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14. ABSTRACT This work focused on obtaining fundamental understanding of how the dynamics of a structure change when cables are attached to it. The work was motivated by the complexity of modeling satellites when structural elements are harnessed with signal and power cables. This problem has been identified by AFRL/VSSV as significant in shock and vibration modeling and verification of satellite systems. We performed basic research to illuminate the relevant structural dynamics producing predictive models of cable-harnessed structures. Our approach was to use novel analytical methods based on homogenization techniques, singularity functions, spectral element methods and model updating methods, complete with experimental validation and model verification. Our work provides an alternative to large order finite element modeling by providing distributed parameter models with "exact" solutions. The basic research provides a better understanding of more complicated Air Force satellite structures that are harnessed with signal and power cables. The ultimate goal was to comprehend and quantify the effect of cable harnesses on structures that cannot be tested prior to launching and to provide a predictive modeling capability. The performed research consisted of both theoretical modeling and experimental validation. Experimental investigation was used for advancing and motivating theoretical modeling considerations by performing a series of successively more complex structural systems used to highlight various dynamic modes.

15. SUBJECT TERMS
cable harnessed satellites, bakeout, precision modeling, spectral element modeling, model updating, homogenization

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Executive Summary: The work as initially proposed was to sort out a long standing modeling problem facing AFRL researchers and others, that cables added to well modeled satellite structures resulted in unknown and drastic changes in their dynamic models. The research results obtained under this funding can be divided into three main thrusts: 1) understanding and modeling the cable dynamics, 2) modeling the effect of the cable on the structure and, 3) modeling the effect of the arrangement of the cabling on the structure.

Cables can account for as much as 30% of the satellite mass or as little as 4%. Early efforts in modeling the additional dynamics of a harnessed satellite consisted of merely accounting for the added mass lumped at the center of mass, but this proved to be unacceptable and in disagreement with experimental test data. Research conducted by the Air Force Research Laboratory Space Vehicles Directorate shows that including cables as a lumped, non-structural mass is no longer adequate for accurate modeling. This is largely because cables behave as structural mass. To complicate matters more there exist no reliable or predictive models of cables. In fact modeling the cables themselves turned out to be one of the more important tasks of the research. Cables are difficult to model because they are often hand woven with many variables such as ply angle, lay direction, wire composition, geometry, shielding or jacketing. Thus our first thrust was to come up with predictive models of the cable dynamics.

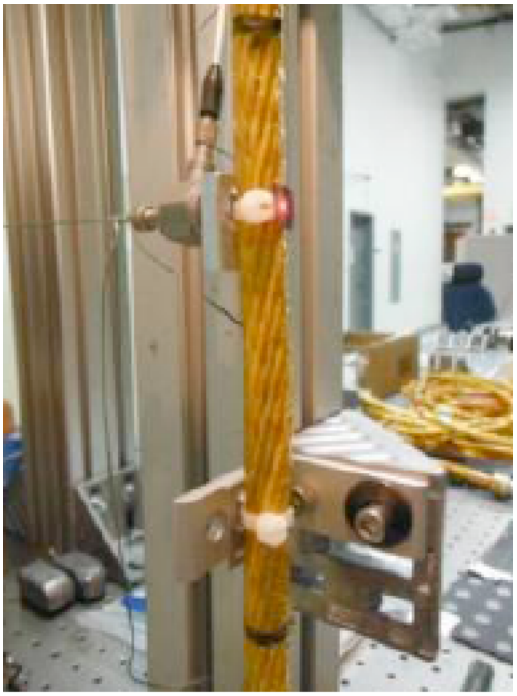
Our second thrust focused on understanding how the cables affect the total system dynamics when mounted on a structure. This includes modeling the ties that connect the cables to the structure, the cables and the structure itself. Simple structure and cable arrangements were used with the hope of illuminating the basic effects. The spectral element method was chosen as the underlying modeling framework with the hope of producing simple low order models that could be used to discover physical effects rather than just numerical modeling. Model updating methods were also used as well as various techniques to model damping.

Or third focus was to use homogenization methods to produce beam like analytical models, which captured the essential character of a cable-harnessed beam. This approach was also used to examine various cable layouts or arrangement of cables on the structure. Homogenization basically takes a repeated structure and formulates a distributed parameter model having the same strain energy.

