STUDIES AND EXPERIMENTS IN STRUCTURAL DYNAMICS AND CONTROL

Khanh D. Pham

30 December 2006

Final Report

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14. ABSTRACT

The objective of this task is to develop enabling structural technologies for future Air Force systems. Four areas of research are currently under investigation: thermal/mechanical to electrical energy conversion utilizing piezoelectrics that explore power augmentation schemes to maximize power available for DoD satellites and the use of piezolectic power generation produced by thermal expansion proves 5% satellite power augmentations possible; lightweight, low frequency acoustic barrier using particle embedded foil that uses in-plane bending waves in a thin foil layer to improve the low frequency characteristics of melamine foam; cable effects on dynamics of large precision structures that develop a design approach to incorporate the effect of cable damping into models for future large deployable structures; and on-orbit deployment detection that explores the use of the existing attitude control subsystem with a newly proposed attitude control algorithm to detect the angular orientation change due to space debris impacts and inspector satellite dock for purposes of structural health monitoring and self-awareness.

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Piezoelectrics, enabling structural technologies

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1. Using In-Plane Bending Wave Excitation to Improve the Low Frequency Response of Acoustic Foam for Launch Fairing Acoustic Mitigation

1.1. Introduction

The launch acoustic environment is severe and damaging to sensitive spacecraft components. Sound pressure levels can exceed 130 dB over the entire frequency range. Because of this, components are designed with more structural mass to withstand these loads than would otherwise be necessary to survive launch. At least 10% and up to 70% of the spacecraft's structural mass is only used to survive launch. Once on-orbit, this mass is essentially useless. The result is a significant reduction of available payload mass and an increase in cost. During launch, a typical fairing will exhibit several acoustically resonant modes related to its length and internal geometry. These modes are excited by acoustic ground reflections during the initial launch phase. Because of the amplification effect of ground reflection, structural vibration excited by the acoustic environment dominates the initial launch phase. By significantly reducing these loads, the structural mass of the payload can be greatly reduced.

Of particular importance are low frequencies, which are those below 500 Hz. Low frequencies are higher power and have longer wavelengths. As a result, the payload fairing does little to attenuate low frequency sound; whereas, it is much more effective at attenuating higher frequencies. In addition, plain acoustic foam, such as melamine foam, performs much better at higher frequencies. As frequency decreases, the performance of plain acoustic foam drastically decreases. The low frequency performance of the foam can be improved by increasing its thickness and mass at the cost of payload capacity. Additionally, acoustic barriers in the foam can be employed to improve low frequency characteristics. For example, adding a heavy septum layer, such as lead, within the foam can be added to increase the transmission loss; however, the added mass reduces the allowable payload capacity. Also, there are active devices designed to specifically mitigate acoustic loads below 500 Hz, but they are generally heavy and bulky. Therefore, passive broadband acoustic protection technology with low volume and mass characteristics is needed. This is especially true for lower frequencies. We present an alternative lightweight acoustic barrier that uses in-plane bending waves in a thin foil layer to improve the low frequency characteristics of melamine foam. The system consists of a thin metal foil bonded to a periodic array of rigid spacers that are then bonded to the surface of a melamine foam substrate. The purpose of the spacer system was to vary the stiffness across the foil in a periodic pattern to excite bending waves in the plane of the foil causing inter-particle interactions. These interactions significantly increase the acoustic response of the layer at low frequencies and are influenced by the foil's material properties, thickness, and the distance between spacers.

1.2. Technical Approach

To verify the excitation of bending waves and to determine their effects, a 6 inch-diameter transmission loss tube was constructed and is shown in Figure 1.

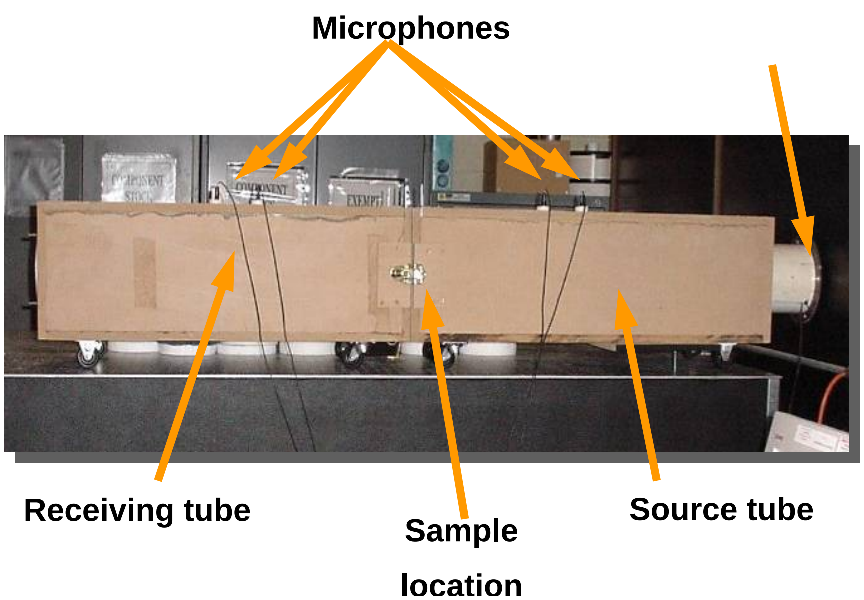

Figure 1: Transmission loss tube consisting of a 6" diameter PVC pipe embedded in concrete and surrounded by 1” thick medium density particle board

