

Effects of Bakeout on Space Flight Cable Stiffness

SEM Student Paper Competition ~ June 3, 2013

Kaitlin Spak

MOTIVATION

Spacecraft cables are critical to the success of any mission. They must be able to withstand the harsh environment of space, including extreme temperatures, radiation, and vibration. This paper explores the effects of bakeout on the stiffness of these cables, which is a critical factor in their design and performance.

OBJECTIVES

- Determine whether space flight cable stiffness is indeed affected by bakeout, as evidenced by changes in dynamic response
- Observe the effects of bakeout on space flight cables and compare the cables pre- and post-bakeout
- Quantify the dynamic response effects of low Earth orbit bakeout on a set of cables generated for determining the design to natural frequency and for damping

BACKGROUND

CABLE CONSTRUCTION
Cables are made of multiple strands of wire, which are twisted together to form a single cable. The construction of the cable affects its stiffness and dynamic response.

CABLE MODELING
Cables are modeled using finite element analysis (FEA) to predict their dynamic response. The model takes into account the cable's geometry, material properties, and boundary conditions.

BENDING STIFFNESS
Bending stiffness is a measure of a cable's resistance to bending. It is affected by the cable's material properties and its cross-sectional area.

BAKEOUT
Bakeout is a process used to remove moisture and other contaminants from cables. It is typically performed in a vacuum oven at a high temperature for a period of time.

EXPERIMENTAL PROCEDURE

Several cables were tested to observe the overall dynamic behavior and develop the test set up. Cables were excited with a modal shaker and the dynamic response was measured with a laser vibrometer at the driving point. Factors affecting the cable response were investigated and a standard run was developed to ensure future cable tests will be comparable.

Cable type chosen
The cables chosen for testing were of various types and materials, including copper and aluminum.

Test fixture designed
A test fixture was designed to hold the cables in place and apply a controlled force to excite them.

Standard run developed
A standard run was developed to ensure that all cable tests were performed under the same conditions.

Machine-produced cables ordered and tested
Machine-produced cables were ordered and tested to compare their dynamic response to that of the hand-made cables.

TEST SET UP DETAILS

The test set up consisted of a modal shaker, a laser vibrometer, and a data acquisition system. The cables were suspended in a vacuum oven and excited by the modal shaker. The dynamic response was measured by the laser vibrometer and recorded by the data acquisition system.

Results compared: Mode shapes, natural frequencies, damping values

RESULTS: UNBAKED VERSUS BAKED

The results show that the dynamic response of the cables changes significantly after bakeout. The natural frequencies of the cables decrease, and the damping increases. This is particularly evident for the 1x17 and 1x19 cables.

1x17 Cables
1x17 Unbaked Average: 45.75 Hz
1x17 Baked Average: 34.85 Hz

1x19 Cables
1x19 Unbaked Average: 76.49 Hz
1x19 Baked Average: 59.72 Hz

Cable	1x17 Results		1x19 Results	
	Unbaked	Baked	Unbaked	Baked
1x17	45.75	34.85	76.49	59.72
1x19	76.49	59.72	45.75	34.85

CONCLUSIONS, CONTRIBUTIONS, AND FUTURE WORK

- No literature exists on the effect of bakeout treatment on cable stiffness. This work provides concrete data that bakeout does indeed change the dynamic response of space flight cables.
 - After a low Earth orbit bakeout, the first and second natural frequencies decreased for all cables between 7 and 28%.
 - After a low Earth orbit bakeout, damping values increased for all single-strand cables.
 - It is clear that this combination of wire type and bakeout results in a significant reduction in bending stiffness.
 - Current cable frequency data refers to unbaked cables, which may have a higher frequency than flight-ready cables; spacecraft designers should keep this in mind if using currently published data.
- Future Work:**
- Different bakeout treatments may have different results.
 - Different wire coating may have different results; the presence of plasticizers that would outgas would likely cause stiffening after bakeout.
 - More extensive chemical research could be done to identify the softening mechanisms due to bakeout treatment.

ACKNOWLEDGEMENTS

Many thanks to the organizations and universities that have supported this research and provided equipment:

- NASA Space Technology Research Fellowship Program
- Virginia Space Grant Consortium
- Air Force Office of Scientific Research
- AIAA San Gabriel Valley Chapter
- Jet Propulsion Laboratory
- Virginia Tech
- University of Michigan
- Southern California Braiding Co.

Advisor: Dr. Daniel Inman, Univ. of Michigan
Mentor: Dr. Greg Agnes, JPL

REFERENCES

1. NASA, "Space Flight Cable Handbook," NASA Technical Report SP-1076, 1970.

2. NASA, "Space Flight Cable Handbook," NASA Technical Report SP-1076, 1970.

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Effects of Bakeout on Space Flight Cable Stiffness

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MOTIVATION

Cable is used for a wide range of applications in space systems. Cable must be able to support the weight of the cable and the weight of the payload. Cable must be able to support the weight of the payload and the weight of the cable. Cable must be able to support the weight of the payload and the weight of the cable.

OBJECTIVES

- Determine whether space flight cable stiffness is indeed affected by bakeout, as evidenced by changes in dynamic response
- Observe the effects of bakeout on space flight cables and compare the cables pre- and post-bakeout
- Quantify the dynamic response effects of low Earth orbit bakeout on a system of cables generated by determining the change in natural frequency and/or damping

BACKGROUND

CABLE CONSTRUCTION
 Cable construction involves the combination of different materials to create a cable that is strong, flexible, and durable.

CABLE MODELING
 Cable modeling involves the use of computer software to simulate the behavior of a cable under various conditions.

BENDING STIFFNESS
 Bending stiffness is a measure of a cable's resistance to bending. It is determined by the cable's material properties and its geometry.

BAKEOUT
 Bakeout is a process used to remove moisture and other contaminants from a cable. It is typically done in a vacuum oven at a high temperature.

EXPERIMENTAL PROCEDURE

Several cables were tested to observe the overall dynamic behavior and develop the test set up. Cables were excited with a modal shaker and the dynamic response was measured with a laser vibrometer at the driving point. Factors affecting the cable response were investigated and a standard run was developed to ensure future cable tests will be comparable.

Cable type chosen
 Cable type chosen based on availability and requirements.

Test fixture designed
 Test fixture designed to hold the cable and measure its response.

Standard run developed
 Standard run developed to ensure consistency in testing.

Machine-produced cables ordered and tested
 Machine-produced cables ordered and tested to compare with hand-made cables.

Most reliable cables determined and baked out at 105°C (E-5 torr) for 72 hours, then re-tested
 Most reliable cables determined and baked out at 105°C (E-5 torr) for 72 hours, then re-tested.

Results compared:
 Mode shapes, natural frequencies, damping values.

RESULTS: UNBAKED VERSUS BAKED

Results show that baked out cables show decrease in natural frequency and increase in damping.

ID	UNBAKED STATE		BAKED STATE	
	1st Frequency [Hz]	1st Damping [%]	1st Frequency [Hz]	1st Damping [%]
1x7	41.25	4.3	41.3	3.45
1x10	18.81	8.9	18.21	8.87
1x13	68.44	6.3	67.4	4.05
1x18	87.8	87.4	87.4	8.8
1x48	104.6	116	108	6.6
7x7	117.6	108	116	8.87
Avg	82.86	88.2	84.2	8.42
Unbaked	83.24	83.4	83.4	8.32
Baked	82.86	88.2	84.2	8.42

CONCLUSIONS, CONTRIBUTIONS, AND FUTURE WORK

- No literature exists on the effect of bakeout treatment on cable stiffness. This work provides concrete data that bakeout does indeed change the dynamic response of space flight cables.
 - After a low Earth orbit bakeout, the first and second natural frequencies decreased for all cables between 7 and 28%.
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 - Current cable frequency data refers to unbaked cables, which may have a higher frequency than flight-ready cables; spacecraft designers should keep this in mind if using currently published data.
- Future Work:**
 - Different bakeout treatments may have different results.
 - Different wire coating may have different results; the presence of plasticizers that would outgas would likely cause stiffening after bakeout.
 - More extensive chemical research could be done to identify the softening mechanisms due to bakeout treatment.

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1. NASA, "Space Flight Cable Handbook," NASA Technical Report SP-1975-309, 1975.
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SEM Student Paper Ka

MOTIVATION

Space structures of all types require power and signal cables



Cables are now making up a greater percentage of the total structure mass than in heritage systems

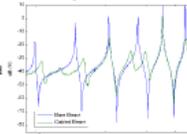
- Cable mass percentage is 10% at a typical NASA center, literature cites 4-30%
- Material science advances result in high strength-to-weight-ratio materials
- Cable materials remain unchanged
- Increase in signal and power needs, requiring cables



Mars Rover Curiosity weighed 7,275 pounds during EDL, and has 400 pounds of cables (5.5% cable mass)

Cables must be included in models of space structures

- Cables change structure behavior
- Knowledge of structure behavior is necessary for evaluation of failure risk and control system development
- Testing of space structures is often performed before cabling is completed

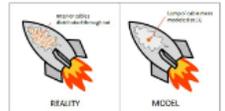


"Accurate prediction of structural dynamics, including the impact of cable harnesses, is of interest to the military space community as it reduces program risk, allows more realistic requirements on vibration mitigation systems and assures that mission performance metrics can be met." -AFRL



Cables must be modeled as structural mass with bending stiffness

- Cables were originally modeled as strings
- Space flight cables were traditionally modeled as lumped mass
- Literature review and industry findings show that lumped mass models and string models are no longer sufficiently accurate for dynamic behavior prediction
- No predictive model yet exists; in addition, cable research from AFRL and other sources do not consider bakeout effects



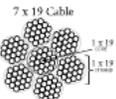
Determination of cable bending stiffness is necessary; bakeout may change cable stiffness

BACKGROUND

CABLE CONSTRUCTION

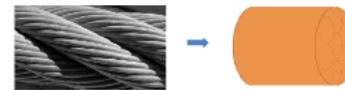


- Characteristics to consider:
- Core and layer wire materials
 - Number of wires
 - Type and thickness of insulation and shielding
 - Lay geometry
 - Lay angle and direction
 - Ties and overwrapping



CABLE MODELING

Cables can be modeled as a homogeneous beam with damping terms (Kane & Mott, 2011)



Cable properties

Beam properties

ρ, A, E, I, G

(+ DAMPING TERMS!)

