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RECENT DEVELOPMENTS IN SMART ADAPTIVE STRUCTURES FOR SOLAR SAILCRAFT

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ABSTRACT

The "Smart Adaptive Structures for Solar Sailcraft" development activity at MSFC has investigated issues associated with understanding how to model and scale the subsystem and multi-body system dynamics of a gossamer solar sailcraft with the objective of designing sailcraft attitude control systems. This research and development activity addressed three key tasks that leveraged existing facilities and core competencies of MSFC to investigate dynamics and control issues of solar sails. Key aspects of this effort included modeling and testing of a 30 m deployable boom; modeling of the multi-body system dynamics of a gossamer sailcraft; investigation of control-structures interaction for gossamer sailcraft; and development and experimental demonstration of adaptive control technologies to mitigate control-structures interaction.

INTRODUCTION

For the past several years NASA has been investing considerable resources to advance the technology for solar sail propulsion. Teams have conducted research on analytical methods for modeling the shape of the sail and support structures and motion of the sailcraft under solar radiation pressure loading. Others have developed prototype solar sail hardware systems including the sail membranes, structural supports, deployment mechanisms, and control actuation systems. Understanding the dynamics and control of large gossamer space structures has been one of the focus areas for technology development conducted at the NASA Marshall Space Flight Center (MSFC).

The "Smart Adaptive Structures for Solar Sailcraft" development activity at MSFC has investigated issues associated with understanding how to model and scale the subsystem and multi-body system dynamics of a gossamer solar sailcraft with the objective of designing sailcraft attitude control systems. This research and development activity addressed three key tasks that leveraged existing facilities and core competencies of MSFC to investigate dynamics and control issues of solar sails. Key aspects of this effort included modeling and testing of a 30 m deployable boom; modeling of the multi-body system dynamics of a gossamer sailcraft; investigation of control-structures interaction for gossamer sailcraft by semi-active control methods using unobtrusive sensors and effectors; and development and experimental demonstration of adaptive control technologies to mitigate control-structures interaction. The results of the first two tasks are presented herein and the third task is addressed in a companion paper [1].

MODELING, SCALING AND TEST VERIFICATION

Verifying the models and analytical tools on a sub-scale system is a first step in the process of validating the technology in a larger scale flight experiment. Since the global shape of a solar sailcraft is largely dominated by the membrane support structure, the ability to accurately model the support structure in a way that scales to larger sail dimensions is of fundamental importance. Toward that end, the 30 meter coilable, deployable Solar Array Flight Experiment (SAFE) boom at MSFC was utilized since it is structurally and dynamically similar to candidate solar-sailcraft systems under investigation.

This first task concentrated on developing a dynamic model of a long retractable boom and validating the scalability of the model at various deployed lengths. Extensive tests with various loading configurations were conducted with the 30 meter boom and experimental data were then compared with the corresponding response of the analytical model. The sailcraft structural systems will operate in a zero gravity environment but tests will be performed in a one-g environment. Accordingly, the analytical models must explicitly account for gravity in a manner that allows us to validate the model in a one-g environment and subsequently derive a zero-g model.

These results affirmed the general consensus that gossamer space structure model validation with ground testing is very challenging due to geometric constraints, loading conditions, and experiment interfaces – all or many of which are not present in the flight configuration and must be accounted for in the modeling process. Due to the difficulty in obtaining a priori structural dynamics models with sufficient fidelity to mitigate potential control-structure interaction, advanced vibration control methods may be necessary for gossamer spacecraft applications with control-structure interaction. The following material summarizes the results presented in Reference 2.

MATHEMATICAL MODELS FOR BOOM BENDING

Several standard assumptions were made in the development of mathematical models such as small cross-sectional dimensions compared to beam length; small bending deformations; and negligible change in length due to axial forces. Considering a beam clamped at one end and free at the other end, the equations of transverse motion $y(s,t)$ in response to applied forces and moments are derived as follows. At rest, the beam is vertical to minimize gravity effects and thereby simulate the zero gravity effects of space on the lateral deformations. Note that we assumed the beam is uniform and lacks a tip-mass in bending motion. The beam under investigation assumes there is no axial motion and its equation of motion is,

$$\frac{\partial^2}{\partial s^2}\left[EI\frac{\partial^2 y}{\partial s^2}\right]-T(L)\frac{\partial^2 y}{\partial s^2}+mg\left((s-L)\frac{\partial^2 y}{\partial s^2}+\frac{\partial y}{\partial s}\right)+m\frac{\partial^2 y}{\partial t^2}=w(s,t) \quad (4)$$

Admissible functions are used in our analysis because of difficulties computing the analytical mode shape functions $\phi_j(s)$. The admissible functions are the mode shape functions of the classical Euler-Bernoulli Beam, i.e:

$$u_j(s)=c_{1j}\sin(\beta_j s)+c_{2j}\cos(\beta_j s)+c_{3j}\sinh(\beta_j s)+c_{4j}\cosh(\beta_j s) \quad (5)$$

where β_j, and c_{1j}, c_{2j}, c_{3j}, c_{4j}, $j=1,2,3,\ldots$ are computed from boundary conditions.