Four microphones, two on the upstream side and two on the downstream side, were used to measure the acoustic environment within the tube. For each sample, two cases were run with different boundary conditions at the end of the tube. The first boundary condition consisted of an open tube end. The second boundary consisted of an anechoic termination consisting of three various acoustic foams. The average absorption of the system from 100 to 1000 Hz was 0.97. A loudspeaker was mounted at the opposite end and was used to generate a plane wave field in the standing wave transmission loss tube. The complex sound field was then measured at each of the four microphone locations. Using the transfer matrix approach described by Song and Bolton, the transmission coefficient was calculated. The transmission loss was then calculated using the transmission coefficient (T) and the equation 1.

$$TL = 20\log_{10}\left(\frac{1}{T}\right) \tag{1}$$

Two different concepts were tested. The first, shown in Figure 2, consisted of a layer of 1 mil thick aluminum foil bonded to a periodic array of spherical particles that were then bonded to a flat Willtec melamine foam substrate. Willtec, produced by Illbruck Inc., has an open-celled, fiber free structure making it lightweight and flexible. Additionally, the open cells enhance the sound damping characteristics over a wide frequency range. The Willtec foam was also chosen for testing because of its high thermal resistance and operating temperature range, which is critical for launch vehicle fairings. The thicknesses of the foam substrates tested were 1" and 2". The array of spherical particles consisted of a 2 cm by 2 cm grid of 2 mm chrome steel balls. The spacing was specifically chosen to target 500 Hz based on the equation for in-plane bending waves in a plate.

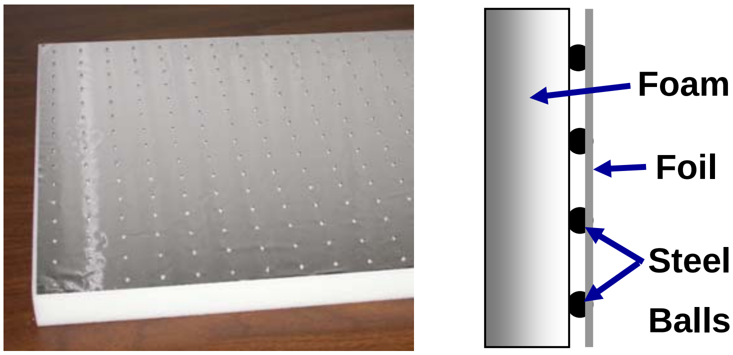

Figure 2: Low frequency acoustic mitigation treatment consisting of a 2 cm by 2 cm array of 2 mm steel balls embedded in a 1 mil thick aluminum foil layer and bonded to a 1" thick melamine foam substrate

The second concept tested eliminated the steel balls and replaced them with a 2 cm spacing of ridges cut into the melamine foam. Again, 1 mil thick aluminum foil and 1" and 2” thick foam substrates were used. Figure 3 shows a picture of the test samples and a schematic of the system. The advantages with this system are a decrease in mass, a simplified fabrication process, and the elimination of flight safety issues related to the steel balls. The disadvantage is a reduction in performance. The foam ridges have a higher compliance than the steel balls, which results in higher damping and a reduction in bending wave excitation. In addition to these samples, plain foam and plain foil samples for each thickness were tested. The plain foam and plain foil samples were used as a baseline measurement for improvement.

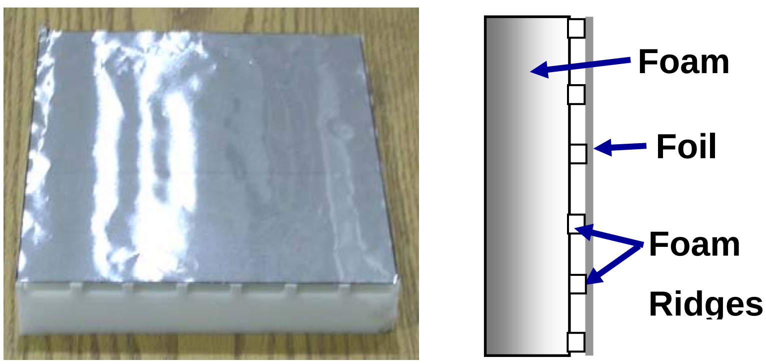

Figure 3: Low frequency acoustic mitigation treatment consisting of a 2 cm array of foam ridges 1 mil thick aluminum foil layer and bonded to a 1” thick melamine foam substrate

For each test, the sample panel was mounted in an aluminum housing that was then installed into the transmission loss tube. An aluminum housing was used to ensure similar boundary conditions between each test and to provide a consistent method for installation of the sample within the tube. The samples were mounted so that the plain foam sample faced the source tube and the foil side faced the receiving tube. For each test, the temperature and the humidity of the room were measured, and the corrected speed of sound was calculated. During testing the room temperature was maintained within ±5 °C. The voltage to the loudspeaker was adjusted so that the microphone voltage exceeded the background noise by at least 10 dB. Because lower frequencies were of the most interest in this experiment, measurements were taken for frequencies from 200 Hz to 1000 Hz. Measurements were not taken below 200 Hz because of limitations in the loudspeaker.

1.3. Results and Conclusions

The results for the 1" and 2" samples, which are shown on Figure 4, demonstrate a significant improvement at 500 Hz for the bending wave samples compared to the plain foam and plain foil samples. For frequencies above 500 Hz, all samples outperformed the plain foam samples, and the results compared to the plain foil samples were mixed. Over the entire range, the 2" plain foam sample averaged the highest transmission loss. However, the 2" steel ball bending wave sample performed the best below 500 Hz.

