2004

NASA FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER

THE UNIVERSITY OF ALABAMA
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE
ALABAMA A&M UNIVERSITY

STUDY OF A 30-M BOOM FOR SOLAR SAIL-CRAFT: MODEL EXTENDIBILITY AND CONTROL STRATEGY

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Introduction

Space travel propelled by solar sails is motivated by the fact that the momentum exchange that occurs when photons are reflected and/or absorbed by a large solar sail generates a small but constant acceleration. This acceleration can induce a constant thrust in very large sails that is sufficient to maintain a polar observing satellite in a constant position relative to the Sun or Earth. For long distance propulsion, square sails (with side length greater than 150 meters) can reach Jupiter in two years and Pluto in less than ten years.

Converting such design concepts to real-world systems will require accurate analytical models and model parameters. This requires extensive structural dynamics tests. However, the low mass and high flexibility of large and light weight structures such as solar sails makes them unsuitable for ground testing. As a result, validating analytical models is an extremely difficult problem. On the other hand, a fundamental question can be asked. That is whether an analytical model that represents a small-scale version of a solar-sail boom can be extended to much larger versions of the same boom. To answer this question, we considered a long deployable boom that will be used to support the solar sails of the sail-craft. The length of fully deployed booms of the actual solar sail-craft will exceed 100 meters. However, the test-bed we used in our study is a 30 meter retractable boom at MSFC. We first develop analytical models based on Lagrange's equations and the standard Euler-Bernoulli beam. Then the response of the models will be compared with test data of the 30 meter boom at various deployed lengths. For this stage of study, our analysis was limited to experimental data obtained at 12ft and 18ft deployment lengths. The comparison results are positive but speculative. To observe properly validate the analytic model, experiments at longer deployment lengths, up to the full 30 meter, have been requested. We expect the study to answer the extendibility question of the analytical models.

In operation, rapid temperature changes can be induced in solar sails as they transition from day to night and vice versa. This generates time dependent thermally induced forces, which may in turn create oscillation in structural members such as booms. Such oscillations have an adverse effect on system operations, precise pointing of instruments and antennas and can lead to self excited vibrations of increasing amplitude. The latter phenomenon is known as thermal flutter and can lead to the catastrophic failure of structural systems. To remedy this problem, an active vibration suppression system has been developed. It was shown that piezoelectric actuators used in conjunction with a Proportional Feedback Control (PFC) law (or Velocity Feedback Control (VFC) law) can induce moments that can suppress structural vibrations and prevent flutter instability in spacecraft booms. In this study, we will investigate control strategies using piezoelectric transducers in active, passive, and/or hybrid control configurations. Advantages and disadvantages of each configuration will be studied and experiments to determine their capabilities and limitations will be planned. In particular, special attention will be given to the hybrid control, also known as energy recycling, configuration due to its unique characteristics.

UTF Mast Load-Deflection/Load Deflection Cut Wire Test Configurations

Figure 1 shows UTF mast load-deflection cut wire test configuration. The displacement data collected from the tip position of the boom was used for preliminary model comparison.