The data analysis consists of using the mathematical model to predict (1) natural frequencies and (2) mode shapes of the first three modes. The analysis is completed by comparing these predicted natural frequencies and mode shapes with those measured from experimental data for a corresponding configuration (deployment length and axial load). This analysis is repeated for every test configuration.

DATA ANALYSIS FOR BOOM BENDING

From the impulse response due to the transverse forces induced by an impact hammer, the modal parameters, the corresponding natural frequencies predicted by the mathematical model are computed and tabulated below.

		Experimentally Obtained			Model Predicted			Model Error		
L (Meters)	T_c (lb)	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)	f_1 (%)	f_2 (%)	f_3 (%)
10	0	1.0990	6.3965	N/A	1.3454	8.2999	22.9846	22.42	29.76	N/A
22.5	0	0.2819	1.5602	3.7780	0.3155	1.6825	4.7204	11.92	7.82	24.94
22.5	5	0.5574	1.6124	N/A	0.3047	1.6671	4.7074	-45.34	3.39	N/A
22.5	10	0.7030	1.6175	N/A	0.2932	1.6515	4.6944	-58.29	2.10	N/A
30	0	0.2180	0.9260	2.4300	0.2123	0.9582	2.7014	-2.61	3.48	11.17
30	5	0.3452	0.9549	2.4952	0.2043	0.9424	2.6883	-40.82	-1.31	7.74
30	10	0.4187	0.9846	2.4547	0.1959	0.9263	2.6752	-53.21	-5.92	8.98

Table 1. Experimentally Obtained/Model Predicted Natural Frequencies

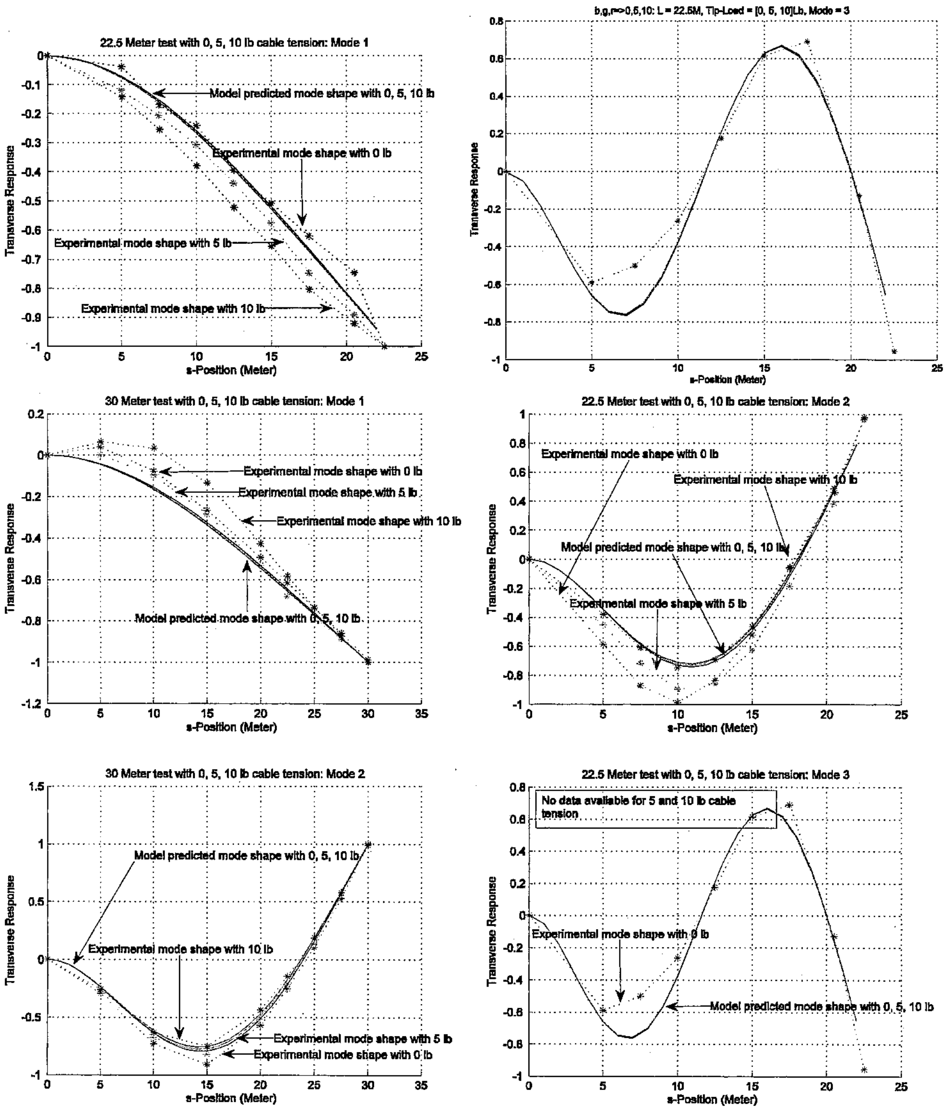

Figure 1. 22.5 and 30 Meter Tests with 0, 5, 10 lb cable tension

These results are obtained from experimental data with different tension loads being applied at the tip. This analysis is limited to the first three modes because they account for most of the beam's vibration motion. Evident from this analysis is the reduction in model error as the beam length increases. This is not unexpected due to the model assumptions (such as the slenderness ratio) which become more valid for longer lengths. This observation directly relates to scalability assumptions by imposing constraints associated with modeling assumptions on the valid range of scaling.