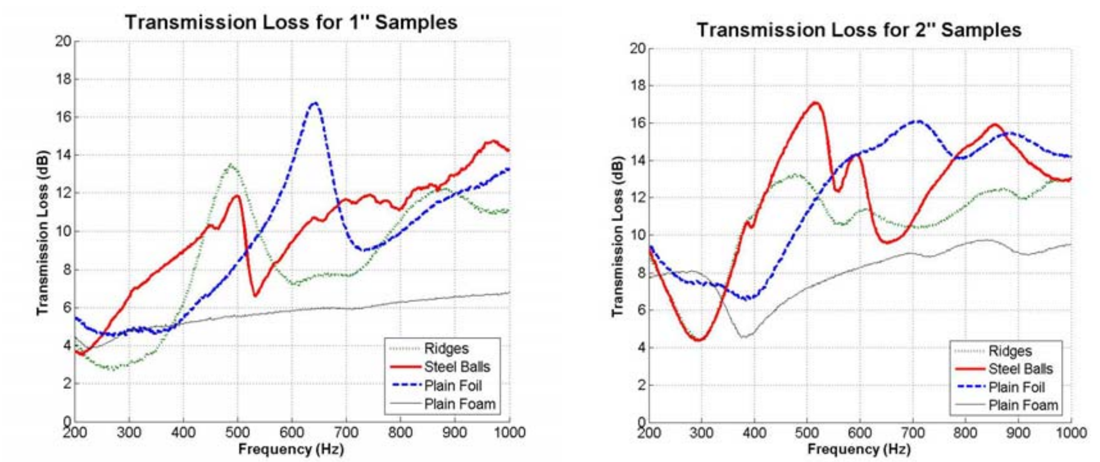

Figure 4: The transmission loss results for the 1" and 2" samples are shown for the ridged, the steel ball, the plain foil, and the plain foam samples

From the transmission loss data, we concluded that the melamine foam substrate damped the system to the point that bending waves could not be excited in the foil when it was directly bonded to the foam. However, by intercalating the particles between the foam substrate and the aluminum foil, bending waves were excited in the foil and the TL increased in the target frequency range. The result was that the modified blanket performed just as well as the 2" thick plain melamine foam for frequencies above 500 Hz and better than the 2" foam below 500 Hz.

In the last phase of the effort, we showed that the same effect could be achieved by removing the spherical particles and replacing them with ridges cut into the foam. We also tested a concept where ridges were cut in both directions, essentially leaving a grid pattern similar to the steel balls. Unfortunately, the foam did not provide enough stiffness and the results closely resembled those of the plain foil.

Using the results from these tests, we are developing a flight experiment to test the concept on a small sounding rocket mission to validate the results of our testing in a realistic flight environment. The flight is currently scheduled for 2Q FY07 aboard the Re-Entry Structures Experiment (RESE), which will fly out of White Sands Missile Range, New Mexico. References [1]-[13] contain a complete historical background and recent developments for related works in the field.

2. Thermal/Mechanical to Electrical Energy Conversion Utilizing Piezoelectrics

2.1. *Introduction*

Spacecraft systems traditionally utilize photovoltaic/chemical battery energy generation and storage systems. The fragile nature of high efficiency crystalline solar cells does not make them an ideal candidate for the rigors of space flight. Further, the use of crystalline solar cells typically mandates the use of chemical battery energy storage due to the eclipse time of most utilized Earth orbits. This presents further difficulties for spacecraft designers as the battery is typically the largest component mass on the satellite.

Piezoelectrics have traditionally been used in aerospace and other engineering disciplines for sensors and, to a lesser degree, actuators. Recent work by DARPA and MIT/others have focused on the use of piezoelectrics in personal power generation schemes with positive results, although the power generation potential is low due to the low masses and energies involved (heel strike power generation, for example). The drawback in these schemes is the lack of energy generating capability (i.e. mass) of an average human (energy = force x stroke).

The focus of this research is to utilize piezoelectrics as a satellite power generation source utilizing the temperature gradient between the satellite components or sun and deep space; and focus on the technology as an augmentation for existing satellite power generation and storage systems. The piezoelectric system has the benefit of being able to generate power during eclipse, since a temperature gradient still exists in eclipse and is the only required energy driver. This represents a benefit over traditional photovoltaic systems.

The technology, if successfully developed, also has a strong potential application in civil engineering. The mechanical strain energy involved in a semi-truck traversing and deflecting a bridge, for example, is significant. This specific example utilizes a direct piezoelectric mechanical to electric conversion, but thermal to electric paths like the satellite application above exist as well (rail lines, continuous paved sections, etc.). For both aerospace and civil applications, the technology has the additional benefit of reducing deleterious effects while generating power (i.e. the strain energy would be transferred into usable energy).

2.2. Technical Approach

1. Obtain piezoelectric baseline material properties. This task includes a survey of existing suppliers, acquisition of select material, and independent verification of material properties at the Air Force Research Laboratory/Space Vehicles Directorate, AFRL/VSSV. In addition, composite piezoelectric/substrate material properties are developed and evaluated.

2. Characterize power generation capabilities of selected piezoelectric/composite materials under thermal/mechanical loading. This task will be completed at VSSV utilizing existing equipment/capability.

3. Prepare small scale prototype bench test system. Develop a theoretical basis to explain experimental results.

4. Report research results and conclusions. Upon successful prototype demonstration, recommend future research direction/focus.