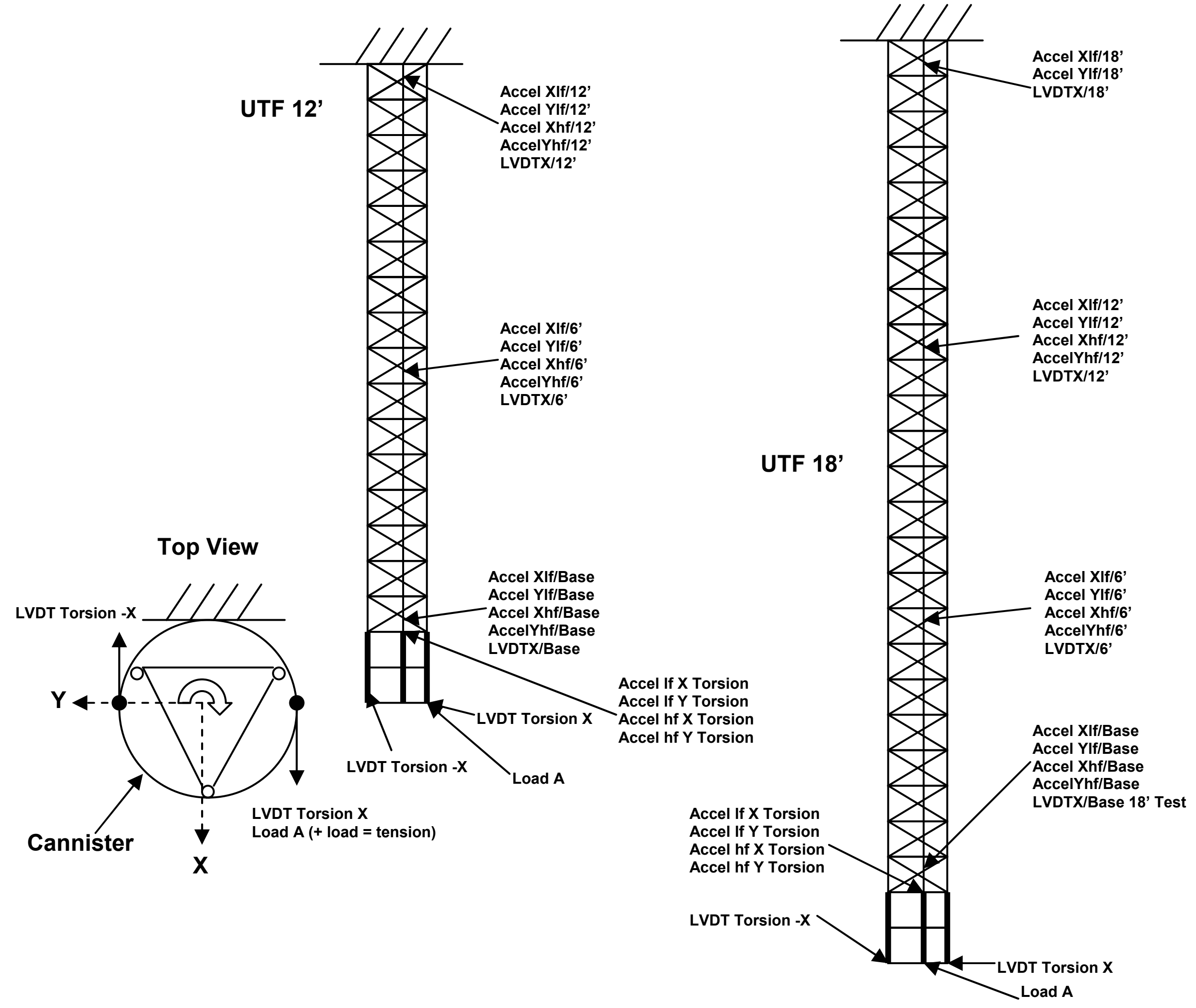

Figure 1: UTF Mast Torsion Load-Deflection Test/Cut Wire Torsion Load-Deflection Test Configurations

Analytical Models

Consider a beam in transverse vibration. Under the assumption that the cross-sectional dimensions are small compared with the length of the beam, both the shear and rotary inertia effects can be neglected. Then kinetic energy $T(t)$ and potential energy $V(t)$ are:

$$T(t) = \frac{1}{2}\int_0^L \left[\frac{\partial y(x,t)}{\partial t}\right]^2 m(x)dx + \frac{1}{2}\left[\frac{\partial y(L,t)}{\partial t}\right]^2 m_p \tag{1}$$

$$V(t) = \frac{1}{2}\int_0^L EI(x)\left[\frac{\partial \varphi(x,t)}{\partial x}\right]^2 dx \qquad (2)$$

To determine the transverse displacement $y(x,t)$, we assume separation of variables, that is,

$$y(x,t) = \sum_{j=1}^{n} \phi_j(x) q_j(t). \qquad (3)$$

Remark: The beam is assumed to be uniform, that is, $EI(x)$=constant, $m(x)$=constant.

Substituting for the expressions above in Lagrange's equation, a state space model was developed and (A,B,C,D) matrices were computed for both 12ft and 18ft boom lengths under the following assumptions.

Model 1: Though inconsistent with eq. (1), we derived mode shape functions $\phi_j(x)$ assuming (for simplicity) the boom is an Euler-Bernoulli beam with *no tip mass*.

Model 2: To improve the accuracy of the model (Model 1), we derived alternative mode shape functions $\phi_j(x)$ assuming the boom is an Euler-Bernoulli beam with a short tip mass m_p.

Results

Two different EI values were used for each boom length. $EI = 20x10^6$ lb-in^2 was read from the graph provided by the boom manufacturer, ABLE, Inc. Another value of EI used was estimated from experimental data. Figure 2 shows the response comparison (analytical model predictions and experimental data) of the 12ft booms for each EI value.