All three of the focus areas include analysis, simulation and experimental validation. In many cases the experimental tests did not agree with model predictions and in these cases the experimental trends were used to modify the modeling.

Cable Modeling: Here we present experimental test results that will drive models to follow. After extensive searching for cable models a much needed survey paper was put together [1]. In particular, as damping was a key mystery in earlier AF efforts, we focused on categorizing and discussing the various damping models of cables. Next a series of experiments where performed to attempt to identify the type of damping typical to spacecraft harnessing cables. Reference [5] contains the experimental details.

Basically, we tested as section of a space qualified cable between two clamps as illustrated in Figure 1.



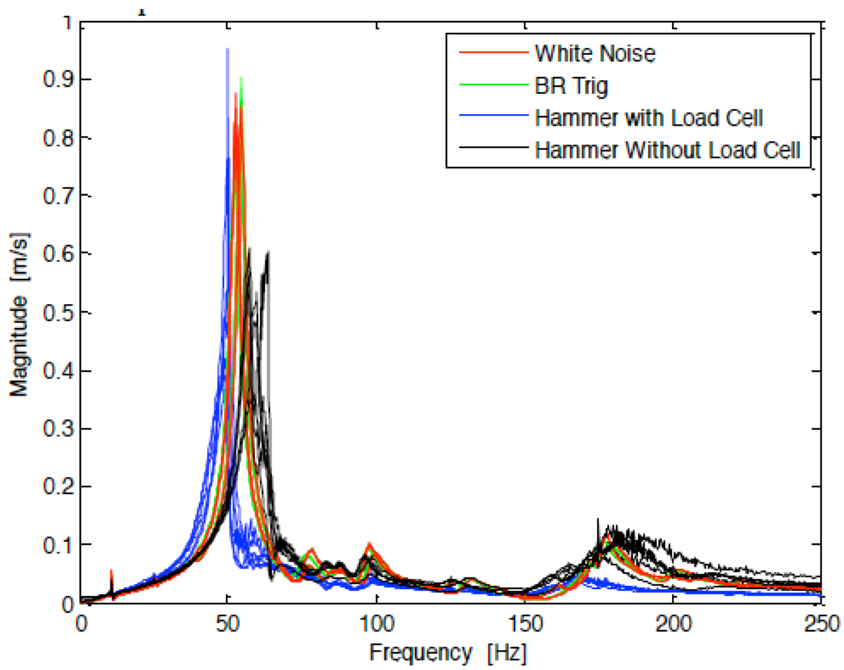


Figure 1 (left) Close up a sample cable tested for its dynamic properties, fixed between two standard cable attachment fixtures. (right) Sample transfer function data taken from the experiment at left.

The tests included a study of various excitation and measurement methods for a variety of different tensions. The cable scans were valuable in verifying the first and second mode shapes and thus, natural frequencies. The trends for each test were fairly clear when analyzed at the conclusion of each day's testing, but when responses and frequencies were compared from day to day, there was great variation, even between "standard" runs. An interesting result from the simultaneous measurement of the perpendicular vibrations was the observation that the symmetrical-appearing cable does not have the same natural frequencies in both directions. The cable is actually stiffer in one plane, which is not intuitive. It is hypothesized that the twisting of the cable, coiled storage and/or Kapton overwrap method may be responsible for this lack of symmetrical response. It is also worth noting that this could explain dual first frequencies shown between the two sets of cable sections.

Conclusive results were obtained for the tests involving string length and tension, cable tension, and zip tie attachment. It was clear that for small cable deflections, the length of the excitation string and tension in the string were not affecting the cable's dynamic response. Cable tension did change the frequency response, with a general trend of higher tension corresponding to higher natural frequencies. This test also showed that "hand-tight" cables were on par with 1-4 lbs of tension in the cable, and that slack cables behave differently and may have more non-linear attributes. Zip tie brand, type and size were not important factors, but the tightness of the zip tie attachment was. Therefore, cable tension and zip tie tightness should be controlled for future testing to reduce variation between standard runs. In addition, cable angle in the test fixture should be noted, as comparison between cables may require different orientations to test the same cable plane.

