1) Grant Overview Chart

NSTRF Research Training Plan for **NASA Grant # NNX11AM61H** Modeling Cable Harness Effects on Spacecraft Structures Virginia Polytechnic Institute and State University, Blacksburg, VA	
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Faculty Advisor /PI	Dr. Daniel J. Inman
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2) Abstract

As spacecraft become more lightweight as a result of advances in material technology, cable harnesses and wiring are making up a greater percentage of the spacecraft's mass. Prior investigations are finding that this mass, which was once just lumped into the total mass of the structure, may be affecting the dynamic response of the craft. The goal of this research is to investigate the effects of cable harnesses on spacecraft structures. Specifically, a model incorporating hysteretic damping and shear effects will be developed to model cables, and experimental data will be used to determine cable parameters. The cable properties and cable model will then be used with the distributed transfer function method (DTFM) to model a cable-harnessed beam. Challenges include the complexity of the cable model when shear effects are added, the difficulty in characterizing damping in general, and the uncertainty added by the composite nature of helical cables made up of discrete individual wires. The student will be using analytical mathematical methods as well as experimental investigation in the form of dynamic testing to approach the problem, and hopes to develop mathematical models that can be validated by the conducted experiments. The cable model will include hysteretic damping added through the Golla-Hughes-McTavish method, and the cabled-beam model will utilize DTFM to provide an exact solution that can handle connections at discrete points. The completion of this research and the training opportunities provided by the NSTRF program will result in a greater understanding of the effects of cables on space structures, insight into the internal damping mechanisms present in helical cables, improved knowledge for spacecraft design, and a student who will publish and present her findings to further the knowledge of the scientific and engineering communities.

3) Research Description

a. Introduction:

The future of space structures involves the use of lightweight structural elements. These lightweight materials are obviously beneficial in terms of reducing the overall weight to launch, but as the spacecraft mass decreases, the cable harnesses and wiring that surround the object make up a greater proportion of the object's mass. Since the control system technology for spacecraft is also developing, requiring more signals and electrical paths, these complex systems mean that an extensive wiring system is required on any given spacecraft, and robust cable harnesses are unlikely to disappear anytime soon. Thus, cable harness mass is becoming a significant structural component of spacecraft structures.

Because these cable harnesses now make up a significant percentage of structure mass for satellites and other spacecraft structures, the Air Force Research Lab (AFRL) at Kirkland Air Force Base has identified the problem of cable harness effects on satellites as being extremely significant for vibration modeling [1]. A more complete understanding of the interaction between the cable harness and the shell of a spacecraft must be developed in order to correctly program control systems, eliminate unnecessary vibrations, and ensure the structural integrity of the spacecraft. In addition, current and future space structures may be too large and too flexible outside of a vacuum to be tested before their launch, so it is imperative that models of these structures be accurate and take into account the growing mass percentage of the cable harness, not as a lumped mass, but as a structural element that can affect the motion of the spacecraft. Based on the questions posed by the AFRL, I (the student) will be investigating the effects of cable harnesses on spacecraft structures.

b. Goal:

The goal of this research is to develop a scientific basis for characterizing the effect of power and signal cables attached to lightweight, flexible spacecraft structures in order to develop models of such systems to gain understanding of the important physical effects that affect their dynamic response. Specific and measurable goals were developed in collaboration with the NASA mentor and student's advisor in November 2012, after initial investigations, experimental practice, and background research. Creating a cable model based on experimental data is paramount, as is quantifying the internal damping inherent in space flight cables. The three major goals of this project are:

1) Add hysteretic damping to Timoshenko beam equations using the Golla-Hughes-McTavish (GHM) damping method with the intent to model cables, to be solved for vibration response using the distributed transfer function method (DTFM)
2) Perform experiments to determine physical parameters of cables including GHM coefficients. Testing may include Instron and vibration testing, and will investigate baked out versus non-baked out cables and geometrically varied cables
3) Use the developed cable models in conjunction with the determined cable parameters to model a cable-beam system using DTFM

Additional secondary goals of the project include:

1) Significant progress on methods of describing structural cable effects and models to predict damped response of cabled beams
2) A database of experimental results characterizing the dynamics response of cable-harnessed structures to vibration input
3) Understanding of the factors involved in cable modeling and publication of the results

These goals (from the original first year training plan) will be met as the major goals are pursued and achieved.

c. Background:
As listed in the reference section, the Air Force Research Laboratory has written several papers on the subject of cable harness effects, and some similar experiments have been performed at JPL. Before learning of JPL's efforts, experiments were conducted at Virginia Tech to start investigating the problem and determine what challenges may arise. The Air Force Research Laboratory ran cable-only tests to determine the parameters of the cables used, and found that the cables could nearly be described by beam theory, but that they were non-linear elements [1]. From background reading, the specific tie down type was determined, as well as types and construction of the cables to be tested. The cables tested at Virginia Tech were basic electrical wires, and JPL has provided space flight cables that would be commonly used on space structures.

At this point, my background research on cable modeling and cable damping modeling is complete and the results of my initial investigation have been accepted for publication in Applied Mechanics Reviews. My research found that cable modeling occurred in three main categories:
- thin rod models, in which each wire is modeled as a thin rod with individual stresses and strains;
- semi-continuous models, in which each layer of wires is homogenized to a constant cylinder;
- beam models, in which the cable is modeled as a solid beam with properties adjusted to describe the cable behavior.

The primary damping mechanisms for cables were:
- inter-wire contact, where damping occurs due to friction between the wires and is generally incorporated into thin rod models;
- variable bending stiffness, in which the bending stiffness for the cable changes depending on the slipping behavior of the wires and generally modeled with beam models or semi-continuous models;
- internal friction and viscoelastic effects, where damping is due to the internal movement of the cable and shear effects, modeled in a variety of ways.