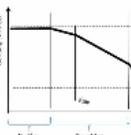
ρ : Density
 A : Cross-sectional area
 G : Modulus of rigidity
 Damping Terms

Bending Stiffness:
 E : Modulus of elasticity
 I : Area moment of inertia

BENDING STIFFNESS

Cable bending stiffness depends on:

- The moduli of elasticity of the cable constitutive materials and the proportions thereof
- The curvature of the cable (experiments must be limited to small displacement to yield a single EI value)
- Cable shape, layout and arrangement (moment of inertia)
- Any treatments that affect any of the above... such as bakeout

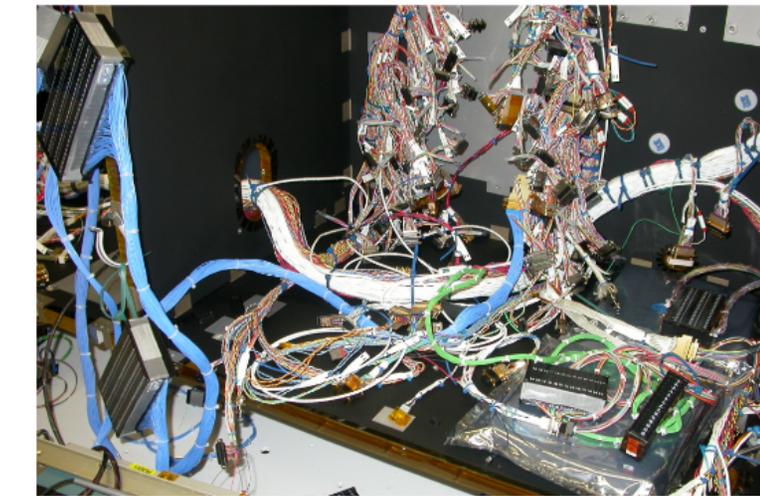
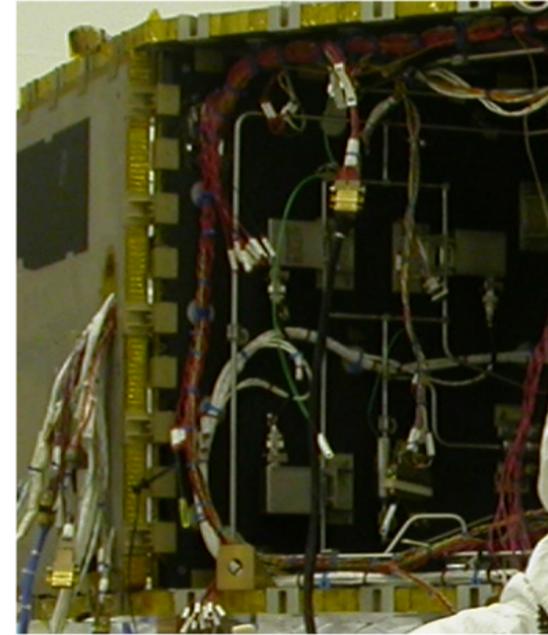


"Results demonstrate that the cable flexural rigidity with constant amount to damping with damping term in the cable equation." (Knapp & Liu, 2000)

No damping is not too difficult to

EXPERIMENTAL PROCEDURE

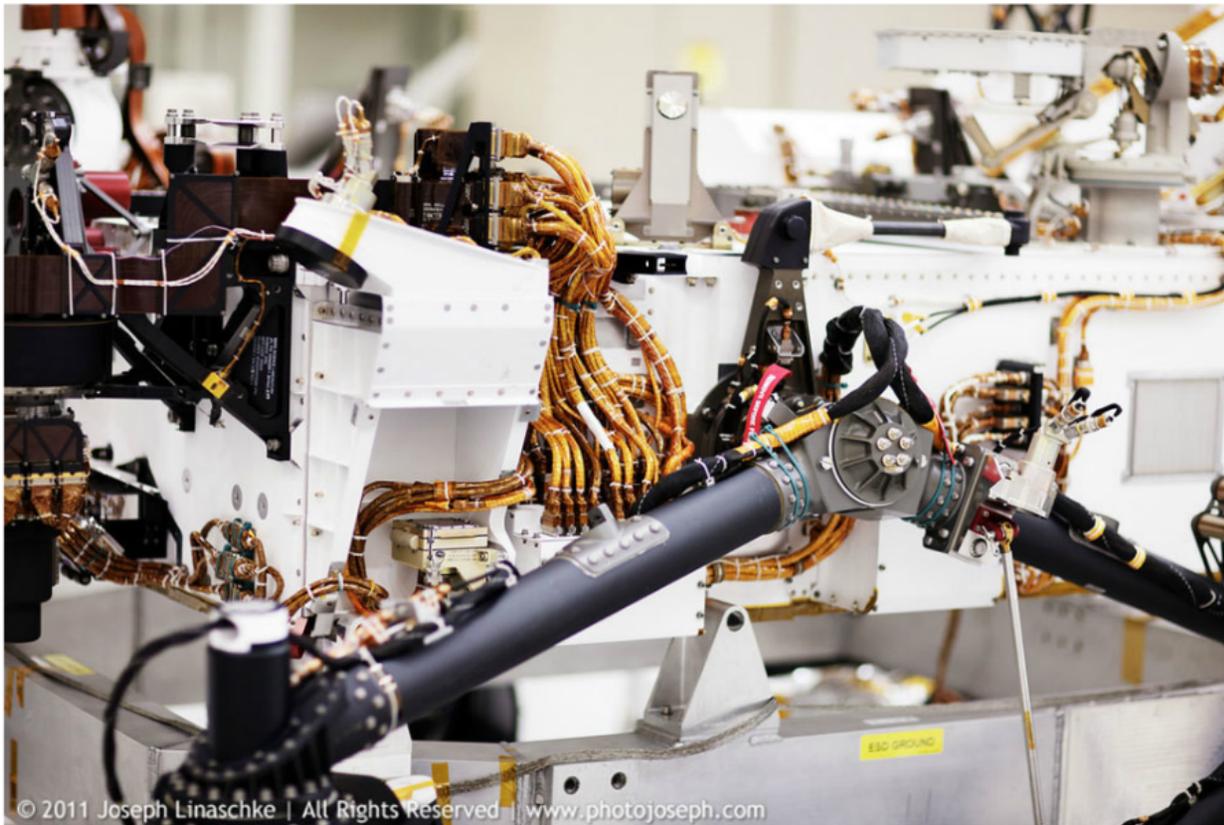
Space structures of all types require power and signal cables



Cables are now making up a greater percentage of the total structure mass than in heritage systems

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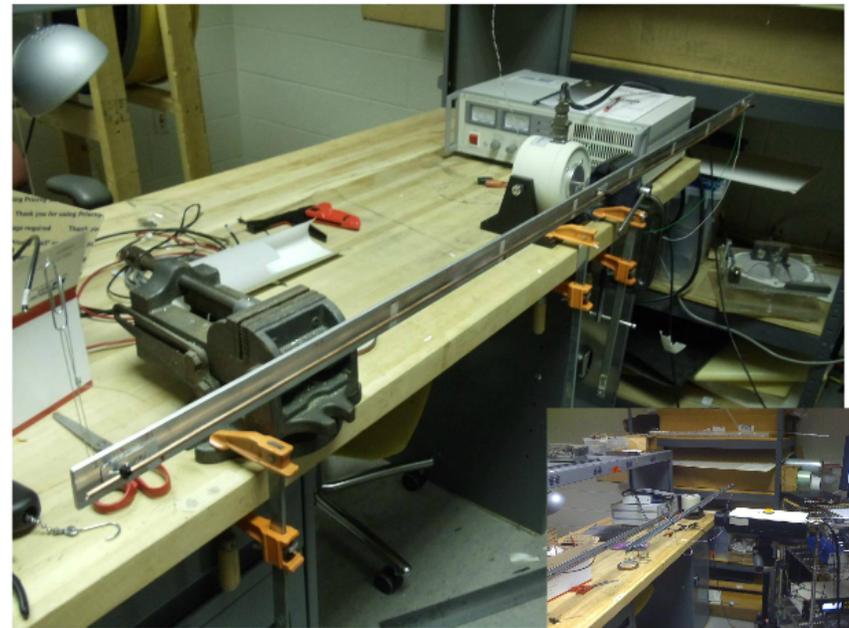
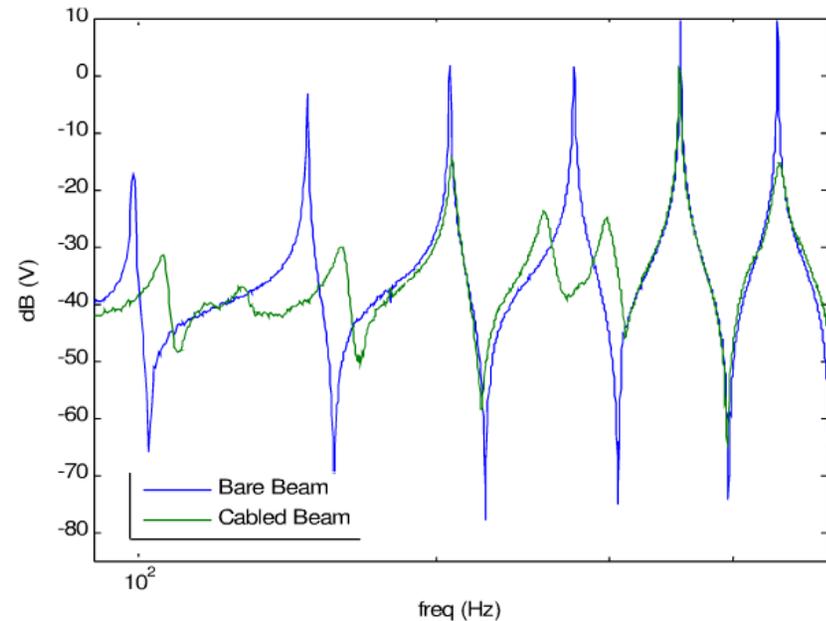