Figure 1 compares model predicted mode shapes with mode shapes reconstructed from experimental data. Note that in some instances no reliable data was available to construct the mode shape of the third mode. While the predictions are reasonably accurate, the experimental modes shapes show a much larger than expected dependency on axial load. It is likely that this discrepancy is due to curvature along the boom which violates the assumptions that the boom is straight. Additional testing to confirm this cause was beyond the scope of this effort.

An effort was made to determine a constant bending stiffness could from static load deflection tests, but the empirically derived bending stiffness was found to vary with the deployed length of the boom. As with the mode shape discrepancies, the inability to determine a constant and uniform stiffness *EI* value from static test data *may* actually be due to the effects of local/global stiffness changes caused by an imperfectly straight boom.

Although the results are not definitive and conclusive, evidence generally suggests that simple linear-time invariant mathematical models can predict the general dynamic behavior of a long boom that is similar to the one used in this study. It seems that most of the mismatches are due to inability of the experimental environment to satisfy some of the assumptions made in developing theoretical models such as the large and un-modeled angular-transverse vibration coupling. Although some of these assumptions are expected to be satisfied more closely in real flight conditions (zero gravity, much longer booms, etc.), one of the most critical questions to be asked may be whether a boom satisfies the perfectly straight beam assumption. Depending on degree of waviness and curvature in the boom, one may have to drop this assumption and develop complicated models that represent coupling between bending and torsional motion.

It can be fairly said that the most pertinent conclusion drawn from this first task is to question the validity of ground verification and scalability of structural dynamic models of gossamer space structures for the purposes of developing control design models. Detailed finite element models can be constructed and test verified to some degree, but these detailed nonlinear models are not scalable in any sense (but rather constitute distinct models for systems of different scales) nor does the test environment and configuration represent the flight environment and configuration. In terms of the gross static structural deformation, loads, or general modal properties, dynamic models may well be of sufficient accuracy. But in the event where feedback control systems interact with structural dynamics of the gossamer system, dynamic models of gossamer structures will not be sufficiently accurate for model based control design and adaptive control methods will likely be necessary.

MULTI-BODY SAILCRAFT DYNAMICS MODELING

Stability and control of a solar sailcraft is a particularly difficult challenge. As illustrated in the first task of this effort, the structural dynamics of very large gossamer structures such as solar sailcraft are notoriously difficult to model, being characterized by low frequency, closely spaced, and lightly damped fundamental modes of vibration. Once excited, these modes will induce slowly decaying, large scale deformations of the sail structure. Uncertain structural deformations, both static and dynamic, result in uncertainty and variability in the thrust vector magnitude and direction which may degrade system performance and potentially destabilize the sailcraft attitude dynamics. Moreover, uncertainties in material properties compound the thrust vector uncertainty. The degree to which the system performance and stability are degraded is a function of the robustness of the control system and knowledge of the system dynamics.

The second task employed the TREETOPS multi-body dynamics modeling tool to investigate the system level, coupled multi-body dynamics and closed-loop control of a gossamer sailcraft [this section summarizes Reference 3]. Generically speaking, TREETOPS models systems in a tree topology as shown in Figure 2 using interconnected bodies, sensors, and actuators where bodies are modeled as either rigid or flexible.

The TREETOPS solar sailcraft model included the coupled dynamics of the sailcraft bus, sail membranes, flexible booms, and control system sensors and actuators of a representative solar sailcraft and applied environmental torques from gravity gradient and solar radiation pressure. Closed loop attitude maneuvers were investigated with this model to assess system level dynamics and control issues. With this tool, scaling issues and parametric trade studies can be performed to study attitude control system performance, control authority requirements, control avionics architectures, and vibration suppression approaches to mitigate control/structure interaction.