As there is not yet an accurate damped cable model for space flight cables, part of this research will involve developing a model to describe damped space flight cable behavior to incorporate into a double-beam model. The DTFM model is an exact model based on the transfer function of the system that will determine the natural frequencies of the system and provide a frequency response function [2]. The GHM model is a damping model that introduces additional damping coordinates into the system in order to quantify and model the damping exhibited [3]. These methods will be used in my cable model development.

Figure 1 shows this year's representative graphic, comprising a photo of the current cable testing set-up, a representative cable frequency response function, and the governing equation of motion for a cable modeled as a shear beam with damping.

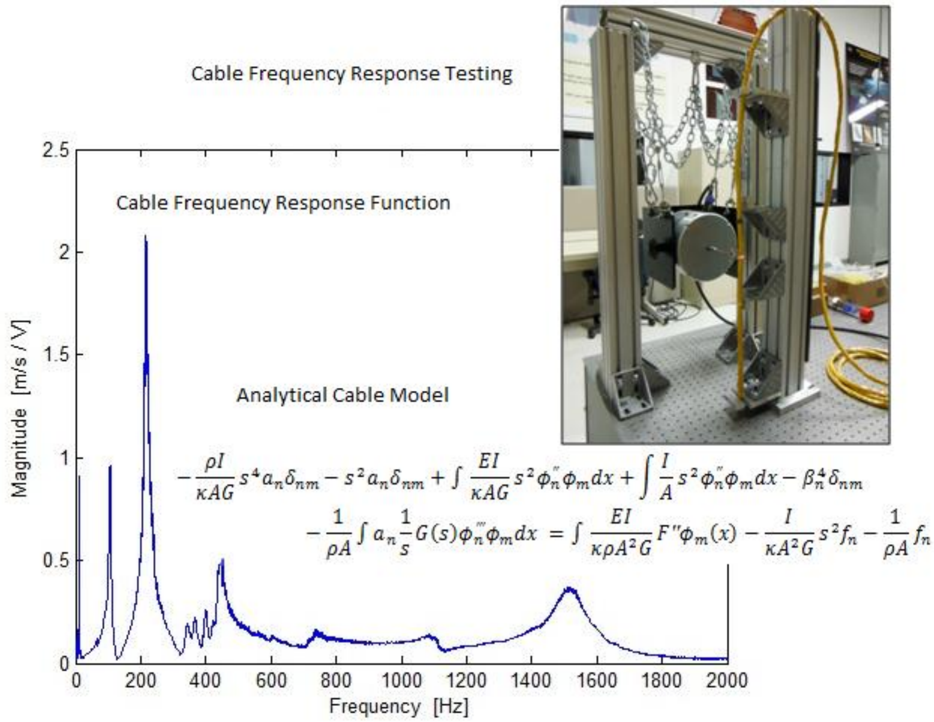

Figure 1. NNX11AM61H representative graphic, showing aspects of the analytical model, experimental testing, and expected experimental results as a frequency response function.

d. Approach/Methodology:

As noted, I have already begun experimental testing of the cables and the cable-beam system. The approach/methodology section will be divided into work performed to date and future work to be performed.

Approach/Methodology: Work Done to Date

This section details the work done from the beginning of the project to the point of the second training plan submittal. The first step was to determine the characteristics of the cables that were being used for the cabled beam experiments. It was decided to use cables that could be readily obtained in a university lab for these preliminary experiments as a way to determine if the method was sound before spending time and money on space-worthy cables. In order to measure the response of the cables, each cable was clamped between two vices at a specific tension. Most cables were tested at tensions of 0, 1, 5, 10 and 20 pounds. A shaker device was set against the cable and the cable was lightly taped to the flat surface of the shaker to ensure that the cable did not bounce away from the shaker and that the cable's motion input was indeed the shaker output. Rather than trust the shaker's readings, a laser vibrometer was set up to measure the motion of the shaker while a second laser vibrometer was trained on the cable and moved from point to point to take readings at various points along the cable. Figure 2 shows the cable parameter set up, with one red cable in the vices with the shaker attached, the additional cables on the lab bench, and the two laser vibrometers in their positions.

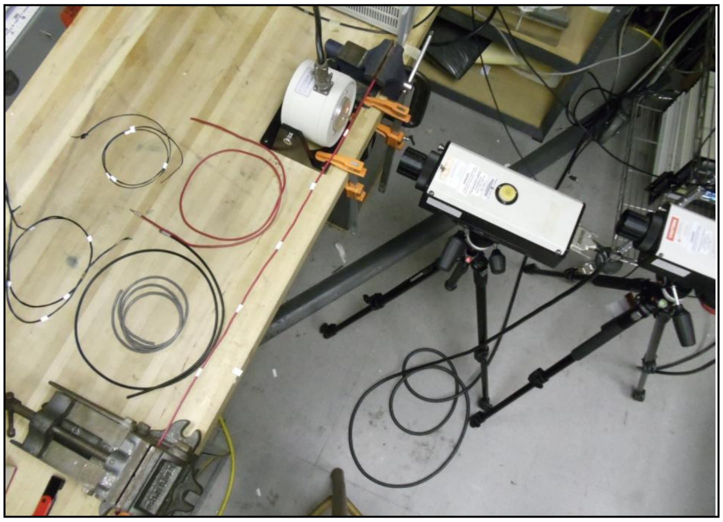

Figure 2. Laboratory set up for cable parameter testing.

Once cable parameters were determined, cables were attached to a beam with TC-105 tie-downs as recommended in the AFRL papers. The cables were tied down at 3, 5, 7 or 9 attachment points and the beam was excited by the use of a piezoelectric patch at one end that excited the beam with random noise. Figure 3 shows the cabled beam test set up; the beam is hanging from the ceiling with no horizontal constraints in order to simulate the free-free condition that would be typical for space structures.

Figure 3a and 3b. Test set up for the cabled beam.