2.3. Results and Conclusions

Research objective 1 was completed in FY05 and the beginning of FY06. Research objectives 2, 3 and 4 have been completed by the end of FY06. Recent report as seen in reference [14] illustrates several interesting results which were obtained in the course of the present research that warrants further investigation. These are summarized below: Firstly, based on the conclusions of the present research, the bridge application shows great promise as a potential energy scavenging application. Further research should be conducted in this area to understand the scalability issues, as well as implementation issues such as bonding, energy storage system interface, environmental effects, etc; secondly, the capacitance of a piezoelectric element was shown to change with the external mechanical boundary and loading condition. It is believed that previous investigations ignored this fact because the frequency of cyclic load application was relatively high, which effectively washed out this effect. However, because of the very low frequency loading, the effect was evident in the present research. From a basic research standpoint, it would be interesting to explore the change of capacitance in a piezoelectric element with load cycle further. This testing was not conducted in the present research as it would require sophisticated test equipment to accurately quantify the resistance and capacitance of the piezoelectric elements during heating and cooling phases. As was noted previously, standard test equipment (which was available in the present research) has electrical circuit properties on the same order as the piezoelectric elements under study, which would make accurate quantification of the piezoelectric element properties difficult/impossible. The piezoelectric element capacitance testing should include, at a minimum, an attempt to understand the mechanism behind the change, and the region of applicability (time, temperature, loading, etc.) of the effect; and thirdly, exploration of potential applications where the unique attributes of a piezoelectric / substrate system show promise (beyond the potential bridge application).

3. Cable Effects on the Dynamics of Large Precision Structures

3.1. Introduction

One issue for improving the accuracy and frequency bandwidth of test verified structural dynamic modeling techniques for precision space structures is power and signal cables. Current methods, such as uncertainty modeling and stochastic robust control are some example methods that have attempted to deal with this issue generically; however, the phenomenology of the problem is not well understood. Early tests at the Air Force

Research Laboratory (AFRL) Space Vehicles Directorate, partially funded by the Air Force Office of Scientific Research, found that cables increased the damping and caused variation in the frequency value. The strength of the effect varied from frequency to frequency. A quantifiable method for predicting cable effects, however, could not be created. Based on these initial tests, more rigorous study was initiated. Three basic areas of investigation were outlined: one, more detailed understanding of the phenomena from the cables to simple structures to more complex structures was needed before a practical modeling approach could be found; two, a survey of academia, government and industry was needed to gather the tribal knowledge of the community and three, testing on a real precision structure was needed to eliminate excitation inputs that might be corrupting measurements and to understand the effect at small measurement scales.

3.2. Technical Approach

Based on the above goals, behavior of the cables had to be understood first. The main questions that needed to be answered were: what are the dissipation mechanisms; how stiffness and damping are affected by bundle parameters (wire size, number of wires, twist, wrapping); and can one model the cables/bundles in a deterministic manner. Coupled to the experimental measurements were objectives to determine if equivalent "effective" cable properties could be derived from loose-cable measured responses. Bottom line was can a simple or not so simple analytical representation of cable-only vibration be developed.

The overall test plan was to identify electrical wire used for space application, survey fabrication procedures for cable bundles and to perform lateral and axial excitation to determine the bending, tension and compression of the cables. Multiple test set-ups were built and different bundles tested. To limit the scope of the study, twisted pair cables wrapped in Kapton tape was seen as relevant to the problem. In general, results were deterministic in nature. So far, the analysis showed that to some extent cables can be approximated as a simple Bernoulli-Euler beam, but exhibit non-constant modal parameters (i.e., modal damping and modal frequencies) as functions of imparted load level. However, more experimental and analytical work is necessary in order to develop models that accurately capture the dynamics of electrical cables.

Next on the overall plan was to take the results of the cable-only measurements and modeling results and couple those to a simple beam. A free-free beam was chosen because it has a simple structural response that is repeatable and would allow the team to focus on cable dynamics not structure. It would also allow quantitative assessment of the damping & modal interactions. The simple free-free beam would also allow for assessment of linearity & repeatability of the system and to capture local sensitivities such as the cables or mounting. More important, the system would allow for hypothesis testing and demonstration and allow for complete analysis and modeling of the system. Installation methods could also be examined. Finally, the beam study was a necessary, but not sufficient step. If analysis or behavior could not be predicted, then the project's goal had a low probably of success.

The overall test matrix varied many parameters from cables size to mounting methods such as a straight cable to a serpentine-like attached cable. Data was taken, analyzed, and then IDed using DynaMod. Top-level results were that a "simple" free-free beam with a cable is not simple after all, with some non-linearities and signs that tuned mass damping may be occurring. Reference [16] discusses the details of the results.

Perturbations to the structural dynamics, due to the cable harness (within the limited 800 Hz band width) have the following different characteristics. Low frequency resonances are most notably changed due to the cable mass. The low-order modal frequencies decrease roughly 3% and the damping ratios are not impacted significantly. High-order modes show much higher modal damping ratios than the low order modes, particularly for mode numbers exceeding and including four. The cable harness introduces a second, heavily damped mode near the beam's fourth resonance. This effect is has the appearance of a Tuned Mass Damper (TMD).