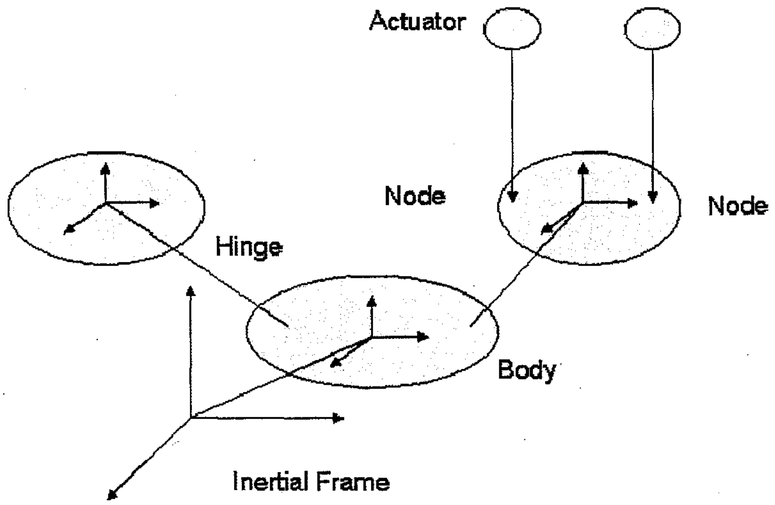

Figure 2: TREETOPS Model Architecture

TREETOPS implements Kane's equations to model multiple interconnected structural subsystems, or "bodies," which may be either flexible or rigid. The interconnections between subsystem bodies are defined by "hinges" with allow up to six degrees of freedom (DOF) relative motion as well as interface dynamics such as linear spring stiffness and damping. A suite of control system sensors and actuators can be attached at various locations on any body with PID, state-space, and user-defined feedback control systems.

The solar sail system architecture for this study is based on a four-quadrant square sailcraft. Most control system architectures for solar sailcraft vary either the center of mass location or the center of pressure location (the resultant of the net solar radiation pressure force) to null the bias torques and generate maneuvering torques. For the architecture modeled in this study, the sail attitude control system (SACS) utilizes masses that translate along the booms for pitch and yaw control (rotation about booms) and sail panel rotation for roll control (rotation about vector normal to plane defined by undeformed booms). Sail panel rotation is accomplished by rotating "roll spreader bars" (RSB) that are attached to the end of the booms. As shown in Figure 3, the TREETOPS model of the solar sail system has fifteen bodies: one body for the spacecraft bus (S/C), four flexible booms, four solar sail membrane quadrants, four roll spreader bars, and two moving masses. All of the bodies are connected by using TREETOPS hinges with the appropriate degree of freedoms (DOF) and tuned linear spring devices.

SAILCRAFT STRUCTURAL MODEL

To simplify the model development for first generation sailcraft model, the sail membranes are modeled as rigid bodies with the correct mass and inertia. By tuning the hinge stiffness at the interconnections between the sail quadrants and booms, the first mode of the membrane dynamics can be modeled and the dynamic coupling between booms and membranes can be accounted for. Future versions can replace the rigid membrane quadrants with flexible dynamics from NASTRAN models of the sail quadrants. In the current sailcraft model, the solar radiation pressure is represented as a force applied normal to the membrane at the center of mass of each quadrant. This force is assumed to be maximum when the membrane is normal to the Sun and varying according to the change of angle between the membrane normal unit vector and the Sun normal unit vector.

Boom flexibility can be modeled in one of two ways. The simplest way is to use a rigid body and connecting a hinge with rotational DOFs such that the hinge stiffness and damping are chosen to represent the dominant bending mode. A higher fidelity approach models each boom as a flexible body by importing the modal properties (mode shapes and slopes, generalized mass and generalized stiffness) of the boom obtained from a NASTRAN normal modes analysis. Both approaches were implemented in this study and the two resulting TREETOPS models were compared and validated against each other. The results presented herein are obtained utilizing the modal properties of first in-plane bending, out-of-plane bending, and torsion modes that were calculated using NASTRAN normal modes analysis of each boom with fixed-free boundary conditions.

SAILCRAFT ATTITUDE CONTROL SYSTEM MODEL

Sailcraft are unique in that the attitude dynamics are coupled with the orbit dynamics since the thrust vector is pointed by controlling the attitude of the sailcraft. Thus to track a reference trajectory, thrust vector commands are converted into the appropriate attitude commands and the attitude control system generates the torques required to maneuver the vehicle to the commanded attitude. For this TREETOPS solar sail spacecraft model, the SACS generates control torques in two axes by varying the center of mass location and hence the moment arm of the resultant solar radiation pressure force. Two point masses are modeled which translate along the x-axis and y-axis booms to generate pitch and yaw torques. For roll attitude control, four roll spreader bars are modeled as individual rigid bodies attached to the end of each boom, each with one rotational DOF about the boom longitudinal axis.

The required torques for the roll, pitch and yaw maneuvers of the spacecraft are calculated using a simple Proportional-Integral-Derivative (PID) controller. The rotational angle commands of the RSBs are derived from the geometric and kinematic relationship between the solar sail membrane and the RSB, which is based on the required torque for the spacecraft roll maneuver. Similarly, the translational movement commands of the moving masses are derived from the required torques for the spacecraft pitch and yaw maneuvers. The motions of the RSB and moving masses are controlled to follow the above commands using a PID actuator control loop for each actuator.