Once cabled beam data was analyzed and compared to a finite element model, the results were close but not exact. Since there was some ambiguity on whether a thin cable such as the ones used in these experiments should be modeled as a string or as a rod, a copper rod was procured and attached to the beam in the same manner as the cables, and the same tests were run. Figure 4 shows the rod attached to the beam with the orange piezoelectric excitation patch, and figure 5 shows the entire rod-beam system.

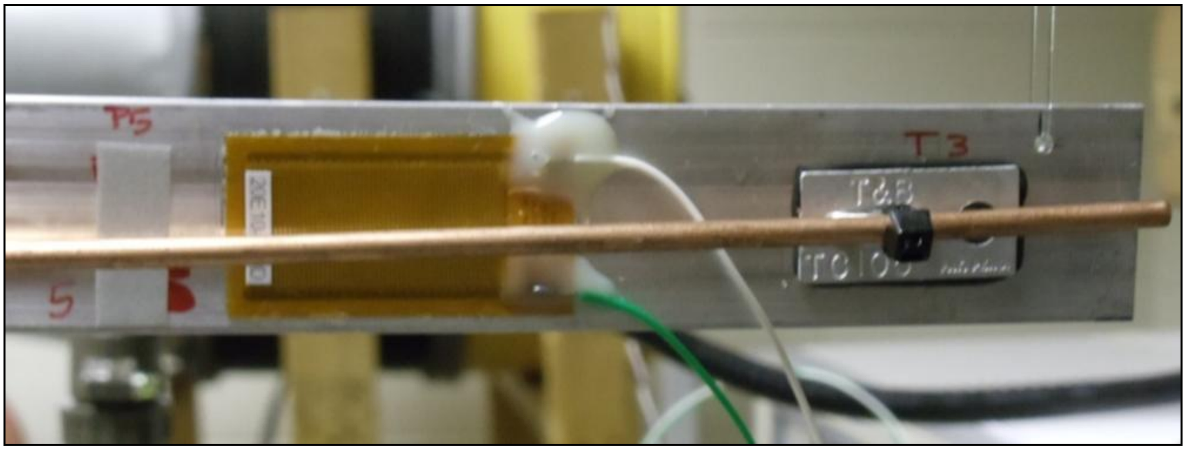

Figure 4. Rod-beam system at point 5 showing piezoelectric patch and tie-down detail.

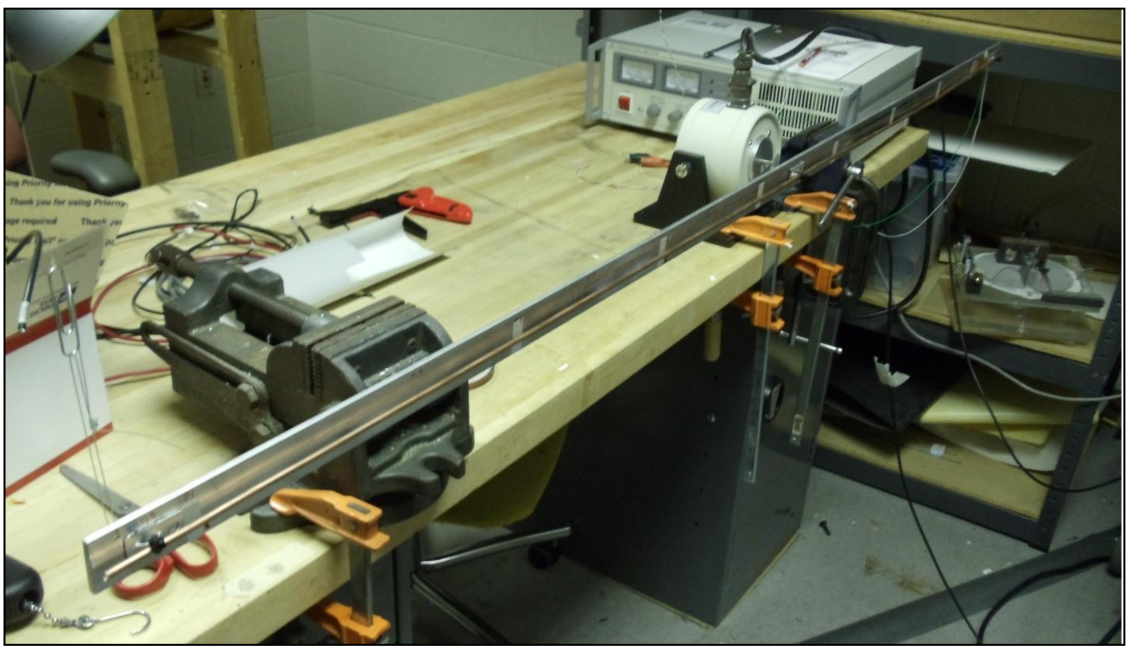
Figure 5. Rod-beam system with three tie-down points.

Data was taken through SigLab, a data acquisition program, and processed in Matlab to compare the different cables and attachment points. Unfortunately low frequency responses (below 100 Hz) were erratic and did not necessarily agree well from cable to cable; despite running multiple tests, trying to keep the set up as controlled as possible, and adjusting the laser vibrometer and data system, better low frequency data could not be obtained, perhaps likely due to the low frequency resonance of the strings used to hang the beams from the ceiling and air currents and other activities in the lab and in the building. Hopefully this will be an aspect of testing that can be mitigated at JPL as they have more isolated testing rooms. The results for frequencies between 100 and 1000 Hz were much clearer and matched well from system to system. The rod-cable system behaved significantly differently than the cabled-beam systems, which were quite close to the response of the bare beam. From these results, a program to measure the damping at each frequency was developed as well. Figure 6 shows the overall results for the bare beam, cabled-beam systems and rod cable system at each point for three tie downs.