Mars Rover Curiosity weighed 7,275 pounds during EDL, and has 400 pounds of cables (5.5% cable mass)

Cables must be included in models of space structures

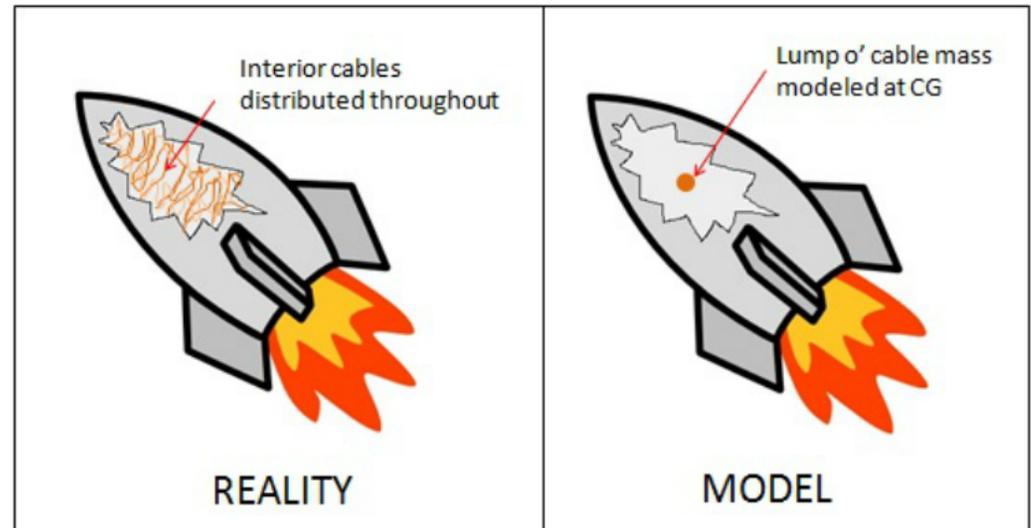
- Cables change structure behavior
- Knowledge of structure behavior is necessary for evaluation of failure risk and control system development
- Testing of space structures is often performed before cabling is completed

"Accurate prediction of structural dynamics, including the impact of cable harnesses, is of interest to the military space community as it reduces program risk, allows more realistic requirements on vibration mitigation systems and assures that mission performance metrics can be met." -AFRL



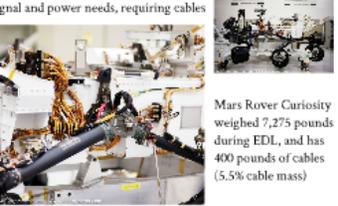
Cables must be modeled as structural mass with bending stiffness

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- No predictive model yet exists; in addition, cable research from AFRL and other sources do not consider bakeout effects



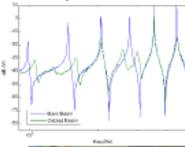
Determination of cable bending stiffness is necessary; bakeout may change cable stiffness

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Cables must be included in models of space structures

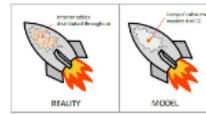
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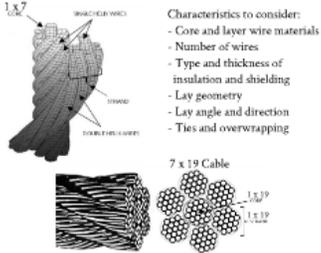
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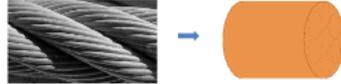
BACKGROUND

CABLE CONSTRUCTION



CABLE MODELING

Cables can be modeled as a homogeneous beam with damping terms included (Castello & Mei, 2011)



Cable properties

Beam properties

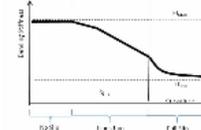
(+ DAMPING TERMS)

ρ : Density
 A : Cross-sectional area
 G : Modulus of rigidity
 Damping Terms
 Bending Stiffness:
 E : Modulus of elasticity
 I : Area moment of inertia

BENDING STIFFNESS

Cable bending stiffness depends on:

- The moduli of elasticity of the cable constitutive materials and the proportions thereof
- The curvature of the cable (experiments must be limited to small displacement to yield a single EI value)
- Cable shape, layout and arrangement (moment of inertia)
- Any treatments that affect any of the above... such as bakeout

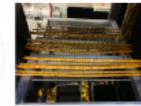


"Results demonstrate that the variation of cable flexural rigidity with curvature is tantamount to damping without use of a damping term in the cable equation of motion." (Knapp & Liu, 2005)

No damping term required if EI(c) is used. However, EI, mod and EI, mod can be useful to investigate apart and different treatments.

BAKEOUT

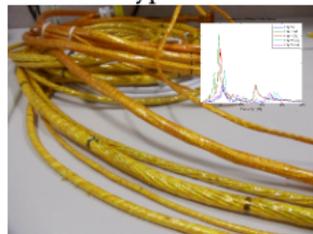
A thermal and vacuum treatment intended to expedite outgassing of volatile materials for cleansing purposes
 Low Earth Orbit Bakeout:
 72 hours at 105 C +/- 5C at pressure of less than 10⁻⁵ torr



EXPERIMENTAL PROCEDURE

Several cables were tested to observe the overall dynamic behavior and develop the test set up. Cables were excited with a modal shaker and the dynamic response was measured with a laser vibrometer at the driving point. Factors affecting the cable response were investigated and a standard run was developed to ensure future cable tests will be comparable.

Cable type chosen



- M27500-26T2T14 wire used (This is AECG standard type with several copper EMI shielding and Teflon (PTFE) jacket)
- Medium sized:
 - 1 by 19 in 2 layers over a core wire
 - Core wire is left hand lay
 - Contra-helically twisted (layers alternate lay direction)
 - The lacer every 4-6"
 - 50k machine wrapped Kapton overwrap
- Typical space flight cable

Test fixture designed

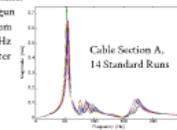


- Required cables with tension of 24 cm
- Cable tension light is placed at top and bottom
- Test section, 20 inch long, may hold cable and target in 20"
- Buffer zones, 4"

Standard run developed

STANDARD RUN

- Cable attached to test fixture with coil plane toward shaker
- TyRap TY525M cable ties with setting 5 on cable tie gun
- Static displacement of cable due to string less than 1 mm
- White noise (random) excitation at 0.3 volts, 0-2000 Hz
- Response measured at driving point by laser vibrometer
- Driving point at 8.5 cm above lower tie
- 2 lbs (8.9 N) cable tension
- Excitation actuated by tensioned 24 cm string
- Low pass 5 kHz filter
- Frequency of interest 0 - 250 Hz
- Test section length of 25.4 cm with two 20.3 cm buffer zones above and below