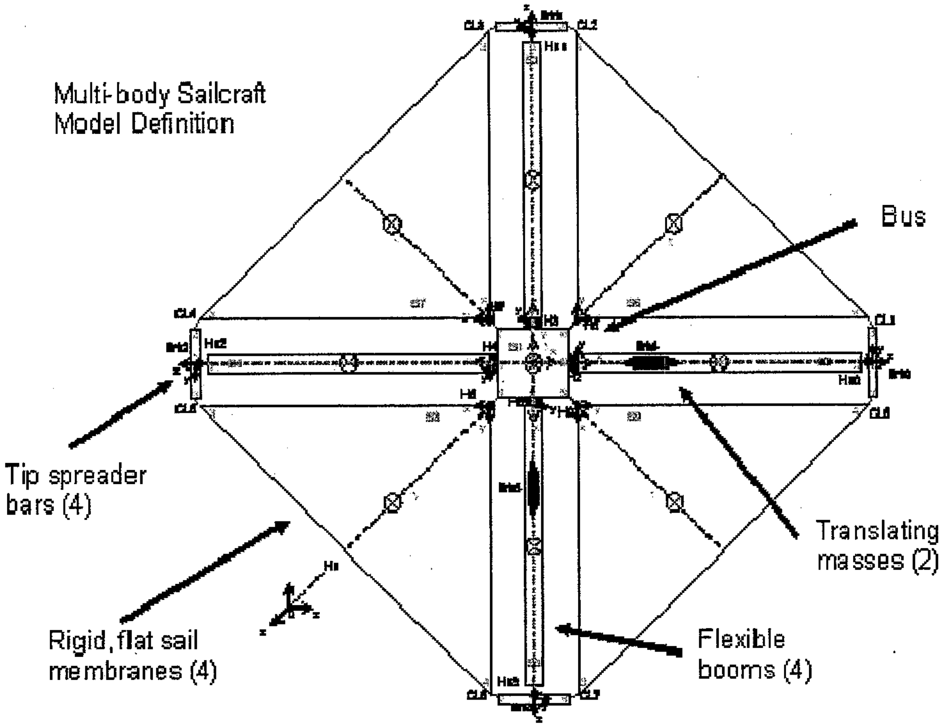

Figure 3: Configuration of TREETOPS Solar Sail Model

The sailcraft system modeled in this manner embodies the coupled flexible body dynamics and closed loop control system architecture of a representative solar sail spacecraft. In all, this model embodies six distinct PID control loops: one for each of pitch, yaw, and roll actuator controllers and one for each of the three vehicle attitude control loops. No attempt was made to tune or optimize the performance or margins of the various control systems in this model; rather, this analysis simply demonstrates the ability of the TREETOPS model to adequately address the key issues associated with the dynamics and control of solar sail spacecraft.

CLOSED LOOP SAILCRAFT ATTITUDE CONTROL SIMULATION

The TREETOPS model was tested by simulating closed loop attitude control of the solar sail spacecraft. Three test cases were run with a ten degree attitude step command in the pitch, yaw, and roll axes, respectively. Vehicle rotations about the x-axis are generated by commanding the control mass to translate along the y-axis (moving the center of pressure and generating a torque about the x-axis). Likewise, rotations about the y-axis are accomplished with the translating mass along the x-axis.

For the first test case a step command of ten degrees was commanded in the pitch axis. The attitude control law generates a commanded position of the moving mass to produce the needed torque. This position command is executed by an inner loop that controls the mass position with a PID control law. Figure 4 shows the closed loop response of the y-axis moving mass as well as the closed loop pitch response.

As can be seen, the simulation was able to successfully to demonstrate a pitch maneuver using translating masses. Again, the time response was not appreciably tuned since the objective was not control design as much as demonstrating correct control system implementation. Due to symmetry of the sail system and the dynamic decoupling of the translating mass control architecture, the yaw response is identical to the pitch response.

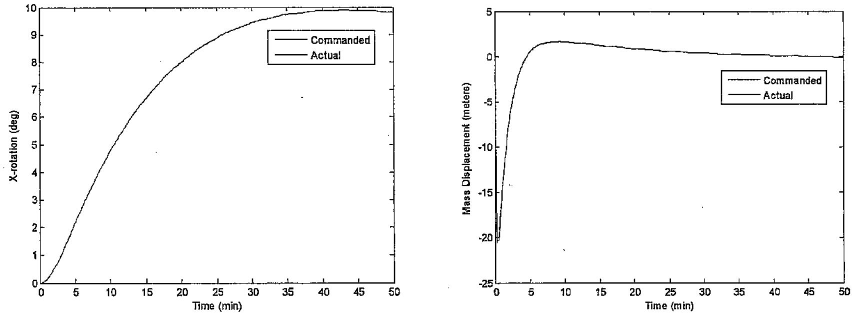

Figure 4: Closed Loop Sail Pitch Response

For the Roll maneuver, the roll spreader bars are commanded to rotate the sail quadrants and generate a component of the solar radiation pressure in the plane defined by the sailcraft booms. This in-plane force produces a roll torque about the vehicle center of mass such that the roll response is accurately modeled in the simulation.