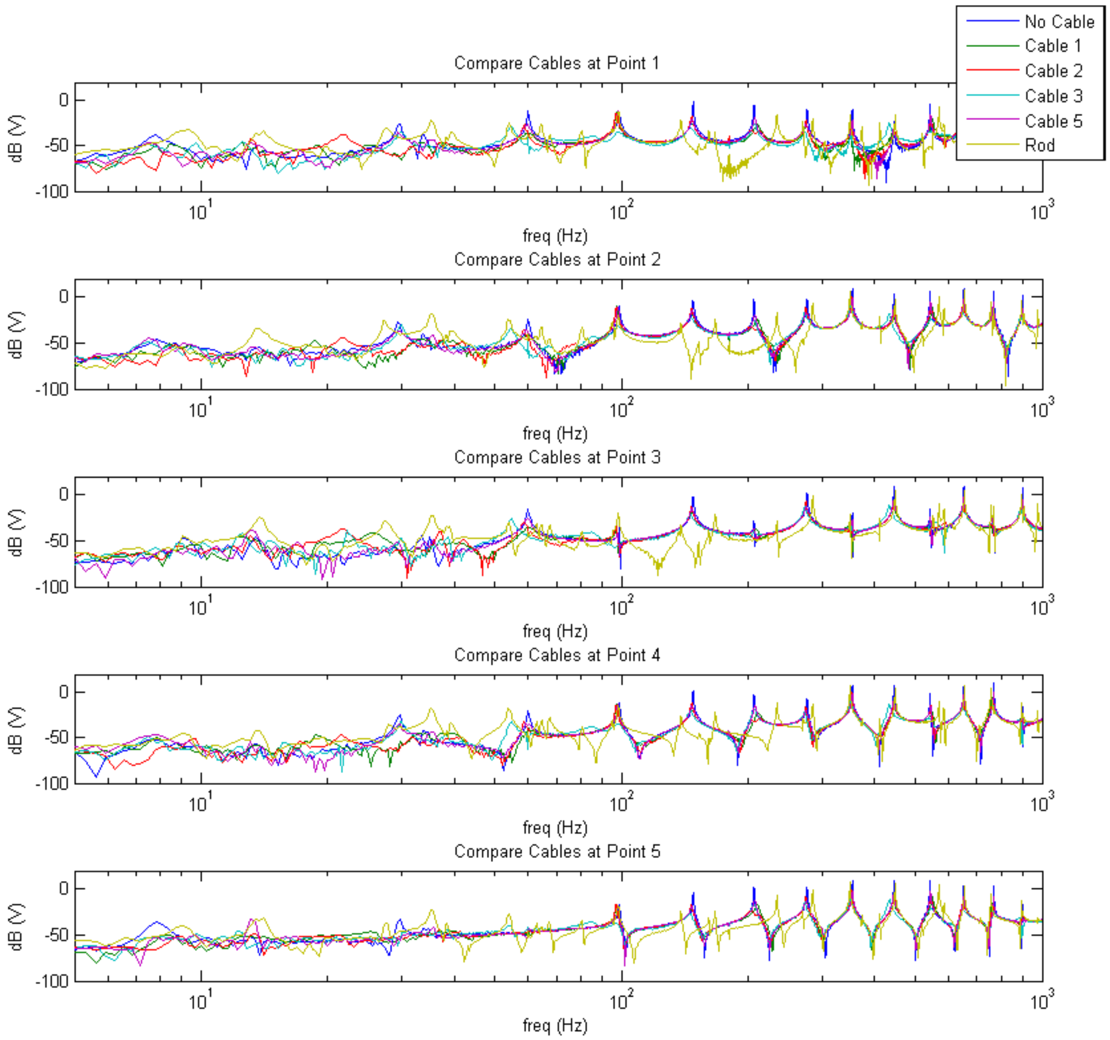

Figure 6. Overall results for three tie-downs; four cables, rod and bare beam compared at points 1 through 5.

Further results from the preliminary cabled-beam testing were reported in the first year training plan and are not repeated here. The tests were consistent from trial to trial and showed that the number and spacing of the tie downs changed the system response as well as the type of cable and the specific point at which the measurement was taken. With so many variables, a lot of data was collected as part of the student's goal of creating a database of baseline experimental responses, but it was confirmed that concentrating on obtaining cable properties was of primary importance.

In addition to the experimental work to be performed, a proposed goal for the project was analytical models to describe the motion that could be validated by the experimental data. The experimental data is being gathered at JPL, and analytical models are being developed simultaneously. Considering the scope of the project as well as background research on cable models, we decided to focus on the distributed transfer function model for cable modeling in lieu of the homogenization approach listed in the first year training plan. The beam model is superior to the semi-continuous homogenization model for dynamic testing, and should yield good analytical results for comparison to the experimental testing. The combined dynamical systems method is being investigated in conjunction with other students, but is only a secondary focus for this project. The completed analytical work includes Rayleigh Ritz cable models (which have been discarded in favor of more exact procedures) and distributed transfer function models (DTFM). The current DTFM model predicts the response for a single section of cable with viscous damping; I would like to be able to predict multiple sections with hysteretic damping, so there is still work to be done here. A DTFM model with GHM damping as a single term (without additional coordinates) was created and will be presented at the 2013 SEM IMAC Conference in February. The lack of additional coordinates meant that the GHM term did not appreciably change the response of the cable from the viscously damped case, and made it clear that a more complicated approach was necessary. Thus, an approach in which the coefficients of the equation of motion are equated to the coefficients of a matrix equation with the additional GHM coordinates included is currently in progress. A very small section of this analysis is included here for illustrative purposes of the procedure:

For an undamped Timoshenko beam, the equations of motion are:

$$S(t,x) = \kappa AG\left(w^{'}(t,x) - \psi(t,x)\right)$$
$$M(t,x) = EI\psi^{'}(t,x)$$

where κ is the shear factor, G is the modulus of rigidity, and EI is the bending stiffness.
But when the beam is made of a viscoelastic material with time hysteresis damping, the stress is:

$$\sigma(x,t) = E\epsilon(x,t) - \int_0^t g(t-\tau)\epsilon(x,s)ds$$

So the moment term becomes:

$$M = EI\psi^{'} - \int_0^t g(t-\tau)w''ds \text{ OR } M = EI\psi^{'} - \int_0^t g(t-\tau)\psi'ds$$