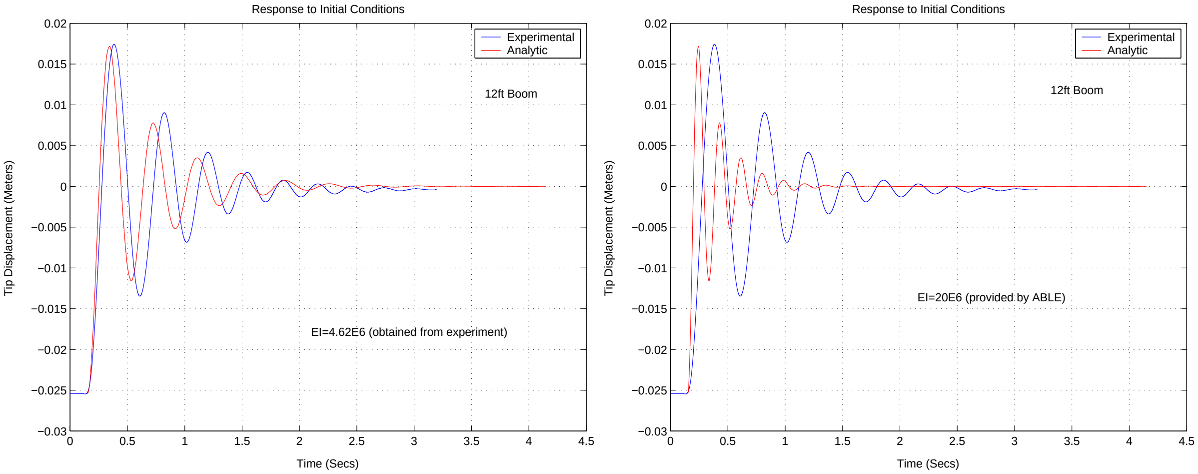

Figure 2. Responses of 12ft boom

Similarly, Figure 3 shows the response comparison (analytical model predictions and experimental data) of the 18ft booms for each EI value. In both cases, the EI values estimated from the experimental data yielded an analytical model predicted response that is closer to that of the experimental data. The results are not conclusive and more data at longer beam lengths is needed to reach firm conclusions. Note that all Figures are based on Model 1.

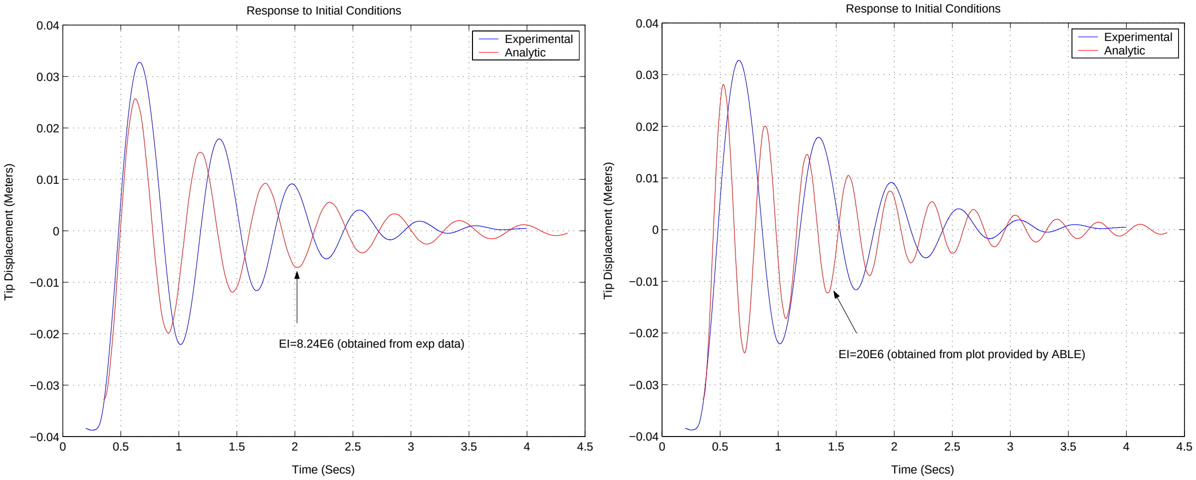

Figure 3. Responses of 18ft boom

Control Configuration Using Piezoelectric Transducers

A theoretical study of active, passive, and energy recycling (hybrid) control configuration has been conducted. Since the structure does not permit excessive added weights due to cabling, mass, and/or an external power source, the energy recycling control configuration may be the “best” if feasible. Laboratory studies are needed to confirm capabilities, limitations and feasibility of this approach.

Resources

The project requires one software tool. Matlab with appropriate toolboxes was the main software tool for verification of models. A laboratory engineer at MSFC provided the experimental data from the boom.

Future Works

More experiments at longer boom lengths have been requested. Once the data is available, the response comparison procedures will be repeated and we expect more conclusive evidence will be found. To evaluate the control strategy, a new test-bed consisting of a long rod with piezoelectric transducers will be constructed. Using that test-bed, the capabilities and limitations of each potential control configuration will be studied. Eventually, the “best” control configuration will be installed on the 30 meter boom for ground testing.

Acknowledgements

The author would like to thank Dr. Mark Whorton of TD54 for providing an opportunity to participate in cutting edge research at NASA, and many hours of valuable discussion and guidance.