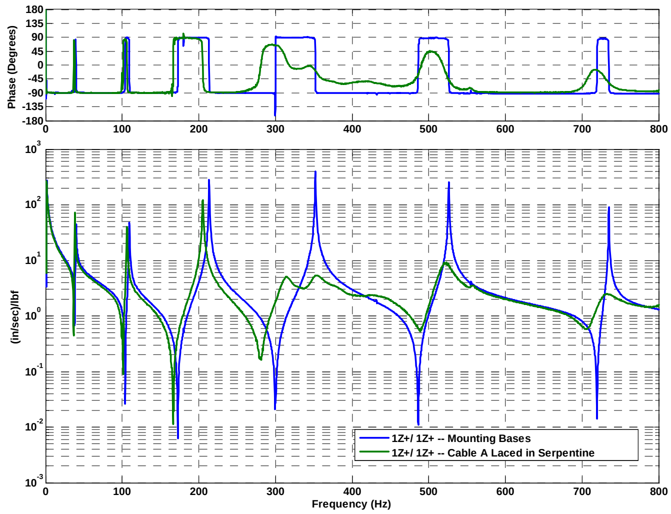

Figure 5: Frequency Response Functions – mounting tabs only and serpentine mounted harness

3.3. Results and Conclusions

Initial work was done to quantify the effects cables have on the dynamics of precision structures. In general, cables appear to have very beam-like responses, but have some non-constant behavior. Tests on simple beams have also proven complex, with high-order modes show much higher modal damping ratios than the low order modes. Tuned mass damper effects were also found. Given the scope of work discovered, it appears that fully understanding this effect may lead to some basic research results. More details regarding recent theoretical and experimental developments can be found in references [15]-[18].

Initially, it was perceived that this work might lead to a quick transition; however, understanding the phenomenology of cables has become very important. For that reason, it is envisioned this work might be a basic research project. Future work in this area will attempt to more accurately model the effect cables have on simple structures and to define the mechanism in which that occurs. In addition, the stability and robustness of the control systems that would use model based plants would be assessed.

4. On-Orbit Deployment Detection

4.1. Introduction

Recent research results [20]-[25] reported at several American Control conferences showed that the statistical control design has been performing quite competitively with other modern control techniques. In the statistical control formulation, a state-feedback controller is designed to minimize the objective function representing a linear combination of finite cumulant indices of a finite horizon integral quadratic performance measure associated to a linear stochastic system. A dynamic programming approach is used to obtain the optimal control solution. This control algorithm is then applied to attenuate dynamical effects due to impulsive disturbances. Motivations for this arise from the need to study control problems related to antennas on the space station subject to impact from space debris and active damping of vibrations of flexible structures caused by impact forces.

4.2. Technical Approach

The intent of this research is to focus on the design of a monitoring device to actively monitor angular orientation and mass properties on a spacecraft to determine if/when an anomaly takes place. This device will then be capable of relating that notice to ground operators for further guidance and thus provide a higher level of self awareness. The outline of the research goes as follows. First, a brief modeling of satellite with reaction wheels and thrusters will be given below. Then some stabilizing controllers minimizing the first three cost cumulant indices from space disturbances to the controlled output are subsequently designed. Finally, the results of simulation are presented along with some discussions.

4.3. Results and Conclusions

The design of a statistical controller using first three cost cumulants was carried out for the attitude hold mode. In Figure 6, the satellite Euler angles, angular rates and wheel speeds were plotted with respect to time. From initial values as indicated in Figure 6, the satellite transient responses went to zero within one sixth of the orbital period. Thus, the statistical control method performed satisfactorily at the attitude hold operation. Figure 7 shows the control action from both reaction wheel cluster and thrusters. It was noted that the action of statistical controller was large at the start and settled down to zero very fast.