By substituting the moment term into the original equations of motion, combining those two equations to eliminate the rotation term, applying an Euler-Bernoulli eigenfunction assumption and using orthogonality and incorporating a *G(s)* term, the equation of motion becomes:

$$\left(-\frac{\rho I}{\kappa AG}a_n\delta_{nm}\right)s^4 + \left(-a_n\delta_{nm} + \frac{EI}{\kappa AG}\int \phi_n^{''}\phi_m dx + \frac{I}{A}\int \phi_n^{''}\phi_m dx\right)s^2 - \beta_n^4\delta_{nm}$$
$$-\frac{a_n}{\rho A}\left(\frac{\alpha_{th}s + \gamma_{th}}{s^2 + \beta_{th}s + \delta_{th}}\right)\int \phi_n^{'''}\phi_m dx = \int \frac{EI}{\kappa\rho A^2 G}F''\phi_m(x) - \frac{I}{\kappa A^2 G}s^2 f_n - \frac{1}{\rho A}f_n$$

This is rearranged to group powers of s, which are then compared to the Laplace transform of a standard matrix formulation for equations of motion, shown below,

$$\left(\begin{bmatrix} m_1 & m_2 & m_3 \\ m_2 & m_4 & m_5 \\ m_3 & m_5 & m_6 \end{bmatrix} s^2 + \begin{bmatrix} c_1 & c_2 & c_3 \\ c_2 & c_4 & c_5 \\ c_3 & c_5 & c_6 \end{bmatrix} s + \begin{bmatrix} k_1 & k_2 & k_3 \\ k_2 & k_4 & k_5 \\ k_3 & k_5 & k_6 \end{bmatrix}\right) \begin{bmatrix} a_n(s) \\ z_n(s) \\ \hat{z}_n(s) \end{bmatrix} = \begin{bmatrix} f_n(s) \\ 0 \\ 0 \end{bmatrix}$$

where the constants m_i, c_i and k_i can be solved in terms of the beam's physical parameters and where z_n and $\hat{z}_n$ are dummy variables representing internal damping. This work is in progress and not all coefficients have been determined yet, but determination of the equations of motion is a significant step that is completed. This work will be published in a journal in detail once the coefficients are determined.

Other significant tasks completed to date include the acquisition of test cables and space-flight cables from a previous mission (shown in Figure 7a and 7b), as well as getting access to the data from JPL's cable tests for comparison and validation.

Figure 7a (left) and 7b (right). Cables provided by JPL for testing. Cables with connectors and darker orange Kapton wrapping have undergone bake out and were actually used on a flight mission.

Approach/Methodology: Work To Be Done

The experiments that have been conducted so far were primarily useful for determining what parameters are worth investigating and developing methods to run meaningful experiments with accurate data. Now that I will be at JPL through August 2013, the experiments can be run in a more controlled environment with actual space cables. As of December 2012, the testing apparatus is set up and experimental data can now be gathered. The first quarter of 2013 will be focused on testing, with cable property results to be reported at the SDM conference in April. Figure 8a shows the test setup at JPL; the shaker is suspended to provide excitation to a clamped or pinned cable. The laser vibrometer measures the cable velocity and provides the frequency response function. Figure 8b shows the suspended shaker and cable test section.

Figure 8a. Cable dynamic testing set up at JPL.

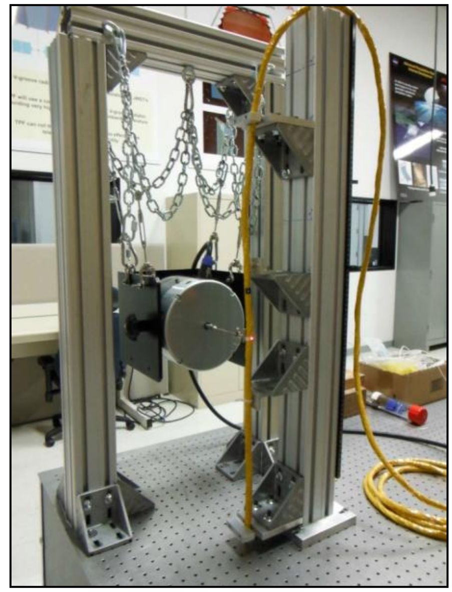

Figure 8b. Suspended shaker.

An important concern with any vibration test is ensuring that the input force is completely transferred to the system of interest, and careful consideration must be given to the stinger attachment for these cable tests. Currently, the shaker is connected to the cable through a tensioned wire, as shown in Figure 9, which is connected to an eye bolt that screws into a very lightweight aluminum block and TC-105 tab connected to the cable with a cable tie. This is a typical connection between a cable and its host structure, and should provide a realistic simulation of how energy would be transferred to the cable from the structure. In addition, the tab and block are very lightweight compared to the cable. The tensioned wire slightly offsets the cable and should eliminate some of the noise from the push-pull transition of a traditional rigid stinger. However, there is some concern about the absence of a load cell to measure the input force. I will first be using a second laser vibrometer (not yet pictured, but acquired!) focused on the input location to provide the reference signal. If this method does not provide accurate results, a rigid stinger and load cell will be used instead. Ewin's work on modal testing procedures [4] will be used to determine best practices for these tests, as well as the procedures from previous cable tests performed at JPL and at AFRL.