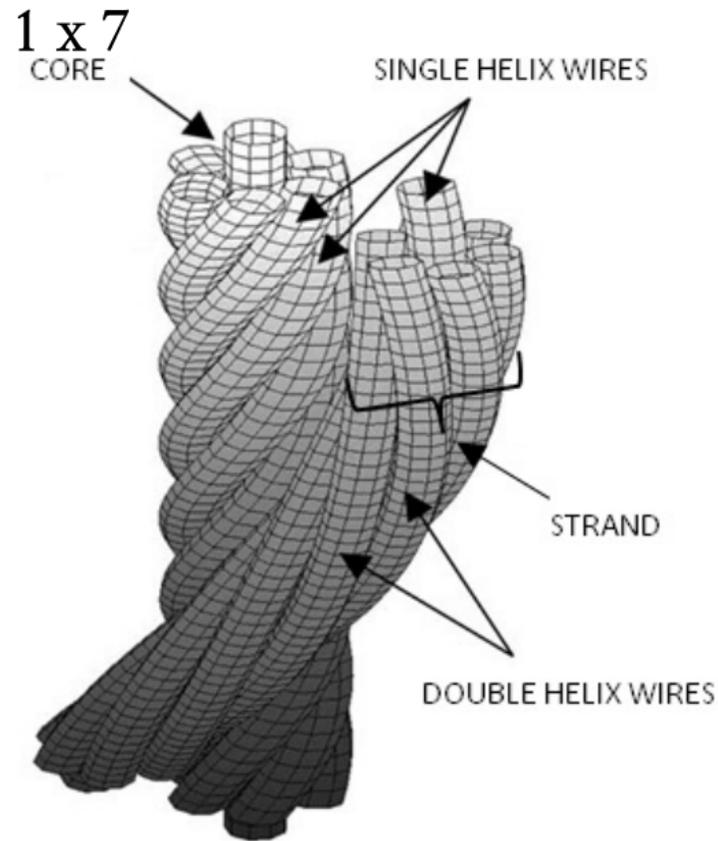


Machine-produced cable



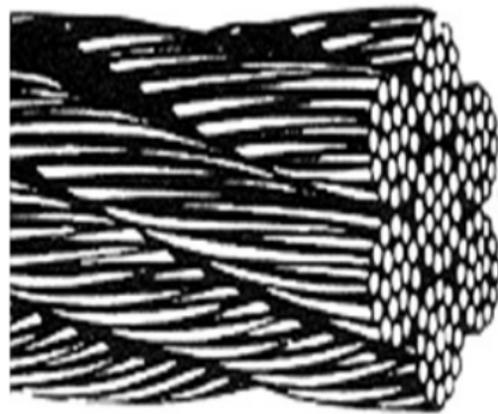
1x7, 1x19, 1x48 and 7x7 contra-helical configurations of M27500-26T2T14 wire

CABLE CONSTRUCTION

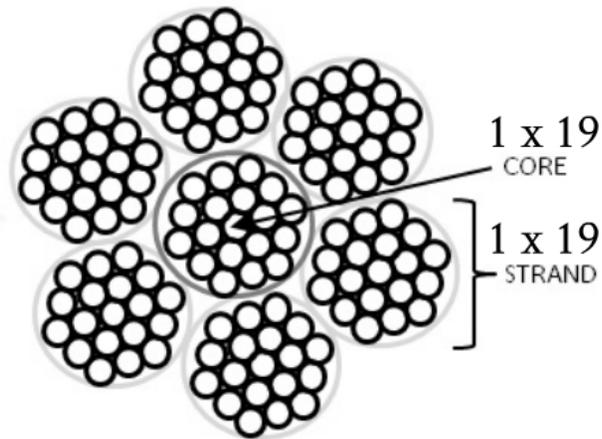


Characteristics to consider:

- Core and layer wire materials
- Number of wires
- Type and thickness of insulation and shielding
- Lay geometry
- Lay angle and direction
- Ties and overwrapping

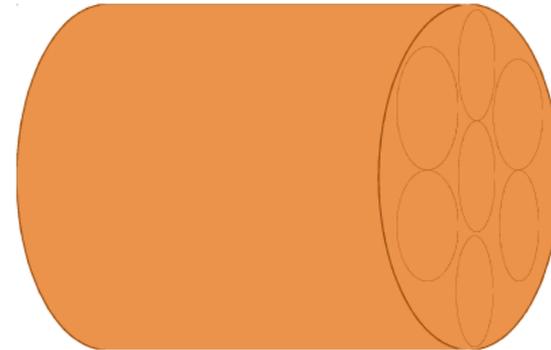
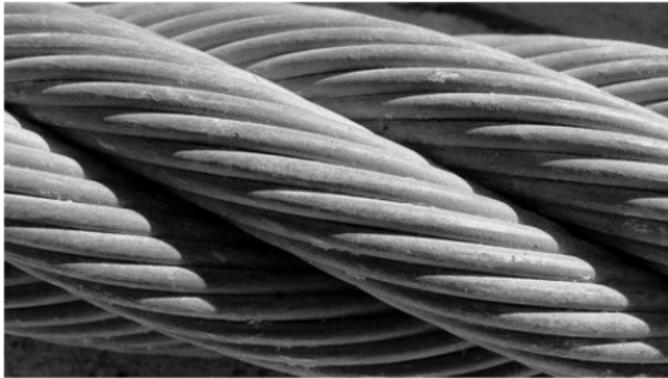


7 x 19 Cable



CABLE MODELING

Cables can be modeled as a homogeneous beam with damping terms included (Castello & Matt, 2011)



Cable properties

Number of wires
Number of layers
Wire size
Wire material



Beam properties

ρ, A, E, I, G

rho: Density

A: Cross-sectional area

G: Modulus of rigidity

Damping Terms

Bending Stiffness:

E: Modulus of elasticity

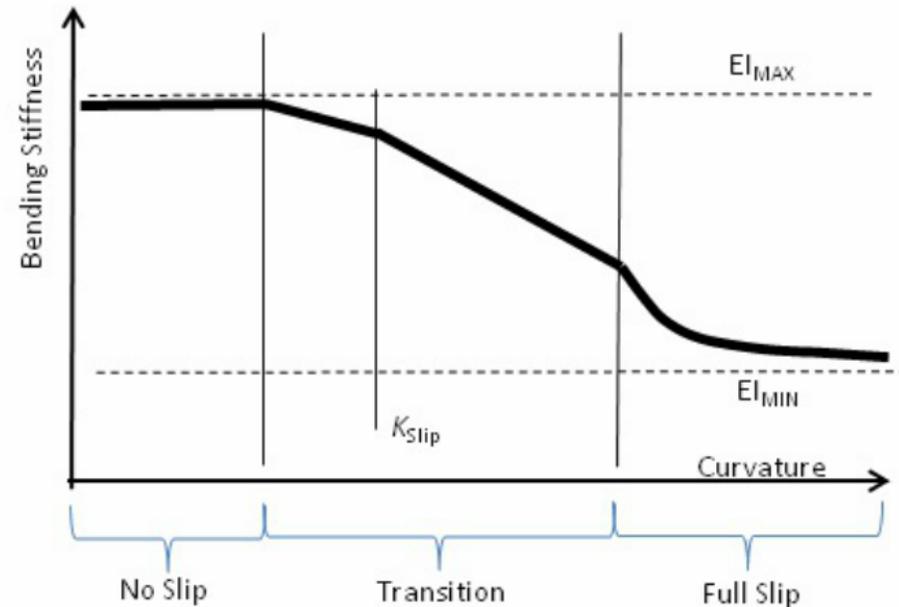
I: Area moment of inertia

(+ DAMPING TERMS!)

BENDING STIFFNESS

Cable bending stiffness depends on:

- The moduli of elasticity of the cable constitutive materials and the proportions thereof
- The curvature of the cable (experiments must be limited to small displacement to yield a single EI value)
- Cable shape, layout and arrangement (moment of inertia)
- Any treatments that affect any of the above... such as bakeout



"Results demonstrate that the variation of cable flexural rigidity with curvature is tantamount to damping without use of a damping term in the cable equation of motion." (Knapp & Liu, 2005)

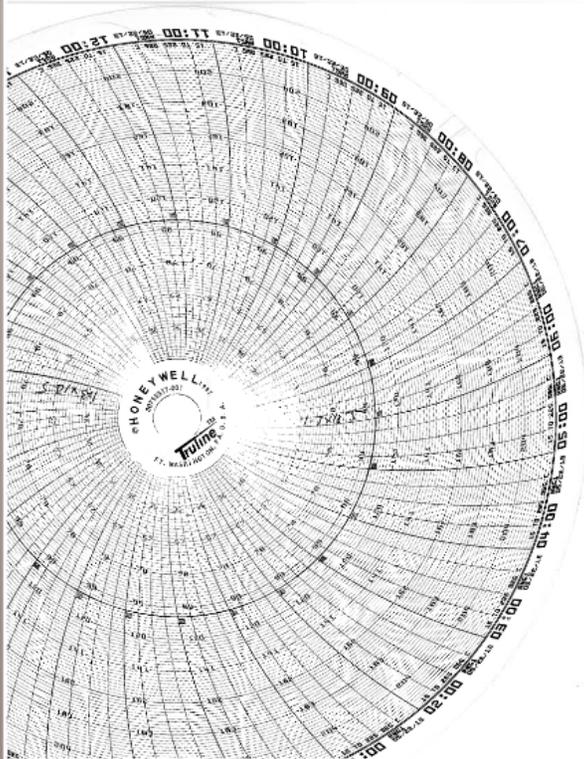
No damping term required if $EI(x,t)$ is used; however, EI_{max} and EI_{min} can be orders of magnitude apart and difficult to determine.