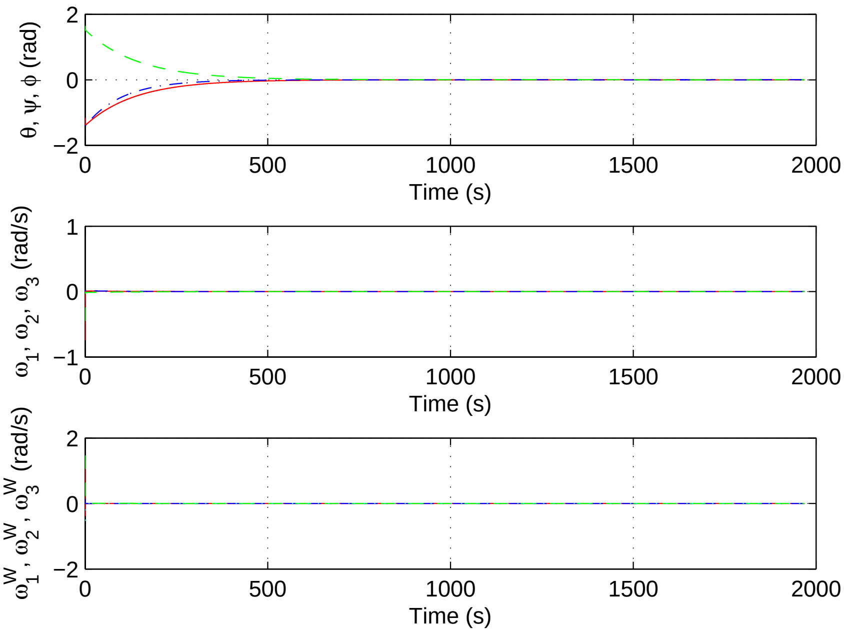

Figure 6: Closed-Loop Responses Due To Statistical Controller Design

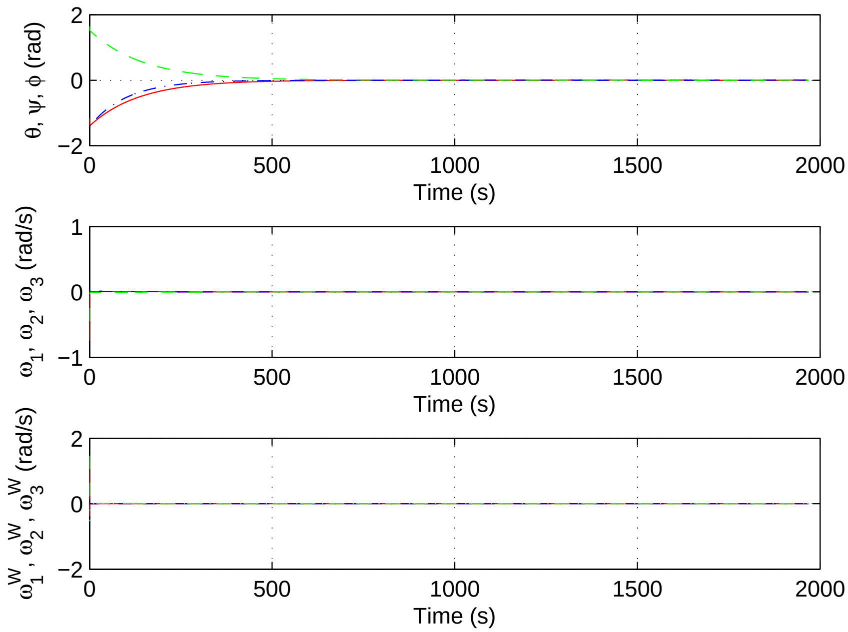

Figure 7: Reaction Wheel and Thruster Torques Due To Statistical Controller Design

In order to evaluate the vulnerability of the host satellite against space debris impact and inspector satellite dock, some numerical simulations were performed. Figure 8 illustrates the effects of two space debris collisions, one with a mass of 0.5 kg and an impact speed of 750 m/s and the other with a mass of 0.3 kg and an impact speed of 800 m/s on the Euler angles, angular rates and wheel speeds of the host satellite. The alterations in host satellite pointing accuracy and angular rates were successfully corrected by statistical control actions of reaction wheel cluster and thrusters as can be seen in Figure 9. Furthermore, the detection of a nano-satellite dock was actually even more formidable than those of space debris collisions as shown in Figures 10 and 11. The results demonstrate that a skillful dock with its velocity vector nearly intersecting the host satellite's center of mass could result in the reactions of the host satellite of orders of magnitudes less than those of debris collisions but nevertheless it was successfully detected by the dynamic detection scheme proposed herein. In conclusions, it was determined that the dynamic detection based on time attitude data was difficult to distinguish whether an event of space debris collision or a docking with moderate and high fidelity had occurred. Perhaps, a future feasibility study involving on-orbit inertia parameter estimation should be investigated. However, the control algorithm will directly transition into the Responsive Space program at AFRL/VS.

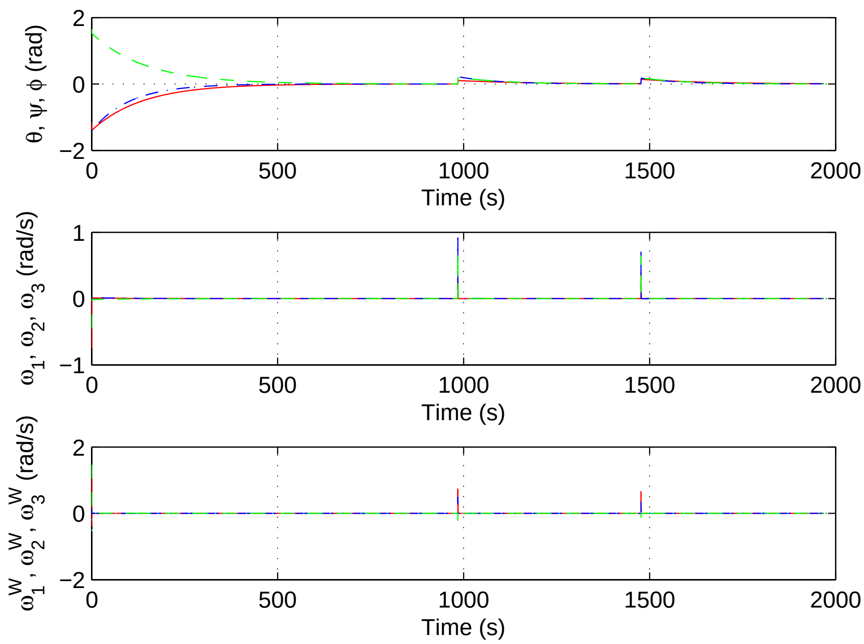

Figure 8: Closed-Loop Responses Due To Space Debris of 0.5kg and 0.3 kg and Impact Speeds of 750 m/s and 800 m/s