The excitation method of the cable went through several iterations, starting with a long solid stinger, hinged stingers, and eventually settling on the tensioned string used for these tests because of its ability to eliminate moments or lateral forces from being applied to the cable. The hammer tests bounded the tensioned string random excitation results, which seemed reasonable. The tests conducted yielded good representations of the cable dynamics, with little interaction from the support structures.

Cable damping models must account for hysteretic effects and frequency dependence as discussed in [6]. This has a significant effect on the dynamics and is not well modeled. We have preliminary models but have not yet been able to successfully compare a theoretical/numerical model with experimental data, so this remains an unsolved problem.

One area of research that emerged as important was the affects of bake out on cable dynamics. Bake out refers to the process of conditioning cables in a vacuum and across a range of temperatures. Once the cables are subjected to bake out their properties change a great deal [2]. Figure 2 illustrates this.

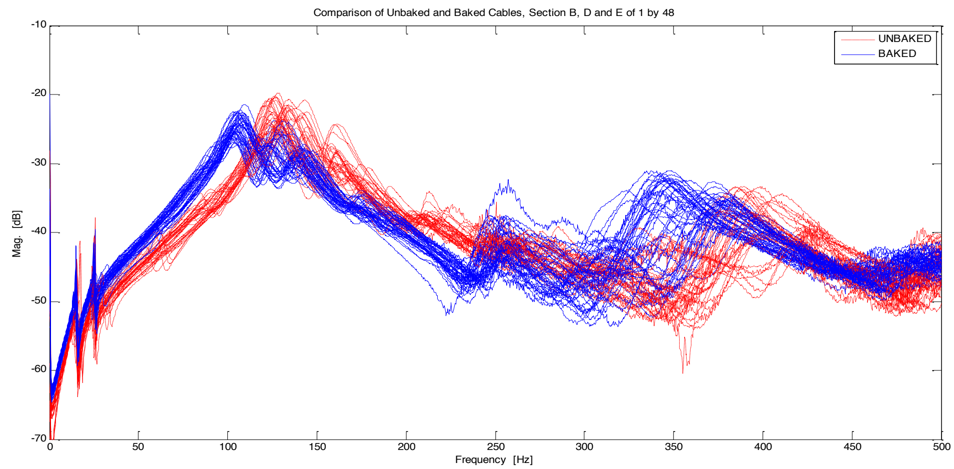


Figure 2 Effects of bakeout on a cable harness showing that the frequencies and damping changes and the result begs for a statistical analysis for modeling the cable dynamics.

As illustrated in Figure 2 the effects of bake out equivalent to low earth orbit introduce three important changes: (1) the frequency response is variable and likely needs some statistical analysis or a bound analysis; (2) the frequencies are lowered by the effect of backout; and (3) the damping increases.

Cable Structure Interaction: Two approaches were employed. The first is spectral element modeling and the second is model updating. The spectral element method (SEM) was employed to model the interaction between the cable dynamics and the dynamics of the host structure. It is well known that SEM produces accurate models with many fewer elements then does standard Finite Element Methods (FEM), and that is the case here as well. Figure 3 illustrates the basic SEM element where the bottom beam is the host structure, the top beam is the cable and the spring in between represents the tie connecting the two components.

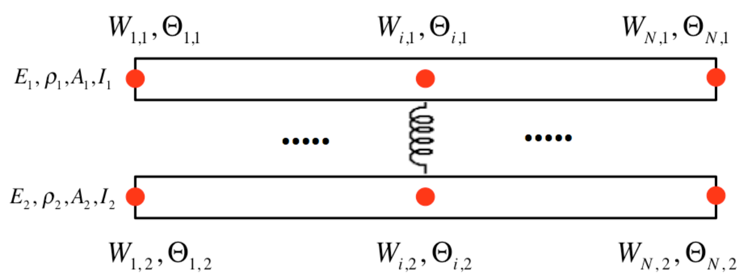


Figure 3 A SEM formulation of a cable harnessed structure.

With the model in hand the effects of the number and placement of connections has been studied.