BAKEOUT

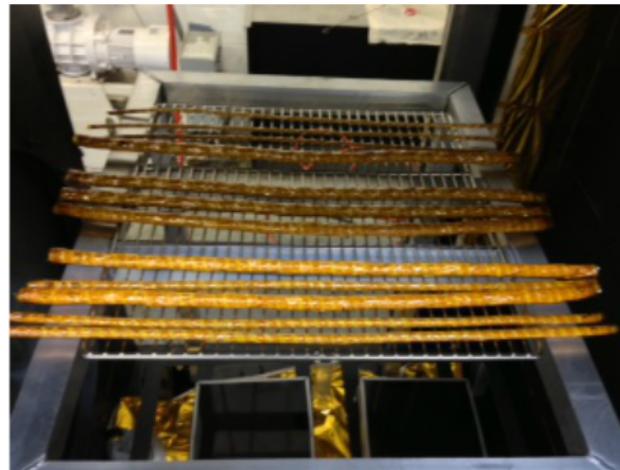
A thermal and vacuum treatment intended to expedite outgassing of volatile materials for cleansing purposes

Low Earth Orbit Bakeout:

72 hours at 105 C +/- 5C at pressure of less than 10^{-5} torr



Temperature Record



Cables On Bakeout Rack



Bakeout Chamber

OBJECTIVES

Thus, because cables make up a significant portion of space structures and affect the structural dynamics, determining the bending stiffness of space flight cables is necessary. Since bending stiffness may be affected by the bakeout procedure, the objectives of this study are to:

- Determine whether space flight cable stiffness is indeed affected by bakeout, as evidenced by changes in dynamic response
- Observe the effects of bakeout on space flight cables and compare the cables pre- and post-bakeout
- Quantify the dynamic response effects of low Earth orbit bakeout on a variety of cable geometries by determining the changes in natural frequency and/or damping

GROUND

Cables must be included in models of space structures

Cables change structure behavior

- Knowledge of structure behavior is necessary to understand of failure risk and control system development
- Tuning of space structure in orbit performed before cabling is completed

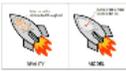
Accurate prediction of structural dynamics, including the impact of cable dynamics, is of interest to the satellite space community as it reduces program risk, allows more realistic requirements on vibration mitigation systems and assures that structural performance metrics can be met. ASRL



Cables must be included as structural mass with loading effects

Cables were originally modeled as springs

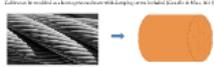
- Space flight cables were traditionally modeled as lumped mass
- Low mass orbit and industry facilities don't have lumped mass models and using models are no longer realistic as more is known about the problem
- No prediction would be given in orbit as cable resonances (SRP) and other sources do not excite latched cables



Determination of cable bending stiffness is necessary; bakeout may change cable stiffness

to be considered. It is important to understand the effects of cable dynamics on the overall system performance and to ensure that the cable response is accurately modeled in the ground and in-orbit simulations.

CABLE MODELING



- Cable properties:
 - Material
 - Length
 - Mass
 - Stiffness
 - Damping
- Beam properties:
 - EA
 - IC
 - IC2
- (= DAMPING TERMS)

Other: Density, Axial cross-sectional area, Moment of Inertia, Modulus of Elasticity, Damping, Torque

Bending Stiffness: EI, Modulus of Elasticity, Area moment of inertia

BENDING STIFFNESS

Cable bending stiffness depends on:

- The bulk modulus of elasticity of the cable construction material and the preparation method
- The diameter of the cable
- Dependence must be taken on small fluctuations in cable size (bakeout)
- Cable shape, length and arrangement
- Geometrical model
- Any preparation that affects any of the above, such as bakeout



It is important to note that the variation of cable diameter greatly influences the relationship between bending stiffness and diameter. The relationship is not linear and is highly sensitive to small variations in diameter.

BAKEOUT

A thermal and vacuum treatment intended to expedite outgassing of volatile materials for cleaning purposes. Low Earth Orbit Bakeout: 72 hours at 105 C +/- 5C at pressure of less than 10⁻⁵ torr



EXPERIMENTAL PROCEDURE

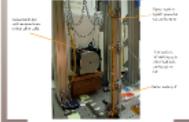
Several cables were tested to observe the overall dynamic behavior and develop the test set up. Cables were excited with a modal shaker and the dynamic response was measured with a laser vibrometer at the driving point. Factors affecting the cable response were investigated and a standard run was developed to ensure future cable tests will be comparable.

Cable type chosen



- 19x19 cables were chosen for this study because of their high strength and low mass. They are also easy to handle and have a long history of use in space applications.
- 7x7 cables were also considered but were rejected due to their higher mass and lower strength.
- 1x19 cables were also considered but were rejected due to their higher mass and lower strength.
- 1x7 cables were also considered but were rejected due to their higher mass and lower strength.

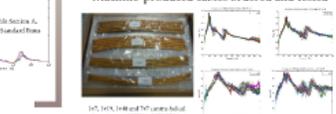
Test fixture designed



Standard run developed

- Cable attached to test fixture and placed in test chamber
- Temperature of test chamber set to 105 C +/- 5 C
- Pressure of test chamber set to 10⁻⁵ torr
- Response measured at driving point by laser vibrometer
- Excitation given at 10 Hz at other points
- 19x19 cable response
- Reduction in mass of 100 lbs
- Empirical 10 Hz drive
- The overall length of 19x19 cables are 26.5 lbs lighter mass above and below

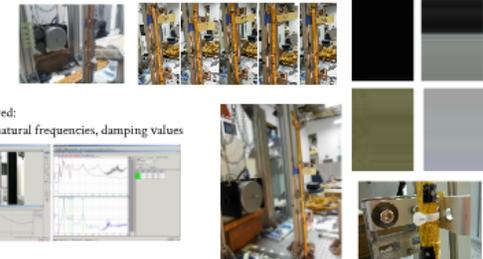
Machine-produced cables ordered and tested



Most reliable cables determined and baked out at 105C, 1E-5 torr for 72 hours, then re-tested



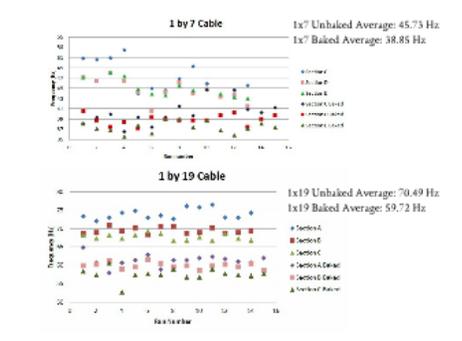
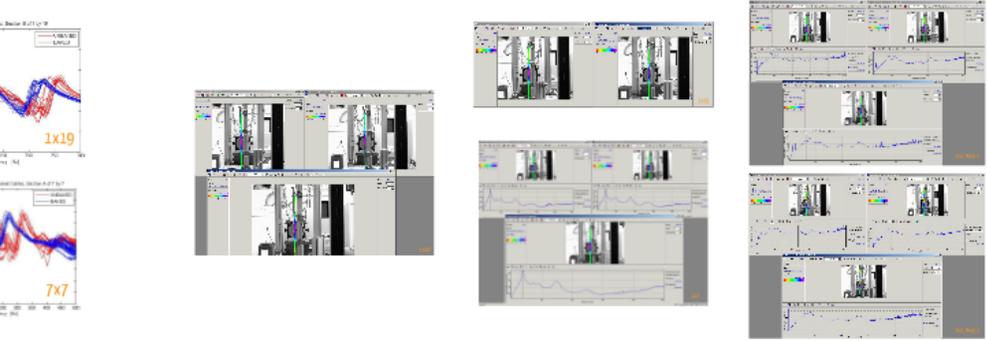
TEST SET UP DETAILS



Results compared: Mode shapes, natural frequencies, damping values



BAKED VERSUS BAKED



Baked out cables show decrease in natural frequency and increase in damping.

	LASER SCANS		ME SCOPE	
	First Frequency (Hz)	% Damping	First Frequency (Hz)	% Damping
1x7	41.25	3.45	61.3	3.45
Unbaked	39.44	4.25		
Baked			68.5	4.65
1x19			68.3	4.65
Unbaked	68.44	4.65		
Baked	57.5	5.5	57.6	5.5
7x7			108	6.87
Unbaked	118.1	6.6		
Baked	107.8	6.87		
1x48			85.5	8.45
Unbaked	81.38	8.45		
Baked	64.06	5.55	65.3	5.55

	% Difference Scan	% Difference Scope
1x7	7.05	7.02
1x19	17.37	17.34
1x48	9.12	8.85
7x7	24.42	27.93

CONCLUSIONS, CONTRIBUTIONS, AND FUTURE WORK

- No literature exists on the effect of bakeout treatment on cable stiffness; this work provides concrete data that bakeout does indeed change the dynamic response of space flight cables

ACKNOWLEDGEMENTS

Many thanks to the organizations and universities that have supported this research and provided equipment

Test fixture designed

Suspended shaker with tensioned wire to load cell on cable



Buffer section - tightly pinned at top and bottom

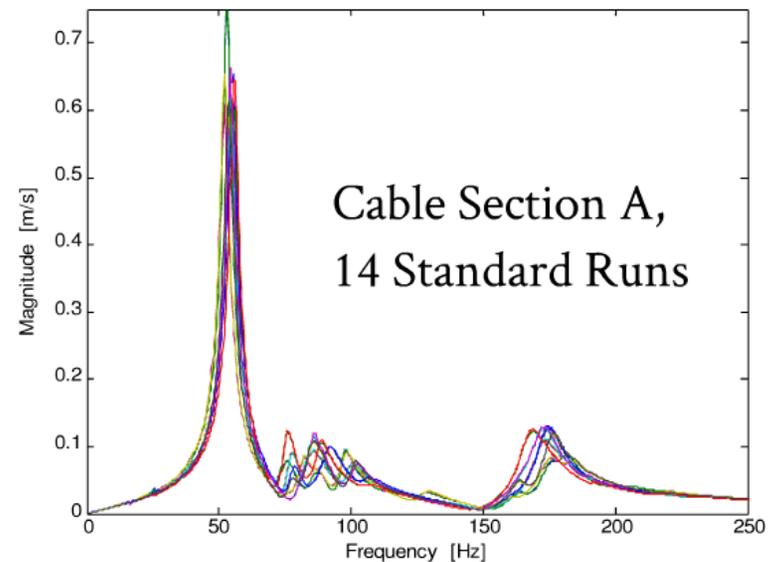
Test section, 10" with targets every half inch and target on DP

Buffer section, 8"