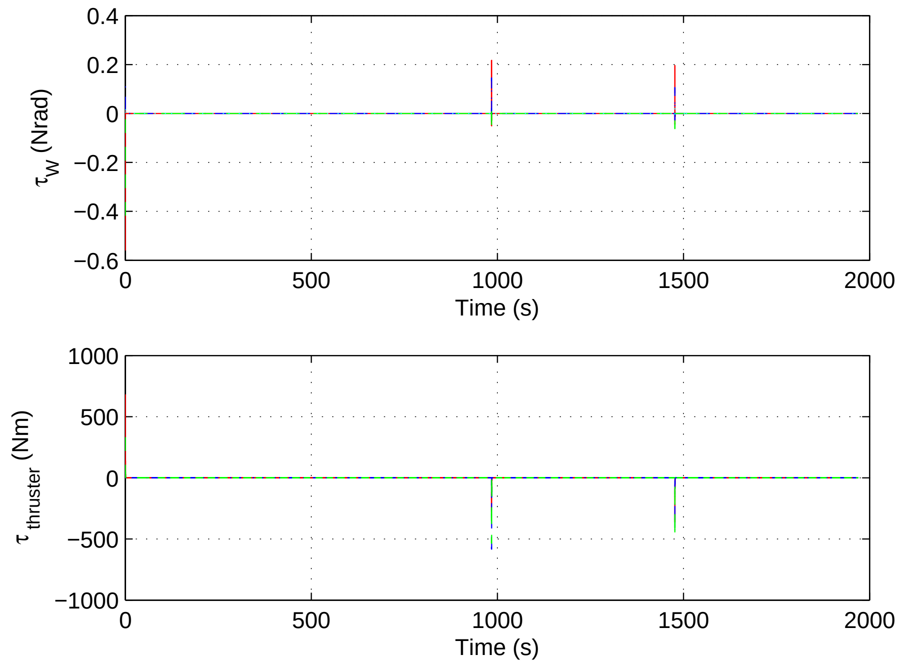

Figure 9: Control Action Due To Space Debris of 0.5 kg and 0.3 kg and Impact Speeds of 750 ms/ and 800 m/s

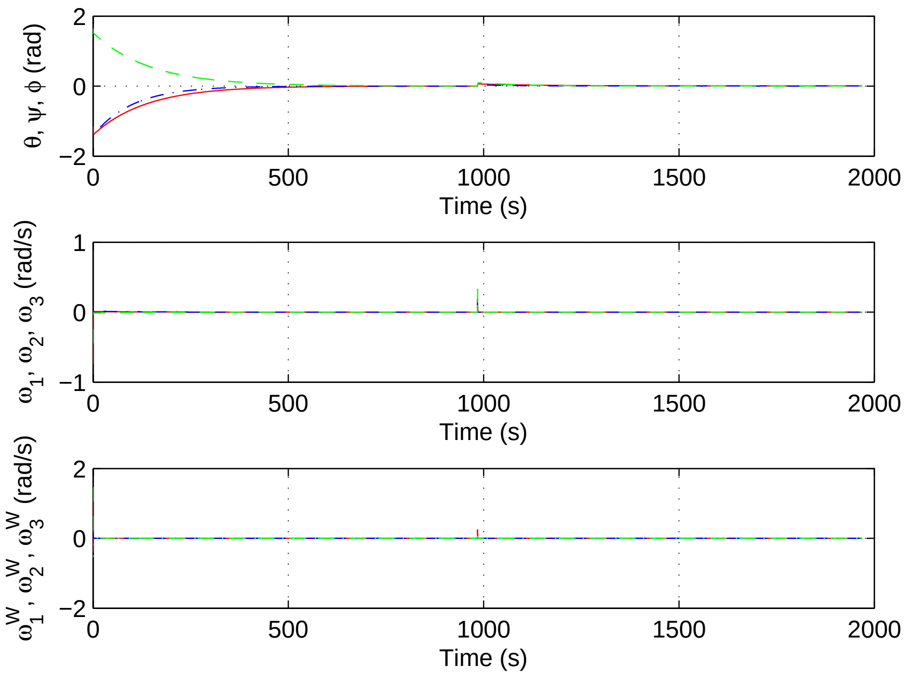

Figure 10: Closed-Loop Responses Due To Inspector Satellite of 20 kg and Docking Speed of 5 m/s

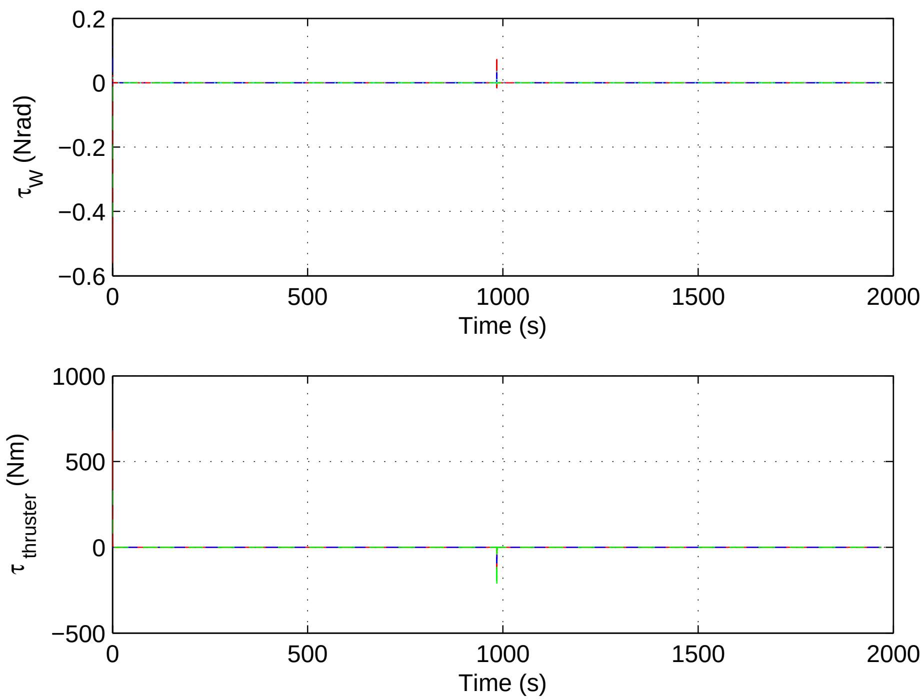

Figure 11: Control Action Due To Inspector Satellite of 20 kg and Docking Speeds of 5 m/s