OBSERVATIONS

Gossamer structures such as solar sailcraft are unique in many ways and will require unique tools for the design and analysis of flight control systems. For example, the orbit and attitude dynamics of large solar sailcraft will be tightly coupled due to the fact that the thrust vector is pointed and the trajectory is determined by the attitude of the sail and the shape of the reflective surface. The surface shape in turn is a function of the attitude relative to the sun and the resultant solar pressure distribution. Must like a case of static aeroelasticity, the thrust produced by the sail is a function of the sail attitude and shape which is in turn a function of the thrust and sail attitude. Moreover for large sailcraft and relatively higher performance maneuver requirements, the frequency domain of the attitude (or even trajectory) control system will likely encompass the fundamental bending modes of the structure. Hence, a detailed analysis of gossamer sailcraft structures will require a tool such as the Treetops model demonstrated here which properly accounts for flexible dynamics, multi-body coupling, and closed loop control systems.

SEMI-ACTIVE CONTROL TECHNIQUES FOR VIBRATION SUPPRESSION

One area that has great potential for gossamer space structure vibration mitigation is the use of Piezo-electric (PZT) actuation devices. PZTs convert mechanical vibration energy to electrical energy with a wide frequency response spectrum and strong electro-mechanical coupling. If bonded to the surface of a flexible structure, they are conceptually capable of operation in the space environment and can therefore be classified as "space-realizable" [4]. Furthermore, thin, light-weight and flexible PZT actuators such as polyvinyledine (PVDF) film and a macro-fiber composite patch can be packaged in an inobtrusive manner on (or within) gossamer structures without introducing significant mass loading. For these reasons, PZT devices have been extensively used as sensors and actuators for active and passive vibration suppression of flexible structures [5].

Active control of vibration involves utilization of powered actuation devices and easily benefits from modern control design techniques. Consequently it can potentially provide the best performance for a given hardware configuration. However, it requires a significant external energy source to drive the actuators and can destabilize the structure if improperly designed [6]. Furthermore the required energy source will introduce significant parasitic masses, and thus this approach is not well suited to solar sail craft where low masses are critical. Passive approaches have the advantage that they can not destabilize the system under any circumstances because they only take vibration energy out of the structure. In this approach a Piezo-electric actuator is shunted (e.g. with a resistor or resistor and actuator). As a result, mechanical vibration energy is converted to electrical energy, which is then dissipated via a passive circuit. This approach typically under-performs active approaches and may require large inductance (i.e. a heavy coil) for low frequency vibration suppression. Since the boom is long and light weight, the dominant modes will have a low frequency. Therefore a heavy coil may be required for each actuator. Since several actuators may be needed, the large total mass of all the coils makes passive control with PZT devices un-ideal for ultra-light weight structures like solar sail craft.

Recently a new vibration suppression approach called "semi-active" or "hybrid" vibration suppression has been introduced. The idea is to convert vibration energy to electrical energy via PZT actuators attached to the vibrating structure, accumulate the electrical energy, and then dissipate the stored energy in a controlled manner. For example, a resistive, capacitive or inductive shunt circuit (for the PZT actuator) is switched on and off according to the phase of a vibrating mode of the structure [6]. Since vibration energy is always extracted from the system, this approach cannot destabilize the system. A benefit of this approach is the fact that external power to drive the actuators is not needed. However, a small external energy source may be needed to power the switching circuit. In view of the above, semi-active control techniques are well suited to vibration suppression of a solar sail boom. However, research on this approach is limited and further studies are needed.

In Reference 7, we showed that a solar sail boom could be modeled as an Euler-Bernoulli beam with clamped-free boundary conditions. As an extension of this effort, we herein use an Euler-Bernoulli beam to illustrate the capabilities of semi-active vibration suppression for solar sail booms. We begin by developing a mathematical model of a classical Euler-Bernoulli beam with clamped-free boundary conditions and integrated PZT actuators/sensors. The model can accommodate multiple PZT actuator/sensor patches at arbitrary locations on the beam. Next we validate the model with experimental input-output data. Since models of solar sail booms are expected to contain significant uncertainties, we consider an active control law (in this case velocity feedback) that is inherently robust to model uncertainties. Semi-active control is then simulated as a switching logic that causes the charge generated in the PZT actuators (due to beam vibration) to have the same sign as the charge that would be induced in the actuator by the active control law. The results of the simulation are provided and compared with equivalent results if a passive approach had been used.

SIMULINK MODELS

Preliminary progress has been made toward experimental demonstration and test results are forthcoming in a future paper. In this study the vibration suppression schemes will be designed to target the first vibration mode. Accordingly, an "optimal" impedance for passive vibration suppression is $L = 1/(\omega^2 \, Ca)$, where ω is the natural frequency of the first mode in radiance per second, and Ca is the inherent capacitance of the PZT actuator. Similarly, an optimal value of impedance for semi-active control is $0.1/(1/(\omega^2 \, Ca)$.

