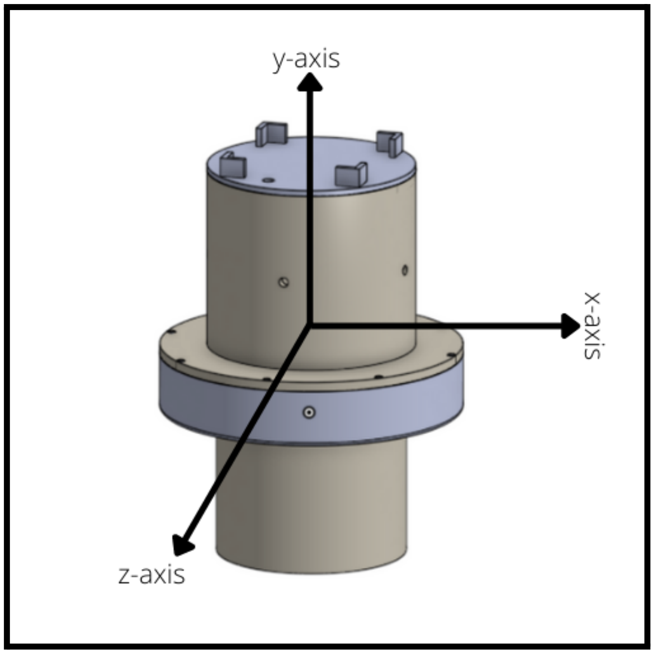

Figure 3: Setup CAD model with local axes

IV. RESULTS

The curve-fit of tension force data was done in MATLAB®.The best fit model equation obtained is given below with the coefficient values given in Table 1.

$$f(x) = a_1 \cdot \sin(b_1 x + c_1) + a_2 \cdot \sin(b_2 x + c_2)$$
(3)

```
Coefficients (with 95% confidence bounds):
  a1 =       1.866  (1.648, 2.084)
  b1 =    0.002467  (0.002141, 0.002793)
  c1 =      0.1269  (0.1122, 0.1415)
  a2 =      0.1021  (0.09915, 0.105)
  b2 =     0.03793  (0.03725, 0.0386)
  c2 =       2.717  (2.652, 2.781)
```

Table 1: Curve-fit coefficient values

Figure 4 shows the curve-fit plot along with the residuals plot for the given fit is shown in Figure 5.

The Tension values are normalized moving means of values recorded over multiple test runs.

The interpolation of angular velocity recorded using IMU in x-axis is displayed. The cubic spline interpolant in x is a piecewise polynomial over p, where x is normalized by mean 92.03 and standard deviation 53.02 and p is a coefficient structure. From plot Figure 6, it can be inferred that some periodic disturbance of oscillation nature is caused in the x-axis. This disturbance needs to be controlled by the control system under development.

Figure 6 shows a surface and contour plot of time, angular velocity and tension values obtained from the numerical model (3).