STANDARD RUN

Standard run developed

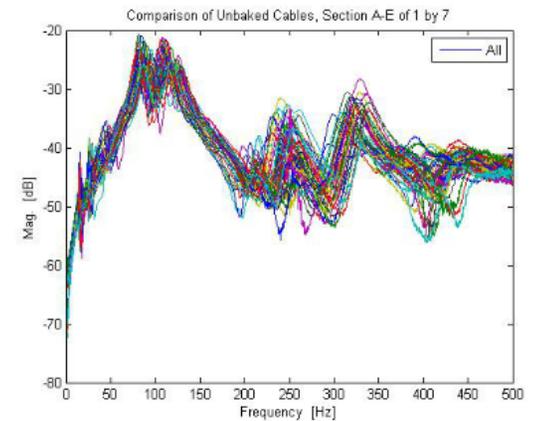
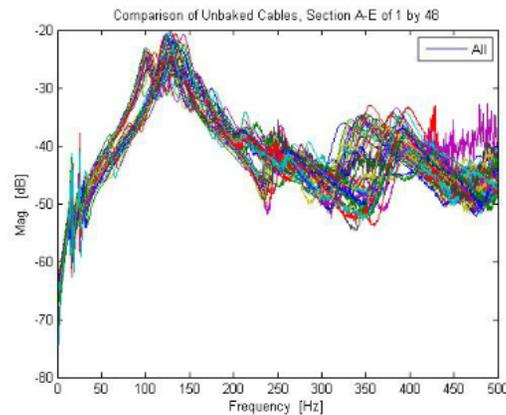
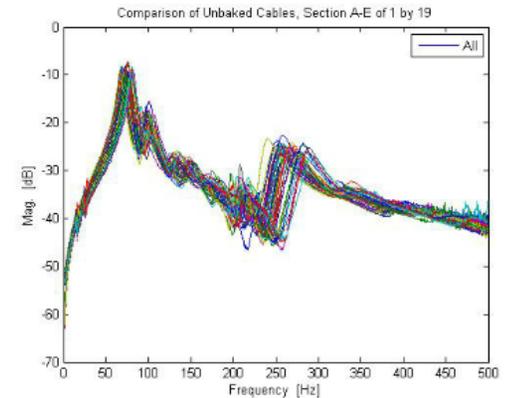
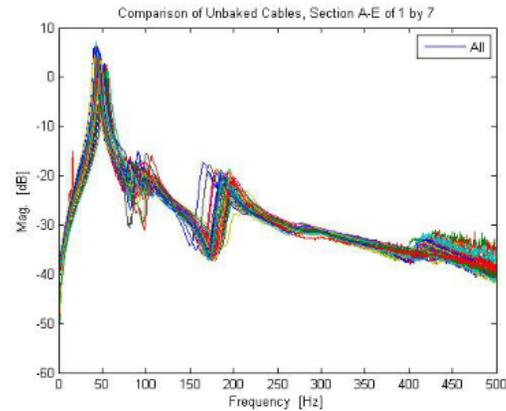
- Cable attached to test fixture with coil plane toward shaker
- TyRap TY525M cable ties with setting 5 on cable tie gun
- Static displacement of cable due to string less than 1 mm
- White noise (random) excitation at 0.3 volts, 0-2000 Hz
- Response measured at driving point by laser vibrometer
- Driving point at 8.5 cm above lower tie
- 2 lbs (8.9 N) cable tension
- Excitation actuated by tensioned 24 cm string
- Low pass 5 kHz filter
- Frequency of interest 0 - 250 Hz
- Test section length of 25.4 cm with two 20.3 cm buffer zones above and below



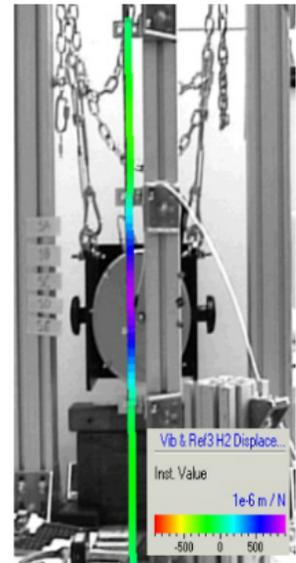
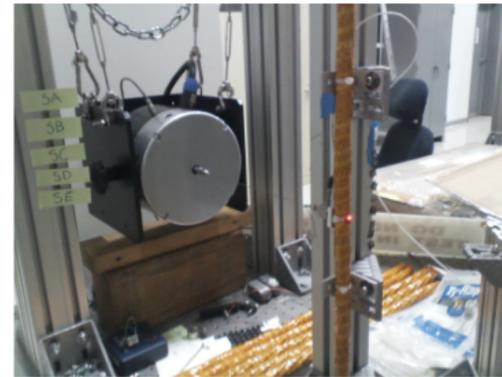
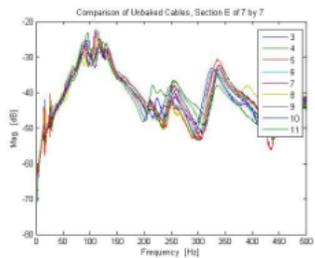
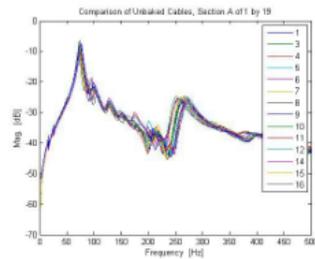
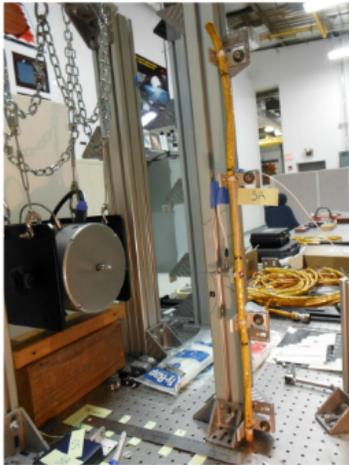
Machine-produced cables ordered and tested



1x7, 1x19, 1x48 and 7x7 contra-helical configurations of M27500-26TG2T14 wire

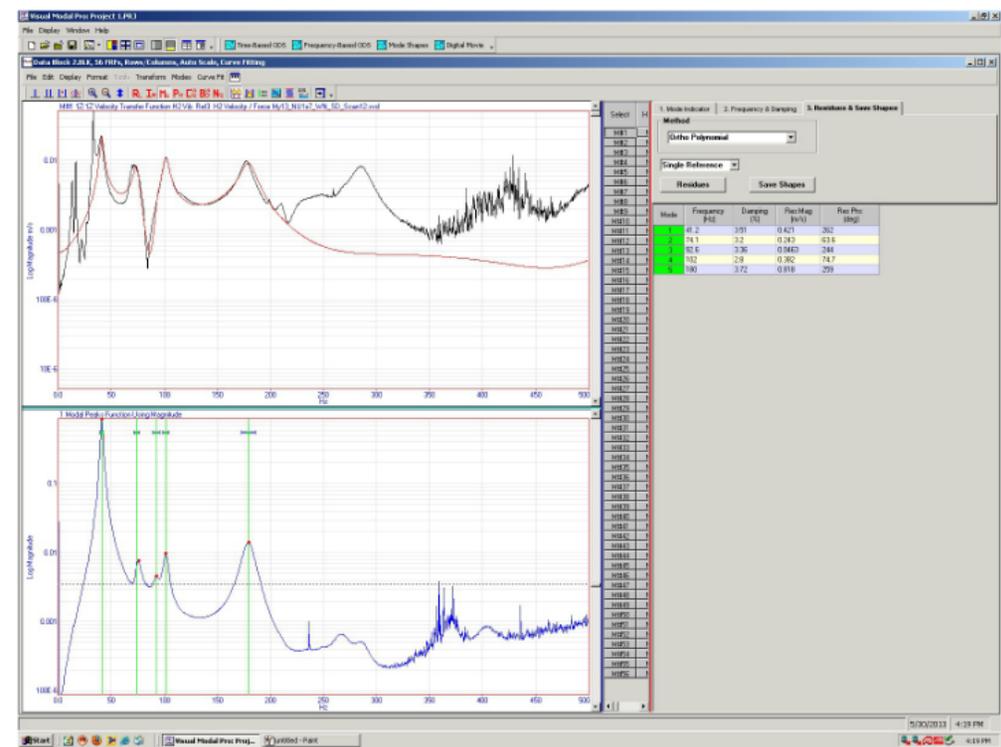
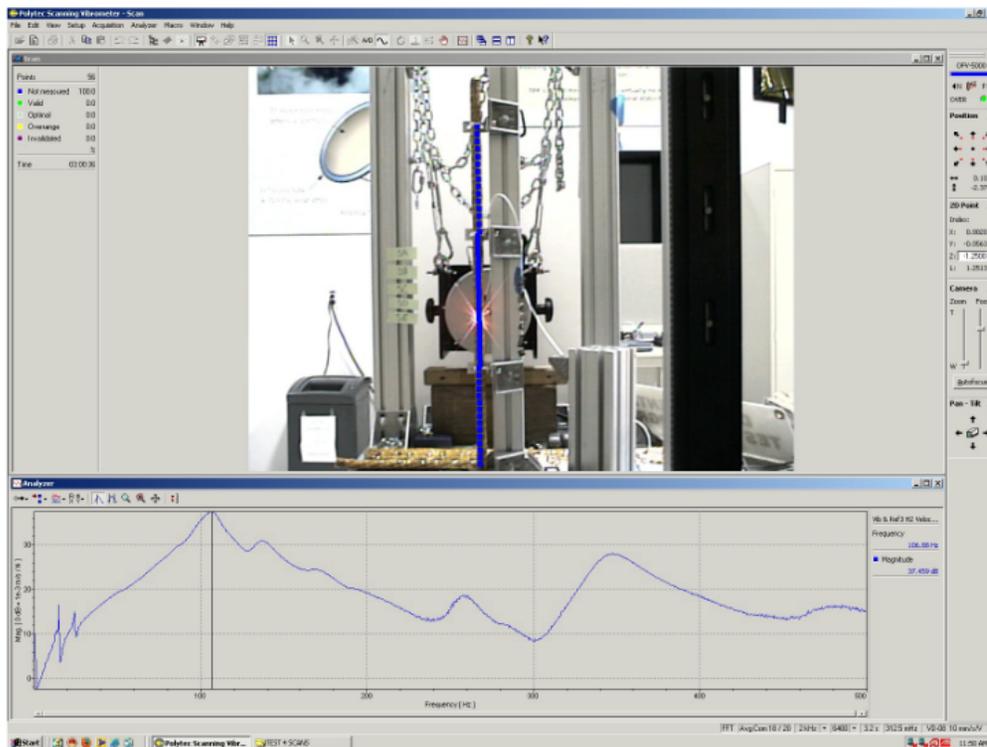