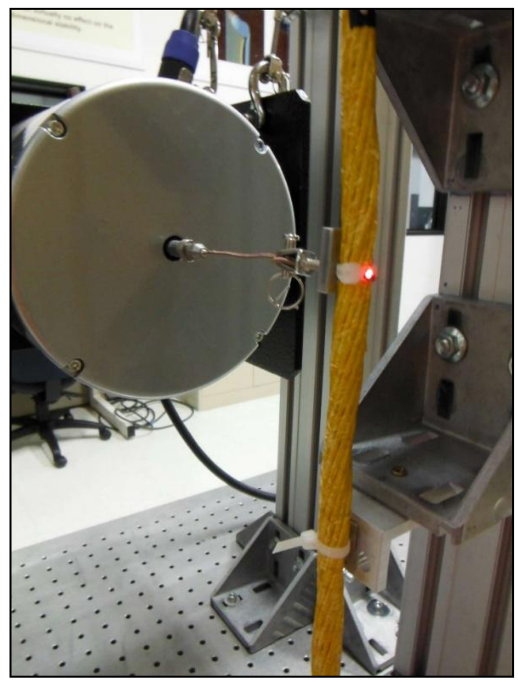

Figure 9. Shaker-cable connection.

As an additional goal this year, I will be investigating the effect of bake-out on flight cables. Discussion with cable engineers at JPL indicated that bake out may change the bending stiffness value of flight cables, so quantifying this difference is a worthwhile endeavor and will be reported at the SEM Conference in June (see section 6 for conference schedule). Currently, JPL has provided a variety of cables for testing, but for investigating the effects of bake out on cables, a set of cables that can be divided into untreated and treated portions will be required. Figure 10 shows the cables that I currently have on hand. The cables on the left side of Figure 10 were flown on a mission and have been baked out, while the cables on the right side are untreated test cables made for precious cable tests.

Figure 10. Space flight cables; darker orange cables on the left are from a flight mission and have undergone bake out.

Hopefully, using the more controlled testing environment at JPL will help to make the lower frequency results less volatile. Once cable property testing is done, the cables will be attached to beams and experiments run to measure the response of the cabled beams. If the Virginia Tech testing is any indication, there should be minimal variation in the frequencies of the beams, but significant damping at each frequency, which should be quantified. By measuring the damping of the various cable configurations, some insight will be gained into the effects that the cable harnesses have.

In the near term, I will be working with the testing equipment to determine the best settings to get the most accurate and useful data. I need to determine whether the tensioned wire with additional laser vibrometer will be acceptable, or if I need to incorporate a load cell and rigid stinger instead. I also need to optimize the laser vibrometer for the cable sizes I am looking at, and determine which types of cables are the "best-behaved" so that I can get a set of cables that go through bake out to compare the bending stiffness values. I also may need to find an Instron testing machine here to do some axial tests on the cables to get axial stiffness values as well.

On the analytical front, the remaining model work entails getting the coefficients for the DTFM model in terms of GHM coordinates, extending the DTFM model to cover multiple sections of cable (for example, a cable punctuated by tie-downs), and eventually extending the DTFM model to predict the response of a cable attached to a beam. This should be similar to the method used for multiple cable sections, as both extensions require a sum of forces at the connection points. I am currently in the process of equating coefficients for the Timoshenko model following Inman's method [5]. The equation of motion was determined (see Approach/Methodology: Work Done to Date section) and the coefficients of the powers of s were set equal between the equation of motion and the matrix form. The matrices were assumed to be symmetrical and the mass matrix was assumed to have zeros for the off diagonal entries. This allowed me to start with 15 unknowns and 12 equations, so I had to make three assumptions (the solution will be non-unique). I have solved for all coefficients down to three unknowns and three equations, but so far there appears to be no solution for the three unknowns based on the values I am using and assumptions made. Therefore, I will be rechecking the material properties and damping values, and then trying different sets of assumptions until I can get to a point where I can present an example with a complete solution. Once these coefficients are determined, I use them in an extended DTFM transfer function matrix, and the next step will be extending that model to handle multiple sections of cable, as noted previously.

e. Expected Outcome(s):

The overarching goal of this research is to develop an in-depth understanding of cable effects on space structures. The specific goals have been listed in section 3b above. Ideally, I will have developed models to describe the response of a cabled system, but since so little is known about the cable interactions and the damping mechanisms, it may be unrealistic to predict damping values and completely model the system response. Ongoing discussion with the mentor and advisor will continue to determine what goals are achievable. As I work towards my primary and secondary goals, the outcome of my work will include not only models and experimental data useful for cable modeling and space structure design, but increased knowledge of how to publish and present scientific findings, operate sophisticated test equipment, and work within NASA's framework to further the NASA goals and solve challenges. Updated expected outcomes for my NASA training experience include:

- A method of describing structural cable effects using the distributed transfer function method, culminating in validated models of a cable-harnessed structure
- A database of experimental results characterizing the dynamic response of cable-harnessed structures to vibration input
- A thorough understanding of experimental requirements and the ability to design and execute a sound and repeatable set of experiments to validate models
- Thorough knowledge of modal vibration testing, to include set up and operation of modal exciters and both scanning and stationary laser vibrometers and data acquisition software
- A basic understanding of cable effects to be shared for the improvement of space structure design and cable modeling
- At least three papers publishing the results of the initial cable damping investigation, the DTFM modeling, and results from experimental data collection leading to knowledge of how to publish clear and concise results to further the knowledge of the scientific community as a whole
- A presentation of my findings at as many relevant conferences as is reasonable based on the findings, (SEM, SEM IMAC and SDM at a minimum) leading to skill, experience and confidence in presenting engineering results and findings to peers and colleagues
- An understanding of NASA's goals and procedures to enable me to contribute to solving NASA's grand challenges in the future

Thank you very much for your consideration and continued support. I look forward to sending copies of the presentations, papers, and conference proceedings that I develop this year based on my research.

f. References Cited

[1] Goodding, J. C., Ardelean, E. V., Babuska, V., Robertson, L. M., and Lane, S. A., "Experimental Techniques and Structural Parameter Estimation Studies of Spacecraft Cables," *Journal of Spacecraft and Rockets*, Vol. 48, No. 6, 2011, pp. 942–957.

[2] Yang B., and Tan C.A., "Transfer Functions of One-Dimensional Distributed Parameter Systems," *Journal of Applied Mechanics*, Vol. 59, Dec. 1992, pp. 1009-1014.