We consider the case where the beam is initially excited by a 100 Volt external signal that acts on the transducer from time t=0.01 to t=0.011 seconds. Once excited, the resulting vibration is suppressed using either a passive or semi-active approach. This scenario was simulated in Simulink with the beam modeled by a transfer function computed from a physics-based model. For ease of exposition, we considered the collocated actuator/sensor case for which velocity feedback is an appropriate active control strategy. Onoda et al. [6] demonstrated that semi-active vibration suppression is achieved by periodically shunting the terminals of a PZT transducer actuator across a series circuit consisting of an inductor and resistor according to simple. First design an active control signal (e.g. velocity feedback) and use it to compute the desired control signal U_Q. Next periodically discharge the charge Q built up in the PZT (due to vibration) such that $Q\,U_Q > 0$ whenever $U_Q > 0$. In other words force Q to have the same sign as U_Q. Accordingly, the following switching rule was devised to achieve this:

Turn on the switch when $U_Q V < 0$ and turn it off when $U_Q V > 0$, where V is the voltage accros the Transducer terminals. This switching logic as well as the passive control strategy was implemented in Simulink.

Onoda et. al [6] successfully implemented semi-active vibration control methods using PZT stack actuators. In their systems, the electrical energy generated when a PZT stack actuator is attached to a vibrating structure was dissipated passively in a manner that yields more vibration suppression than conventional passive methods. In our study, we plan to evaluate the effectiveness of their approach for structures with multiple integrated PZT patches each of which has significantly lower inherent capacitance than PZT stack actuators. As a first step, we developed a multi-actuator model and studied a system with an actuator pair. The results of the Simulink model simulation of the open loop (solid line) and closed loop (dashed line) response under passive control and semi-active control are shown in Figure 5. The superior performance of the semi-active control scheme is readily apparent.

VIBRATION SUPPRESSION TESTBED DEVELOPMENT

Recognizing the challenges to accurate modeling of large gossamer space structures, the third task addressed the techniques and components for robust, high performance gossamer structure vibration control.

CLOSED LOOP CONTROL EXPERIMENTAL DEMONSTRATION

The third task of the Intelligent Adaptive Control for Vibration Suppression effort focused on the development of intelligent adaptive control methods for vibration control and the experimental demonstration of those methods in a representative ground test facility. A companion paper will present the theory, analysis, and experimental results for adaptive control applied to gossamer sailcraft [1]. This section describes the experimental facility developed for experimental evaluation of the adaptive control for vibration suppression of gossamer structures.

The primary test article for the adaptive control demonstration was the SAFE (Solar Array Flight Experiment/Dynamic Augmentation Experiment (SAFE/DAE)) mast / canister system boom illustrated in Figure 5 that had previously flown aboard Shuttle Mission STS-41D. The boom was deployed vertically in a cantilevered configuration to a length of 30 meters.