Finally, a computer-aided software package has been developed to provide a complete statistical description of a finite horizon integral quadratic cost associated with the Gauss-Markov linear dynamical process in the form of a plot of the probability density function. The software toolbox helps increase the depth of understanding and utility of the statistical control theory in terms of how these statistical controllers affect the overall shape of cost densities after control selection stages are taken place. As illustrated from Figure 12, the shape of the cost density becomes more symmetric as the skewness weighting μ_3 increases to achieve better system performance.

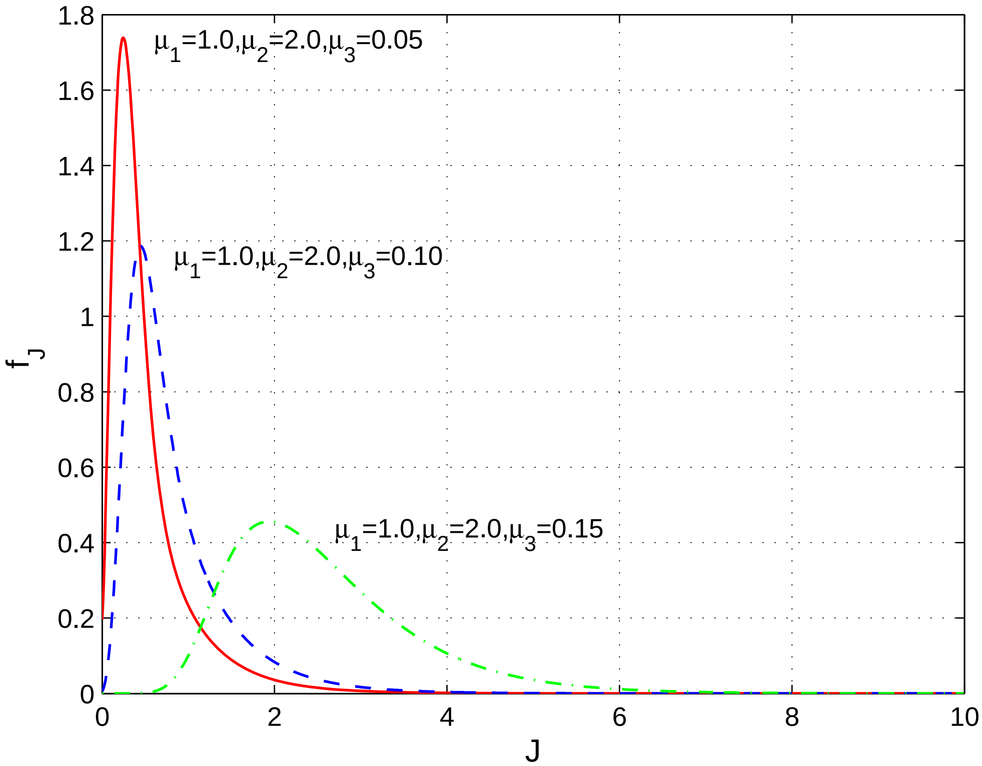

Figure 12: Cost Densities Due To Statistical Controllers

The newly developed statistical control theory is revisited to autonomously control the satellite attitude as well as to provide a means of actively attenuating impulsive disturbances caused by inspector satellite dock and space debris. An integrated approach to the design of online deployment detection of unfriendly attachment by either inspection satellites or space debris collisions is proposed. Dynamic detection of docking events and space debris impacts is carried out using on-board rate gyro and good understanding of rotational dynamics of the host satellite. With the difference between the measured and simulated sensor information, an alarm activation is determined. Furthermore, the scheme also includes a newly developed statistical control algorithm to recover both the dynamic and steady state performances of the original system as much as possible and to reject unknown disturbances. Simulations are performed using several docking and collision scenarios. The simulation results indicate that the existing attitude control system with an innovative and robust statistical controller design shows significant promise for use in attitude hold mode operation despite the presence of impulsive disturbances. Interested readers are referred to references [26]-[28] for complete background, theoretical developments and problem statements. However, there is still a need to determine locations of damages and changes in mass inertia tensors of orbiting satellites. The future investigation introduces a method for estimating the inertia parameter of on-orbit spacecraft. The nonlinear stochastic estimation problem is first cast into a deterministic optimization framework. Then the minimum principle and embedding technique will be employed to approximate a solution for the nonlinear estimation problem. The basic concept and related technical issues will be discussed in future publication.

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4.4. Honors & Awards Received

None

4.5. AFRL Point of Contact

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4.6. Transitions

The technology development of acoustic foam has been transitioned to a flight experiment which is currently scheduled for 2Q FY07 aboard the Re-Entry Structures Experiment (RESE) and the initial results of cable effects are in discussion with Space Radar & other for possible transition work, but the work is not complete.

4.7. New Discoveries

N/A

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