[3] Friswell, M. I., Inman, D.J., and Lam, M. J., "On the Realization of GHM Models in Viscoelasticity," *Journal of Intelligent Material Systems and Structures*, Vol. 8, No. 11, 1997, pp. 986- 993.

[4] Ewins, D.J., Modal Testing: Theory, Practice and Application, 2nd ed., Research Studies Press Ltd; Baldock, Hertfordshire, England, 2000.

[5] Inman, D. J., "Vibration Analysis of Viscoelastic Beams By Separation of Variables and Modal Analysis," *Mechanics Research Communications*, Vol. 16, No. 4, 1989, pp 213-217.

4) Relevance to NASA

This research aligns with NASA's mission directorates, and is specifically applicable to Space Technology Roadmap (STR) Technology Areas 12.2, Structures, and TA 11.2, Modeling. The research involves lightweight space structures and design methods, should improve reliability, will develop test tools and methods, and may lead to further innovative concepts. Because my current research deals directly with space structures, it is easy to see that vibration of space structures would certainly come into play in the study of aeronautics and exploration structures, as any structure being propelled into space will experience vibration and is highly likely to have wiring and cables attached. However, my research will also be applicable to science and space operations. By understanding the vibration modes and effects of these space structures, we may eventually be able to harness some of that unwanted kinetic energy and use it to enhance the power system, providing energy to power sensors and further reducing cables, and thus, weight. In addition, most spacecraft and satellite control systems are dependent on knowing the motion of the object; by further refining our knowledge of spacecraft vibration, we should be able to more accurately model spacecraft and satellite movement, and thus improve the accuracy of space control systems and operations. In this respect, my research also supports TABS 11.2, Modeling, since it will involve software modeling, model checking, and science and engineering modeling. Specifically, the beam model that I am working on to model a flexible cable could be considered a complexity analysis tool and will add formal analysis and traceability in system design. My research will contribute to the understanding of the dynamics of these systems, and will allow a greater degree of confidence in models for the systems used in exploration systems and space operations. I was interested to note that the Space Technology Roadmap for TA11 noted interdependency with TA12; my research is a great example of this connection, as I will be investigating both the structural dynamics of cables as well as attempting to model them.

In reviewing the newest version of the Space Technology Roadmap for TA12, I found even more areas that my work will be directly applicable. Based on my findings, I hope to provide recommendations on cable construction techniques that reduce variability in cable properties, which certainly comes under 12.2.4, Manufacturing Processes. I will be investigating test tools and methods for structures, specifically regarding modal testing, and design and analysis tools for the mechanical system, TA 12.2.2.4 and TA12.2.3.4 respectively.

When it comes to the grand challenges, although this work may not seem transformative as yet, there is significant progress in the study of vibrations related to the field of piezoelectric materials, which can convert mechanical energy from vibrations into electrical energy. If the vibrations of spacecraft structures are well-understood and modeled, there may be a point at which this vibration information could be used to fit piezoelectric energy harvesters onto spacecraft to provide additional power without requiring additional power sources. This would support NASA's Grand Challenge of Affordable Abundant Power, since the information about vibration could be used to harness that kinetic energy and convert it to usable electricity via piezoelectric materials.

This research is also relevant to the Grand Challenge of Efficient In-Space Transportation, as a better understanding of how a spacecraft is moving will allow us to construct better control systems to more accurately and precisely move things around space. Finally, I am realizing that the knowledge and training that I am gaining through my on-site experiences will give me a strong understanding for steps required to contribute to solutions for NASA's grand challenges in the future.

5) Onsite Experience(s)

Rather than spend only ten weeks at a NASA research center, this research will be conducted primarily at the NASA Jet Propulsion Laboratory in Pasadena, California over a matter of months. Because I completed both my qualifying exam at Virginia Tech and all of the PhD coursework by December 2011, I was able to spend the remainder of the program year (January-August) at JPL to conduct this research. This was advantageous for several reasons. First, JPL has also been looking into the issue of cabled-structure dynamics and I was able to benefit from knowledge and equipment already procured. In the initial award year I was able to contact several of the individuals who had done the initial cable research and speak to them candidly about the successes and challenges of the project. In addition, some data from the tests that JPL employees ran was available for me to analyze and compare, and they even still had cables and test fixtures that I could modify for my purposes and use for testing. Secondly, while I had conducted some preliminary cable and cabled-beam testing at Virginia Tech, I found that a more controlled testing environment would be advisable, as even small air currents in the testing area affect the free-free configuration that the testing requires. JPL has facilities for more controlled testing which I was able to set up and use. In addition, although I used ordinary cables of various wiring types and sizes in my preliminary testing, at JPL I have access to the actual cables used to send power and signals on spacecraft, as well as the cable-wrapping and production techniques used for actual spacecraft. This will make the research more directly applicable to NASA's devices and should yield the most realistic and useable data. Finally, by being immersed in a research center that is heavily involved with flight projects, I am finding that this research is focused and applicable to real-world problems, specifically, NASA's grand challenges.

In addition to my main on-site experience at JPL, I've also been able to visit the Langley Research Center and get input on my project from engineers and technologists there. I attend a student research conference in Virginia every April near Hampton, so it is convenient to visit Langley and get different perspectives on my work.

As the second year of my NSTRF grant continues, I will continue to conduct my research at JPL. It has been an outstanding experience so far, with resources and contacts that I had not expected. I have taken full advantage of the variety of presentations and seminars that JPL has on a daily basis and look forward to exploring more of the testing equipment that building 299 has available! I will also plan on visiting the Langley Research Center again this April to update the group there on my work and get feedback.

6) Conferences

Previously attended conferences include 2012 SDM Conference (attendee) and 2012 Virginia Space Grant Consortium Student Research Conference (presenter), both in April 2012. As more research has been completed, more conferences are planned for the upcoming year:

IMAC XXXI: A Conference and Exposition on Structural Dynamics
- February 11-14, 2013
- Hyatt Regency Orange County, Garden Grove, CA
- Accepted, #77, "Comparison of Damping Models for Space Flight Cables"
- This is a structural dynamics conference that I will be presenting analytical and experimental work at.