Most reliable cables determined and baked out at 105C, 1E-5 torr for 72 hours, then re-tested





Results compared: Mode shapes, natural frequencies, damping values



Cable selection criteria:

- Cost and size
- Material
- Number of wires
- Type and thickness of insulation and shielding
- Low geometry
- Low weight and diameter
- Low and low-temperature

Cable bonding criteria:

- Material of cable

Thermal and vacuum treatment intended to expose outgassing of volatile materials for cleaning purposes

Low Earth Orbit Bakeout:

- 72 hours at 105°C, 1E-5 Torr, at pressure of less than 1E-5 Torr

Results:

- Amplitude of cable response
- Frequency of cable response
- Damping of cable response

EXPERIMENTAL PROCEDURE

Several cables were tested to observe the overall dynamic behavior and develop the test set up. Cables were excited with a modal shaker and the dynamic response was measured with a laser vibrometer at the driving point. Factors affecting the cable response were investigated and a standard run was developed to ensure future cable tests will be comparable.

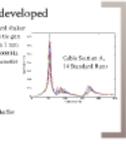
Cable type chosen



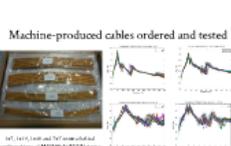
Test fixture designed



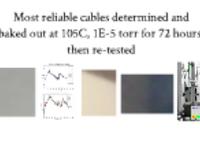
Standard run developed



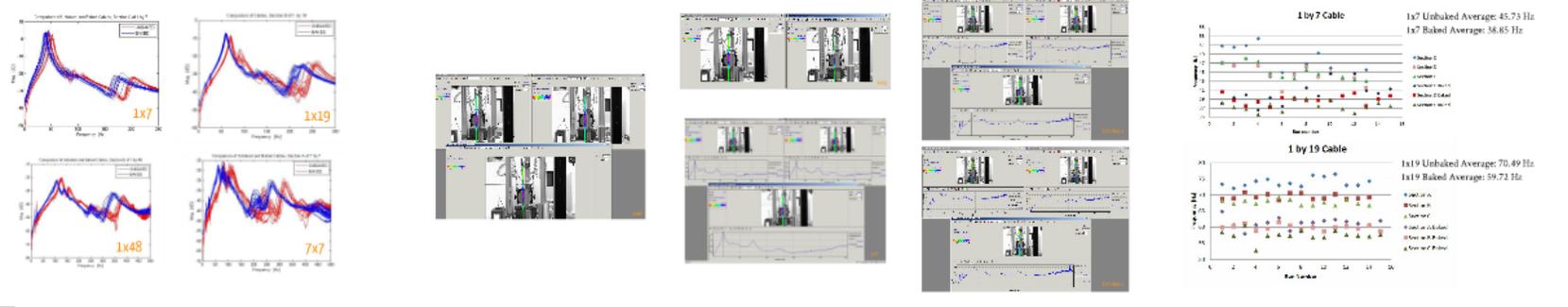
Machine-produced cables ordered and tested



Most reliable cables determined and baked out at 105C, 1E-5 torr for 72 hours, then re-tested



RESULTS: UNBAKED VERSUS BAKED



Baked out cables show decrease in natural frequency and increase in damping.

	LASER SCANS		MF SCOPE	
	First Frequency [Hz]	First Frequency [Hz]	% Damping	% Damping
1x7	Unbaked	45.73	45.3	3.49
	Baked	38.85	38.5	6.25
1x19	Unbaked	68.44	68.3	4.89
	Baked	57.9	57.4	5.3
1x48	Unbaked	118.1	118	4.4
	Baked	107.8	106	6.87
7x7	Unbaked	61.08	61.3	6.05
	Baked	64.06	61.3	5.55

	% Difference Scan	% Difference Scope
1x7	7.05	7.02
1x19	17.37	17.34
1x48	9.12	8.85
7x7	24.42	27.93

CONCLUSIONS, CONTRIBUTIONS, AND FUTURE WORK

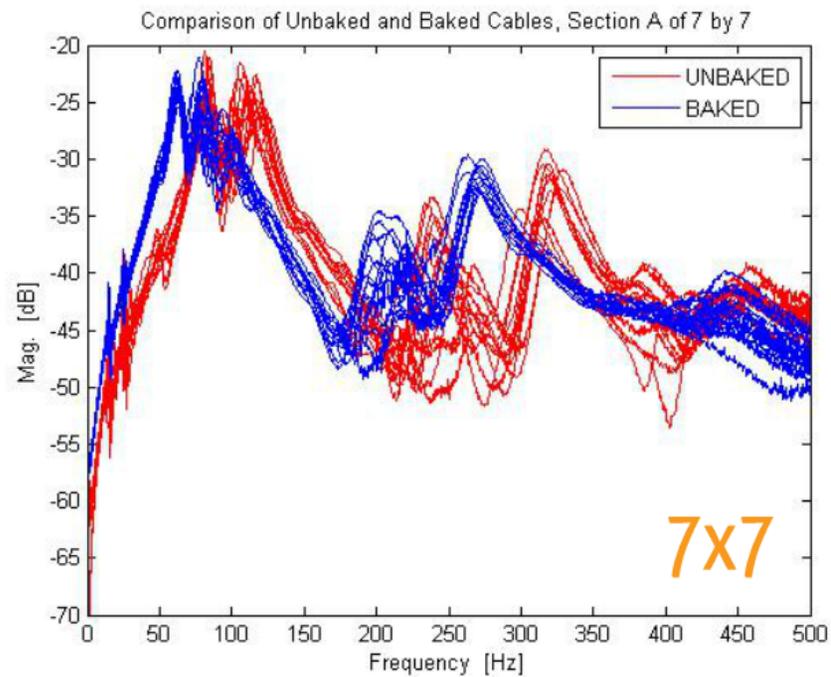
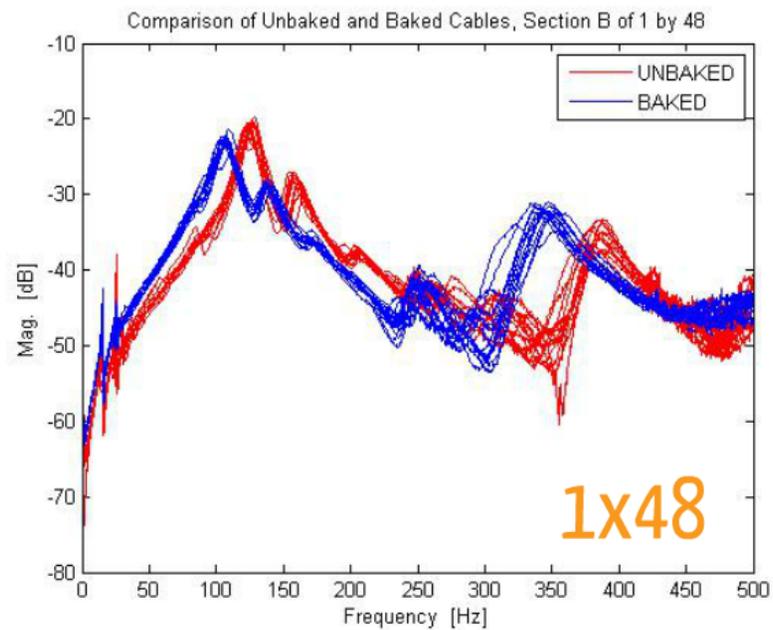
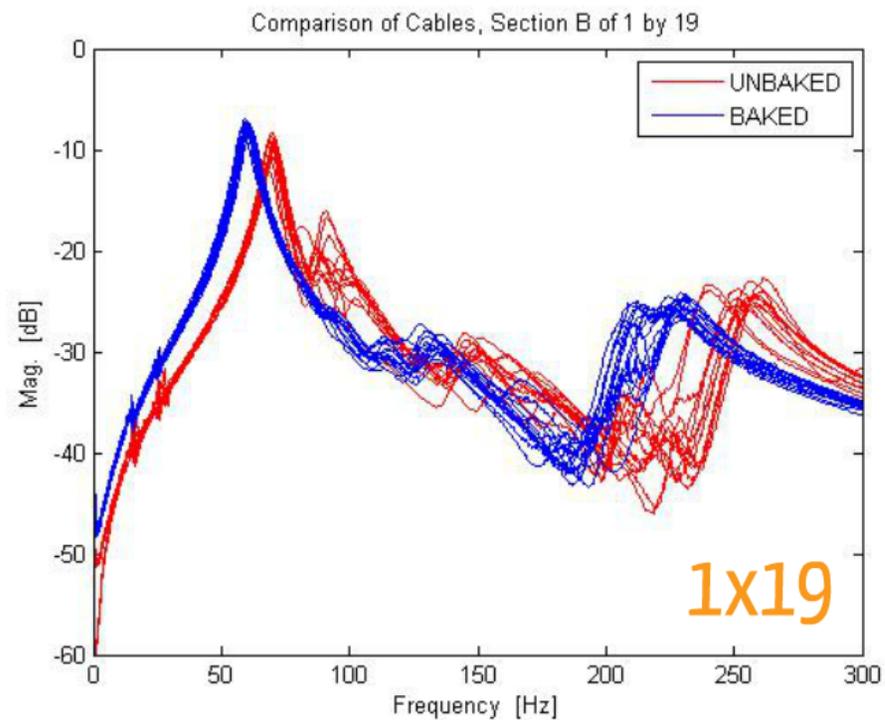
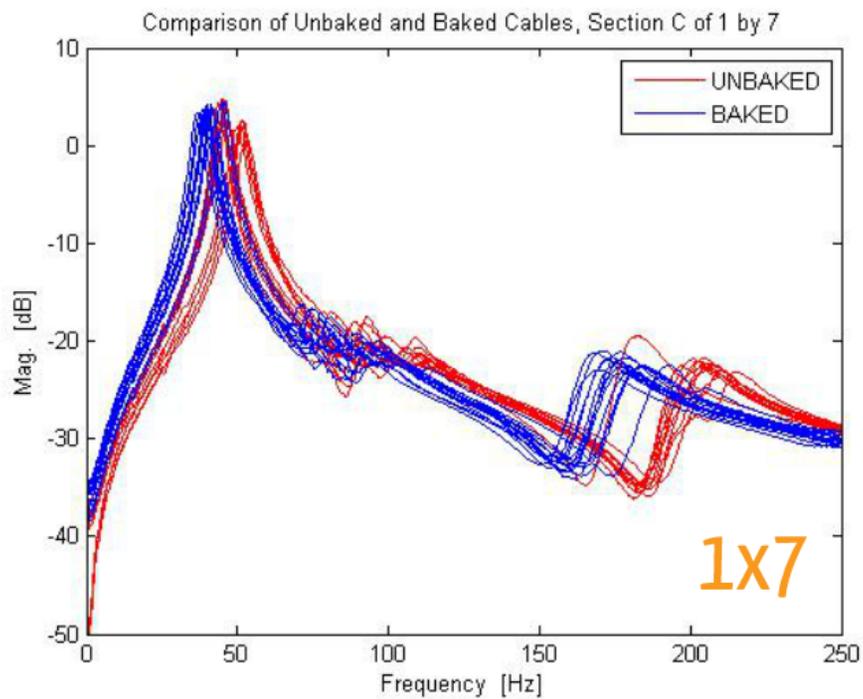
- No literature exists on the effect of bakeout treatment on cable stiffness; this work provides concrete data that bakeout does indeed change the dynamic response of space flight cables
 - After a low Earth orbit bakeout, the first and second natural frequencies decreased for all cables between 7 and 28%.
 - After a low Earth orbit bakeout, damping values increased for all single-strand cables. It is clear that this combination of wire type and bakeout results in a significant reduction in bending stiffness.
 - Current cable frequency data refers to unbaked cables, which may have a higher frequency than flight-ready cables; spacecraft designers should keep this in mind if using currently published data.
- Future work:**
- Different bakeout treatments may have different results
 - Different wire coating may have different results; the presence of plasticizers that would outgas would likely cause stiffening after bakeout
 - More extensive chemical research could be done to identify the softening mechanisms due to bakeout treatment