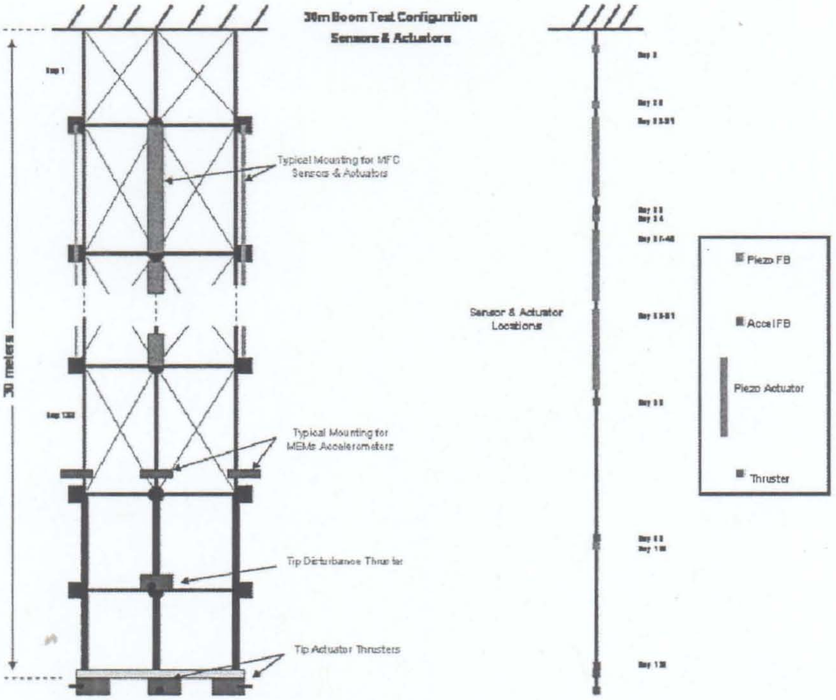

Figure 6: Adaptive Control for Solar Sails Testbed

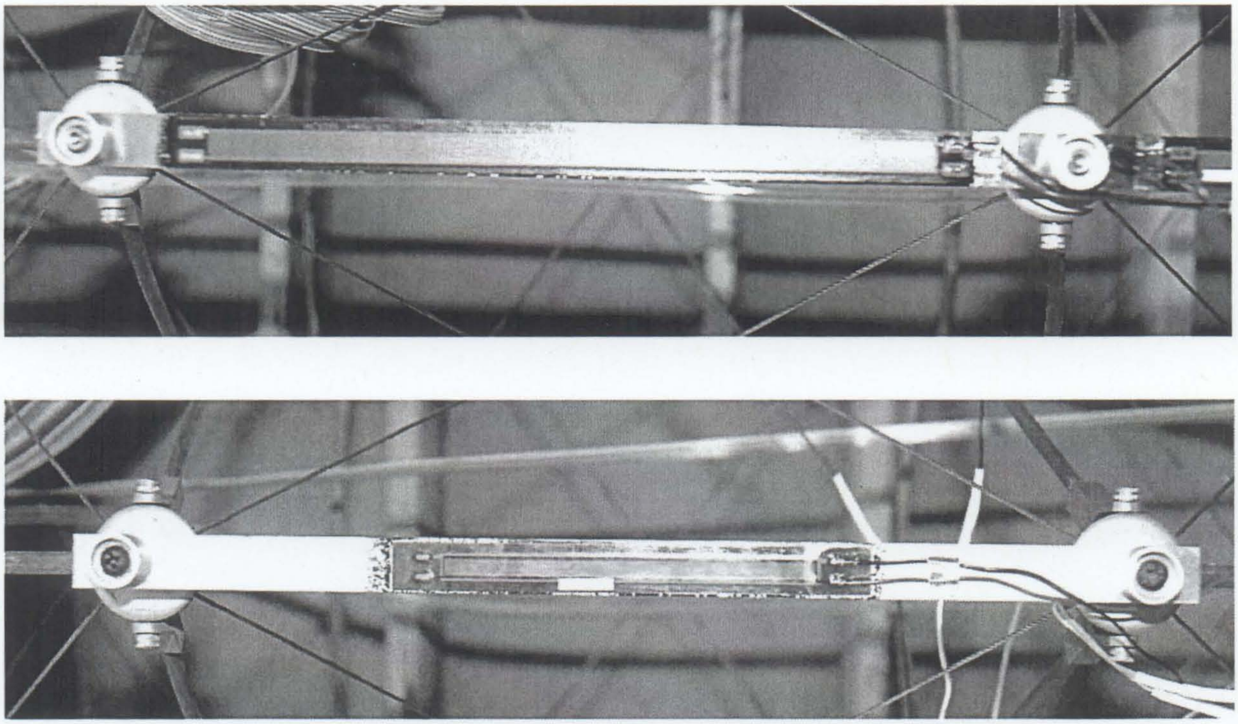

Figure 7: Assembled MFC Actuator & Sensor Coupons Mounted on Boom

The evaluation of passive and active damping devices and feedback sensing required by the task included both traditional devices and emerging technologies. Traditional accelerometers and gas thrusters were used with emphasis placed on investigating the use of macro-fiber composite technology for both sensing and actuation. The macro fiber composite (MFC) offers high performance and flexibility. The MFC consists of rectangular piezo ceramic rods sandwiched between layers of adhesive and electroded polyimide film. This film contains interdigitated electrodes that transfer the applied voltage directly to and from the ribbon shaped rods. This assembly enables in-plane poling, actuation (bending), and sensing in a sealed, durable, ready-to-use package. When embedded in a surface or attached to flexible structures as shown in Figure 7, the MFC actuator can provide distributed solid-state deflection and vibration control as illustrated in Figure 8.

CONCLUDING REMARKS

This paper summarizes the research and development that is the product of a broad, interdisciplinary team team of skilled researchers and engineers over a three year period. The primary contributions of the team are more fully documented in specific references, but this paper serves to provide an overview of the results that contribute to the larger goal of advancing technologies for the control of solar sailcraft. Toward that end, this effort has demonstrated the following key lessons learned:

1. The sufficiency of model validation through ground testing is a function of the purpose of the model. Models of gossamer structures that are validated by ground test are almost certainly not sufficient for the purposes of high performance control design (where there is a potential for control structure interaction) when re-parameterized for the scale and environment of the flight system.
2. Dynamic models of gossamer spacecraft must include multi-body coupling and structural dynamics of flexible structural components. This is not necessarily best accomplished by system level finite element type models which lose relevance with respect to validation when re-parameterized for operational scales and environments. Multi-body dynamics tools such as TREETOPS are effective means of modeling the system dynamics in a manner that is amenable to control system design and analysis.
3. Unobtrusive sensing and actuation using PZTs offers much potential for vibration suppression in gossamer structures using conventional control approaches but especially due to the robustness and mass efficiency of semi-active control approaches.
4. For large gossamer space structures that have relatively stringent control requirements, the inherent uncertainty in structural dynamics presents a significant challenge for classical and standard modern control approaches. Adaptive control methods appear to have significant potential for gossamer structures with control/structures interaction.

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