First the SEM model of a cable harnessed structure with 6 elements was compared to the same structure modeled with 60 FEM. The experimental system considered is a cable mounted on a beam with 5 ties modeled as springs of stiffness 10^5 N/m.. An aluminum beam is considered as a main base structure and modeled by using Euler Bernoulli beam. The cable was modeled as a copper beam using both Euler beam and Timoshenko beam equations.

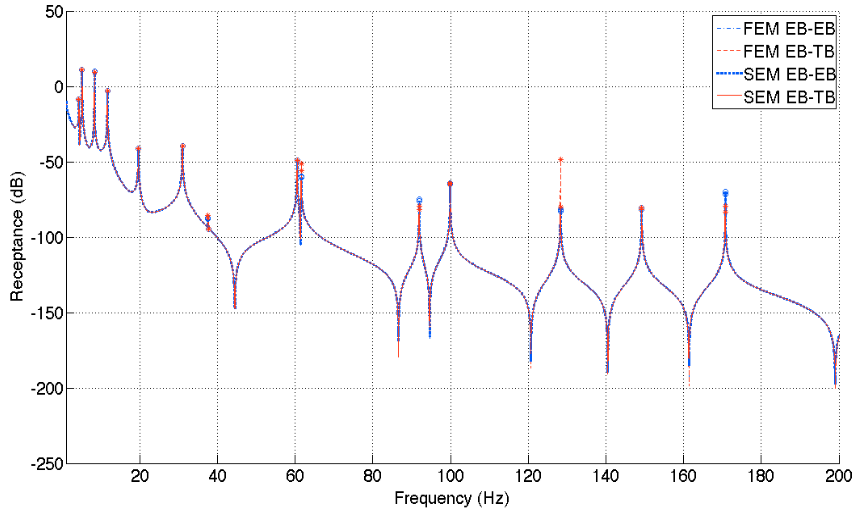


Figure 4 Comparison beteween SEM and FEM modeling of a cable harnessed beam.

Next and vibration test was performed yielding the plot of Figure 5.

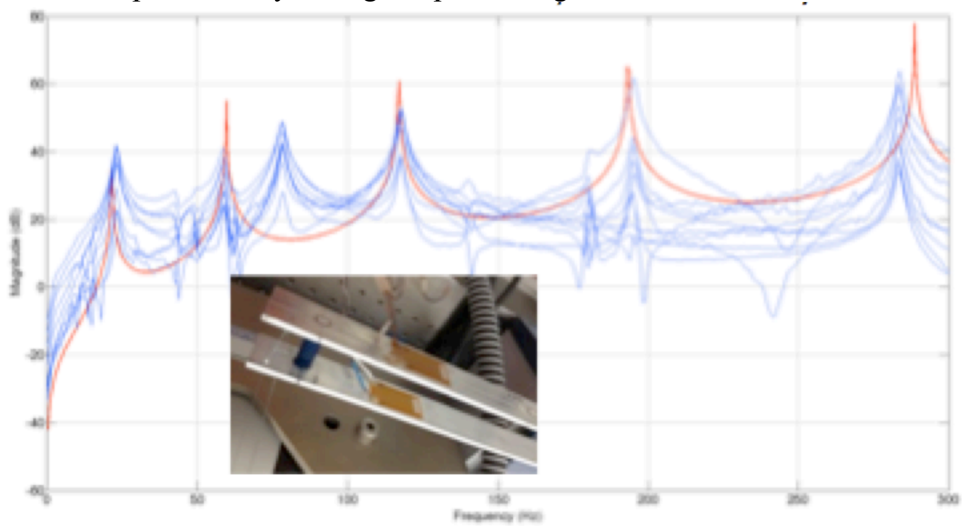


Figure 5 The insert shows the test structure and the plots show theory versus experiment.

The plots in Figure 5 show that the theory based on SEM modeling is a fairly reasonable prediction of the experimental measurements. Note that the blue peak between the two theory peaks at 70 Hz corresponds to the frequency of rotation between the two beams, which is not modeled and would not be present with traditional ties rather than the springs used here.