54th Structures, Structural Dynamics, and Materials Conference (SDM 2013)
- April 8-11, 2013
- Boston Park Plaza Hotel, Boston, MA
- Accepted, "Toward Modeling of Cable-Harnessed Structures: Cable Damping Experiments"
- Another structural dynamics conference to present experimental work, will also go to visit with advisor and run through preliminary presentation

Virginia Space Grant Consortium Student Research Conference 2013
- April 18, 2013
- Old Dominion University, near Hampton, VA
- Accepted, "Model Development for Cable Harnessed Beams, Part 2"
- A student conference to present my analytical research which can be linked to an on-site visit to present my work at NASA Langley.

SEM 2013 Annual Conference and Exposition on Experimental and Applied Mechanics
- June 3-6, 2013
- Westin Lombard Yorktown Center, Lombard, IL
- Abstract to be submitted Jan 7th, "Effect of Bake-Out Treatment on Space Flight Cable Stiffness"
- A conference for experimental and applied mechanics to present my experimental findings regarding the increased stiffness of cables due to bake-out.

Future conferences (if research permits) include the 2014 IMAC and SEM conferences in February 2014 and June 2014, and an International Symposium on Cable Dynamics in July 2014.

7) Schedule

Milestone or Activity	Estimated Date(s)
Research activities and milestones	
Initial cabled-beam experiments at Virginia Tech completed	August 18, 2011
Initial meeting with advisor and mentor to determine project direction	March 13, 2012

Background research completed on cable dynamics	July 2012
Initial Timoshenko DTFM cable model completed	September 2012
Meeting with advisor and mentor to finalize project goals	November 5, 2012
First journal paper (Cable Modeling and Damping Developments, Applied Mechanics Reviews) accepted with minor revisions!	December 2, 2012
"Cable Modeling and Internal Damping Developments" final draft submitted to JPL document review for unlimited external release	December 17, 2012
Experimental set up at JPL complete	December 2012
SEM abstract submitted on the effect of bake-out on cable bending stiffness	January 7, 2013
"Cable Modeling and Internal Damping Developments" final draft due for Applied Mechanics Reviews	January 21, 2013
Additional cable required for DC offset for modal shaker purchased	January 2013
Timoshenko coefficient beam problem solved	January 2013
Design of experiments complete, most "well-behaved" cables established	February 2013
Write up Timoshenko coefficient work for journal paper	March 2013
Cable dynamic response experiments completed	April 2013
Complete baked-out cable testing, write up for SEM conference and perhaps journal paper	May 2013
Data analysis and model validation for cables	July 2013
Develop cabled-beam DTFM model	September 2013
Write up cable experiment results and model comparison for IMAC conference (abstract likely due in June 2013), write up for journal paper	October 2013
Determine further experiments needed, conduct second round of experiments for cabled beam	December 2013
Second round of data analysis and model validation, adding model complexity	February 2014
Write up cabled-beam experiment results and model comparison for SEM conference, write up for journal paper	May 2014
Finish any outstanding work, complete thesis	June 2014
Academic and degree activities and milestones	
Virginia Tech PhD Program Start Date	August 2010
Virginia Tech PhD Qualifier Passed	March 2011
NSTRF Fellowship and Support Began	August 2011
All PhD Courses Completed	December 2011
Dissertation Chapter 1(Intro) Draft Complete	December 2012
Dissertation Ch. 2 (Cable Background) Draft Complete	January 2013
Dissertation Ch. 3 (Technical Background) Draft Complete	April 2013
Preliminary Examination	TBD ~May 2013

Dissertation Ch. 4 (Cable Modeling Approach) and Ch. 5 (Experimental Approach) Draft Complete	~August 2013
Dissertation Ch. 6 (Cabled Beam) Draft Complete	~January 2014
Dissertation Ch. 7 and 8 (Discussion and Conclusion) Draft Complete	~February 2014
Dissertation Defense	TBD
Onsite experiences	
JPL Year One; Weekly meetings with mentor, training and research opportunities	Jan 2012-Aug 2012
LaRC Year One; Presentation of work to date and input and suggestions from NASA engineers	April 2012
JPL Year Two; Weekly meeting with mentor, training and research opportunities continued	Aug 2012- Aug 2013
LaRC Year Two; Presentation of work since last meeting and input on corrections and future work	April 2013
JPL Year Three: On-site experience at JPL will likely continue unless another NASA center has a sudden need for cable research; in this year, any remaining portion of time after dissertation is completed will be spent on training projects at the NASA center	Aug 2013-Aug 2014
Conferences	
Attended 53rd Structures, Structural Dynamics, and Materials Conference, Honolulu, HI	April 23-26, 2012
Presented at Virginia Space Grant Consortium Student Research Conference 2012, Williamsburg, VA	April 5, 2012
Presenting at IMAC XXXI: A Conference and Exposition on Structural Dynamics, Garden Grove, CA	February 11-14, 2013
Presenting at 54th Structures, Structural Dynamics, and Materials Conference, Boston, MA	April 8-11, 2013
Presenting at Virginia Space Grant Consortium Student Research Conference 2013, Old Dominion University, VA	April 18, 2013
Applying to present at SEM 2013 Annual Conference and Exposition on Experimental and Applied Mechanics, Lombard, IL	June 3-6, 2013
IMAC XXXII: A Conference and Exposition on Structural Dynamics, Orlando, FL	February 3-6, 2014 *(Tentative)*
SEM 2014 Annual Conference and Exposition on Experimental and Applied Mechanics, Greenville, SC	June 2-4, 2014 *(Tentative)*
International Symposium on Cable Dynamics, Copenhagen, Denmark	July 2014 *(Tentative)*