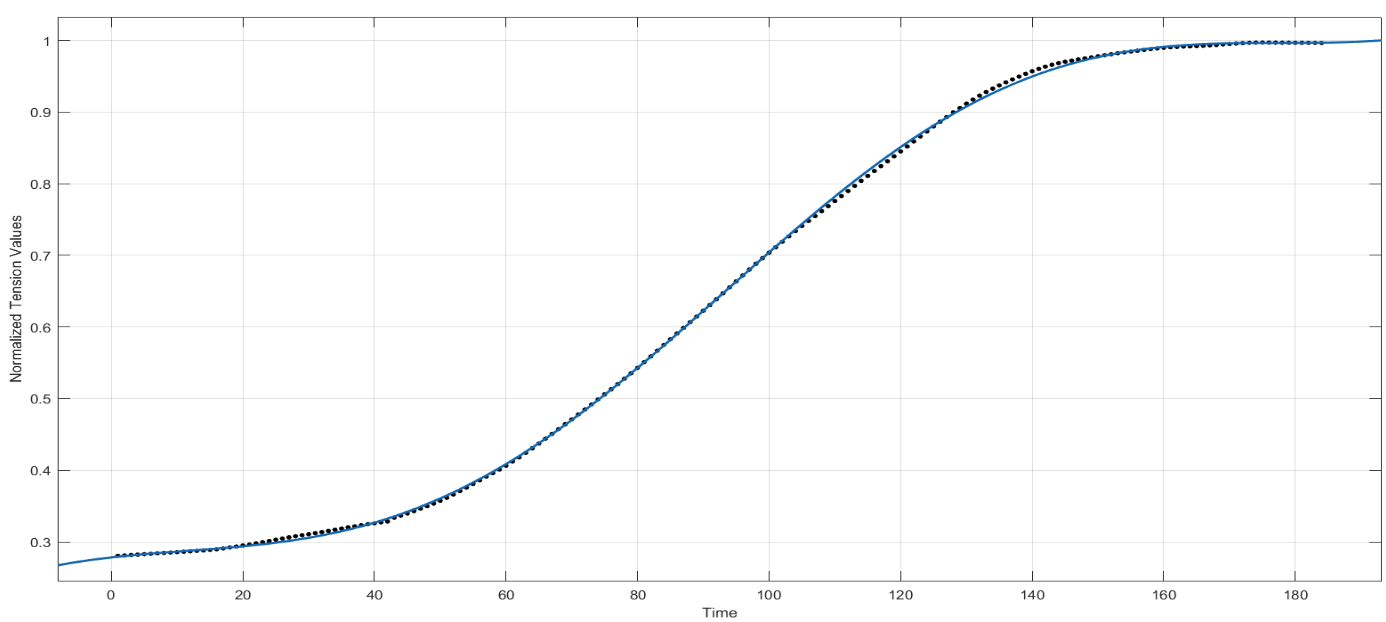

Figure 4: Curve-fit of Normalized Tension Values vs. Time

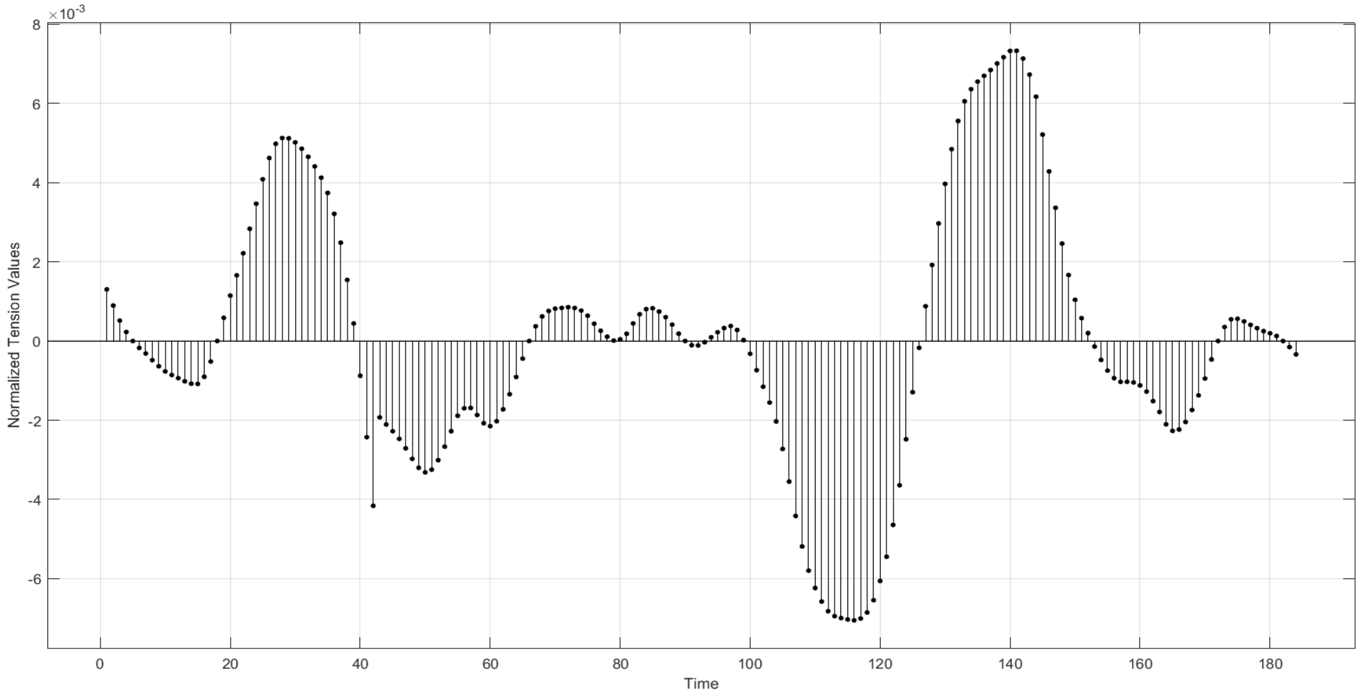

Figure 5: Residuals Plot of Curve-fit in Figure 4

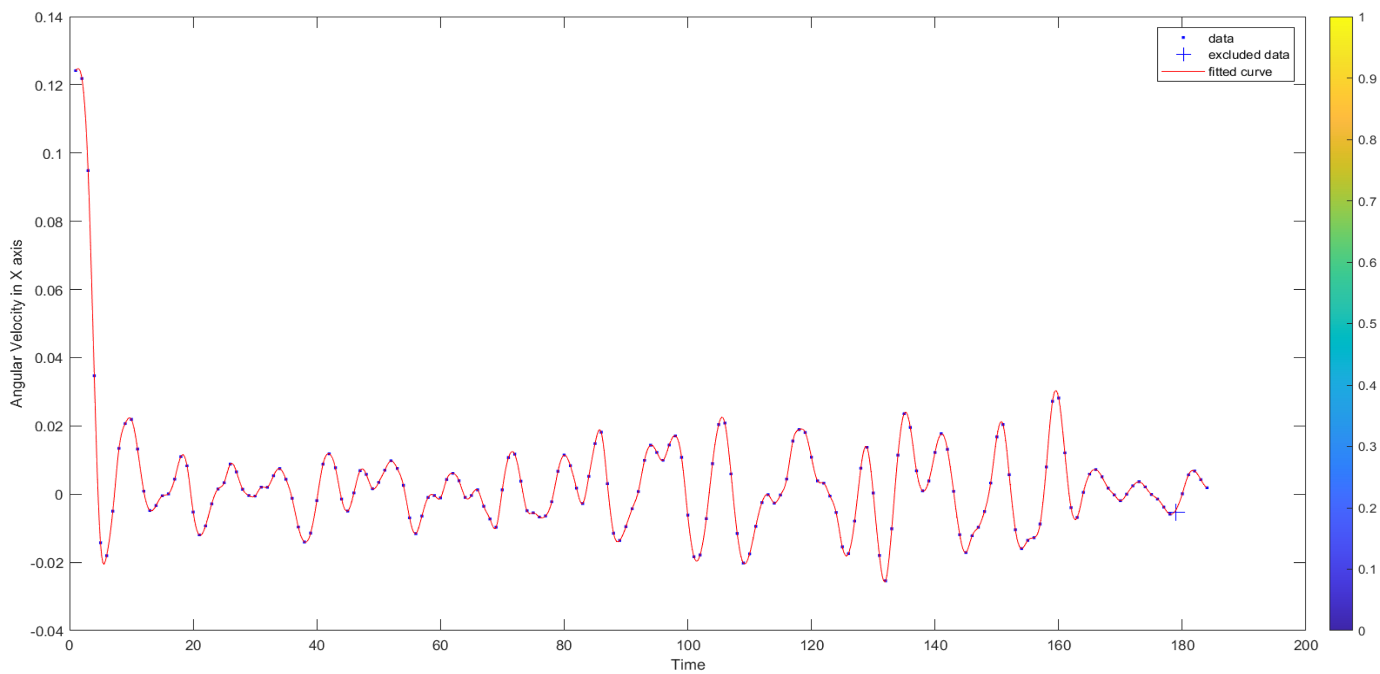

Figure 6: Interpolant of Angular Velocity in X-axis vs. Time

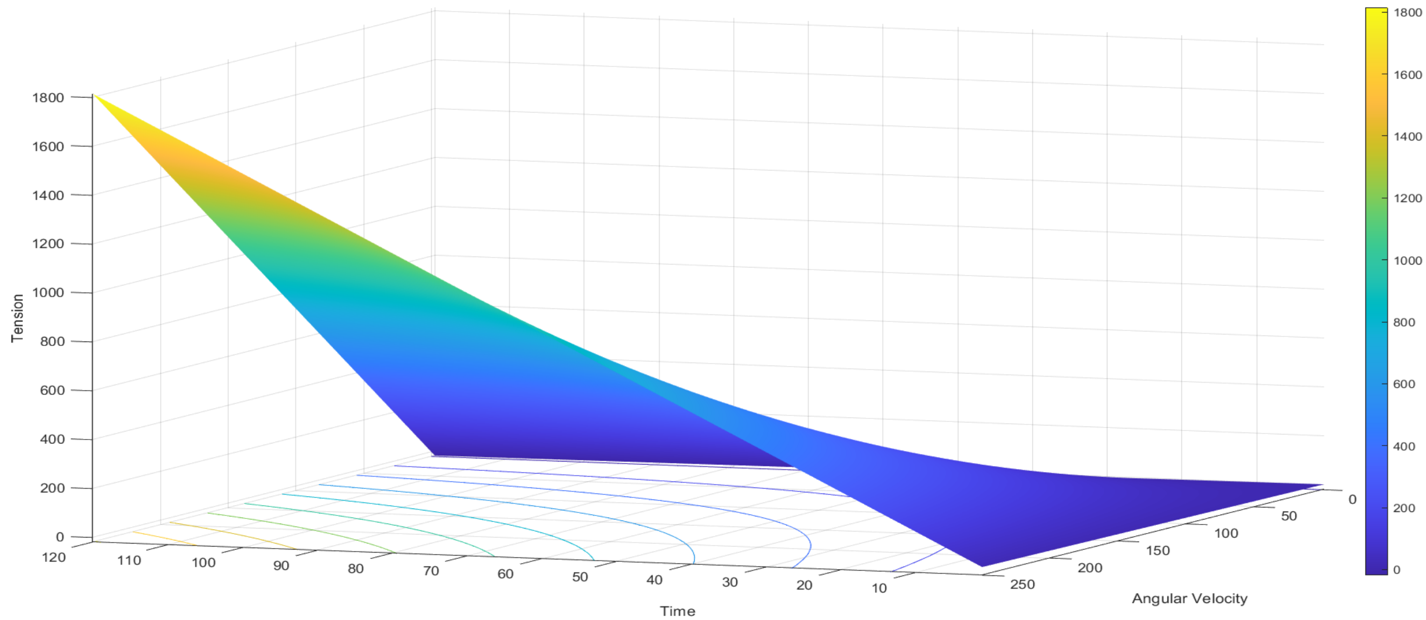

Figure 7: Surface Plot with Time as X-axis, Angular Velocity as Y-axis, and Tension as Z-axis

V. FUTURE WORK

Future work towards refining the models of disturbance and formulas of motion should follow. Development of an active control system is the next milestone towards the development of AirDragMod. More tests with accurate hardware and sail material should be done to obtain