Mode	Measured	FEM	Updated
1	**117.02**	114.48	**117.02**
2	**311.42**	315.64	**311.42**
3	**622.12**	619.24	**622.12**
4	**1027.3**	1025.3	**1027.3**
5	**1547.8**	1536.4	**1547.8**
6	-	**2156.5**	**2156.5**
7	-	**2891.2**	**2891.2**
8	-	**3742.3**	**3742.3**
9	-	**4655.4**	**4655.4**
10	-	**6211.6**	**6211.6**

Table 1 The results of model updating showing that our algorithm does not effect the higher, unmeasured modes.

Our model updating results are given in Table 1. Our method [9] is based on inverse eigenvalue theory based on matrix pencils and the partitioning of the FEM matrices. The first column gives the value of the measured frequencies, the second column gives the frequencies determined by a 10 element FEM and the last column lists the values of the updated frequencies.

Cable Arrangement: The goal of this phase of the research was to derive a distributed parameter models for the hybrid structures- i.e. beam and cable arrangements and to examine the periodic distribution of cables along the host structure. The approach is to use homogenization methodologies. Homogenization techniques have proved very powerful for dynamic modeling of structures with repeated patterns. Kinetic and strain energy of the fundamental element with a given cable pattern were obtained to find the partial differential equations.
As a preliminary step, a model that only includes the additional mass of the cable and ignores any of the stiffening effects is considered (mass updated model). It is proved later that including the strain energy of the cables to come up with a hybrid model significantly increases the accuracy of the frequency response functions and the higher frequencies. The main challenge was obtaining the strain energy of a fundamental element that includes both the effects of the cable and beam. Two major approaches were employed for strain energy derivations:

1. Assuming that the cable attached to the beam acts as a pre-stretched bar member.
2. Assuming that the cable attached to the beam acts as a strained string.

The PDE for each case is derived and differences and advantages are illuminated [4,5,10,11]. For the first model, beams with both rectangular and circular cross-sections of various distinct cable wrapping patterns are considered such as zig-zag and front inclined. When comparing the natural frequencies of this model (beam and cable) with a mass updated beam, it was observed that the percentage shift in the frequencies was independent of boundary conditions and mode numbers; instead they were highly dependent on the cable modulus and radius. An increase in the number of repeated elements resulted in a higher accuracy for the modeling technique used. This is because the error of this model depends on the element length to wavelength ratio, which gives better accuracy when larger number of elements used.

For the second model that employs the assumptions of a string theory for the cable-harnessed beam, beams with rectangular cross-sections and four distinct wrapping patters were considered. When comparing the frequencies of this model (beam and cable) to a mass updated beam, it was observed that the percentage shift in the frequencies was much greater for the lower modes than for the higher modes. This suggests that the stiffening effect of the cable under this model mainly affects the lower modes of vibration and has smaller effects on the higher modes. This is in contrast to the previously discussed model. Furthermore, the percentage increase in the frequencies was heavily dependent on boundary conditions; of the four boundary conditions considered clamped-free produced the largest increases, clamped-clamped produced the smallest increase, with free-free and pinned-free landing in the middle. When comparing this model to a mass updated beam, only an increase in tension caused an increase in the percentage shift of the frequencies. The cable modulus and cable radius had no effect on the percentage shift of the frequencies compared to a mass updated model. Lastly, it was found that the frequency shift for a varying number of repeated elements with a fixed beam length depended greatly on the wrapping pattern of the cable. Figure 6 illustrates the agreement between theoretical predictions and experimental measurements in the frequency domain [10].

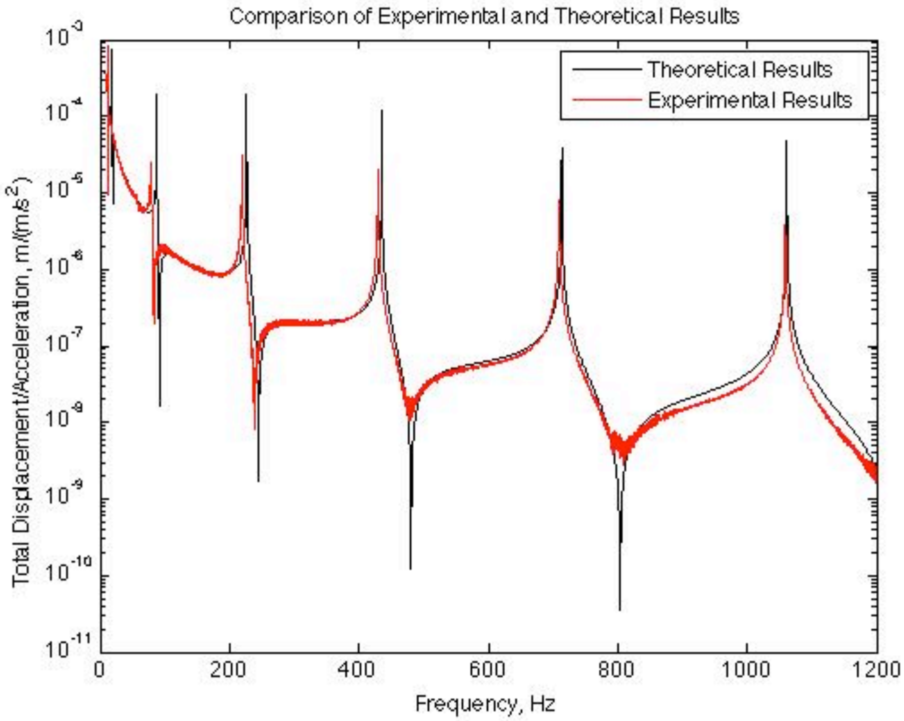


Figure 6 Comparison of experimental and analytical frequency response functions for cable harnessed beam.

Conclusion and Outlook

Several issues identified for modeling cables attached to structures through experiments

- Developed homogenized models of cables
- Developed low order models of cables attached to structures
- Modeled the effects of wrapping sequence

Cables clearly make dramatic changes in the structural response, which cannot be handled by simply including the mass loading effects. Rather flexibility must be taking into consideration. Wherever possible, theories were tested against experiments. Experimental results were used to drive theoretical modeling. It is clear that cables substantially effect the cable-structure system.

Quite a bit of work needs to be done yet in order to provide AFRL with FEM adjustments for cable harnessed structures, especially in the area of damping and in model uncertainty.

Archival Publications During Reporting Period:

[1] Spak, K.S, Agnes, G.S, and Inman, D. J, 2013, "Cable Modeling and Internal Damping Developments", Applied Mechanics Reviews, Vol. 65, Issue 1, DOI:10.1115/1.4023489.

[2] Spak, K.S, Agnes, G.S, and Inman, D.J, TBD, "Changes in Dynamic Response of Spaceflight Cables After Bakeout", in review *Experimental Techniques.*

[3] Choi, J. and Inman, D. J., 2013, "Modeling Dynamics of a Cable Harnessed Structure", *Journal of Vibration and Acoustics,* in revision.

[4] Martin, B. and Salehian, A., "Dynamic Analysis and Testing of Periodically Wrapped Cable-Harnessed Beams", submitted July 2013.

[5] Martin, B., and A. Salehian, A., "Cable-Harnessed Beam Vibration Analysis and Testing Using String Theory", submitted July 2013.

Other Publications Describing Details of Results:

[6] Spak, K.S, Agnes, G.S, and Inman, D.J, 2013, "Comparison of Damping Models for Space Flight Cables", SEM International Modal Analysis Conference, Garden Grove, CA, #77.

[7] Spak, K.S, Agnes, G.S, and Inman, D.J, 2013, "Toward Modeling of Cable Harnessed Structures: Cable Damping Experiments", AIAA SDM Conference, Boston, MA, Paper No. AIAA-2013-1889.

[8] Choi, J.D., and Inman, D.J, 2013, "Spectral analysis method for the cable harnessed structure", IMAC XXXI, Paper No 31.

[9] Choi, J.D., and Inman, D.J, 2013, "Development of modeling for the cable harnessed structure", 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA 2013-1888

[10] Martin, B. and Salehian, A., 2013 "Vibration Analysis of String-Harnessed Beam Structures: A Homogenization Approach", *54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, April 2013.

[11] Martin, B. and Salehian, A., 2013 "Cable-Harnessed Space Structures: A Beam-Cable Approach," *24th IASTED International Conference on Modeling and Simulation*, July 2013.