the model of lateral forces. The result of these tests would also be improved and rectified formula (2) modified. Eventually, the active control system would need to be tested out on a full scale AirDragMod.

VI. CONCLUSIONS

The curve-fit model of tension varying on a sail release motor drive is useful dynamic modeling of such microgravity release systems. The model derived using data and numerical model in two dimensions was visualized using surface plot matching closely with the scatter plot obtained further testifying the accuracy. The vibration data interpolation obtained is needed to understand the intervals of increased disturbance and thus help in development of the active control system. The models obtained can be further extended to create three dimensional models with tests improvised according to results of said models. Additional refinement in formulas would help refine models.

Future work would involve further testing and extensions of setup degree of freedom into 4 to help in three dimension modeling.

REFERENCES

[1] Shukla, Anshuman & Sawant, Pranav & Mohite, KC. (2022). Scalable PnP Drag Sail Module Deorbit System for LEO Satellites. 10.13140/RG.2.2.17377.38244/1.

[2] Daniel. S. Stutts (2000), https://web.mst.edu/~stutts/PRESENTATIONS/ModalAnalysisofaTightString.pdf

[3] https://www.dupont.com/content/dam/dupont/amer/us/en/products/ei-transformation/documents/EI-10142-Kapton-Summary-of-Properties.pdf