ACKNOWLEDGMENTS

Many thanks to the following individuals who have supported this project:

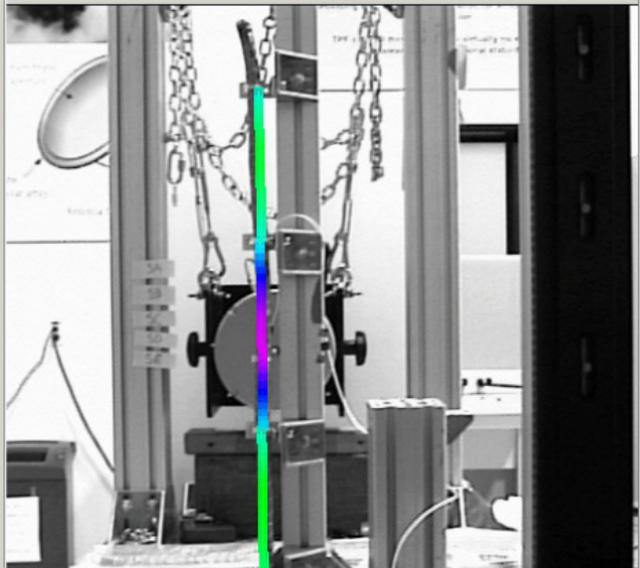
- NASA Space Fellowship
- Virginia Space Foundation
- AIAA Student Paper Competition
- Jet Propulsion Laboratory
- Virginia Tech University
- Southern Cross University

Advisor: Dr. Daniel J. ...
Mentor: Dr. Greg ...



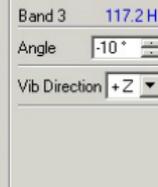
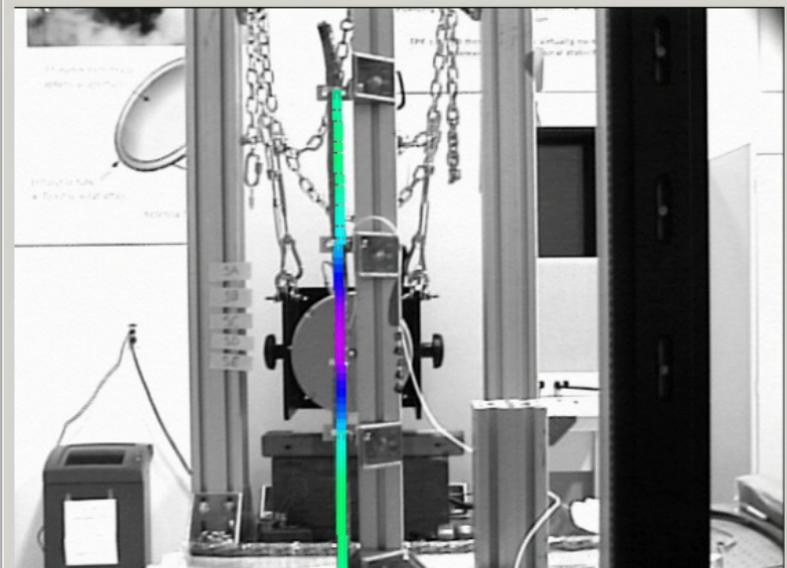
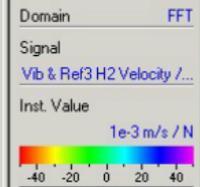
My9_NU1x48_WN_SE_Scan1.svd

3D **2 = 118.1 Hz** **Angle -30°** **Vib Direction +Z**



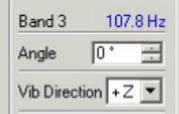
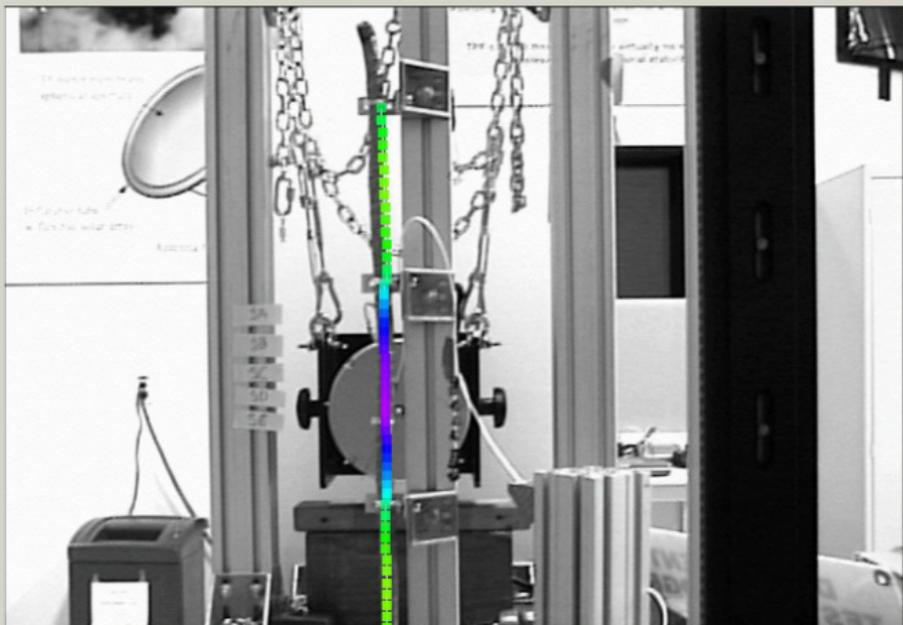
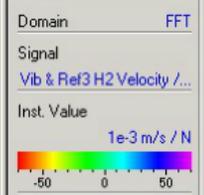
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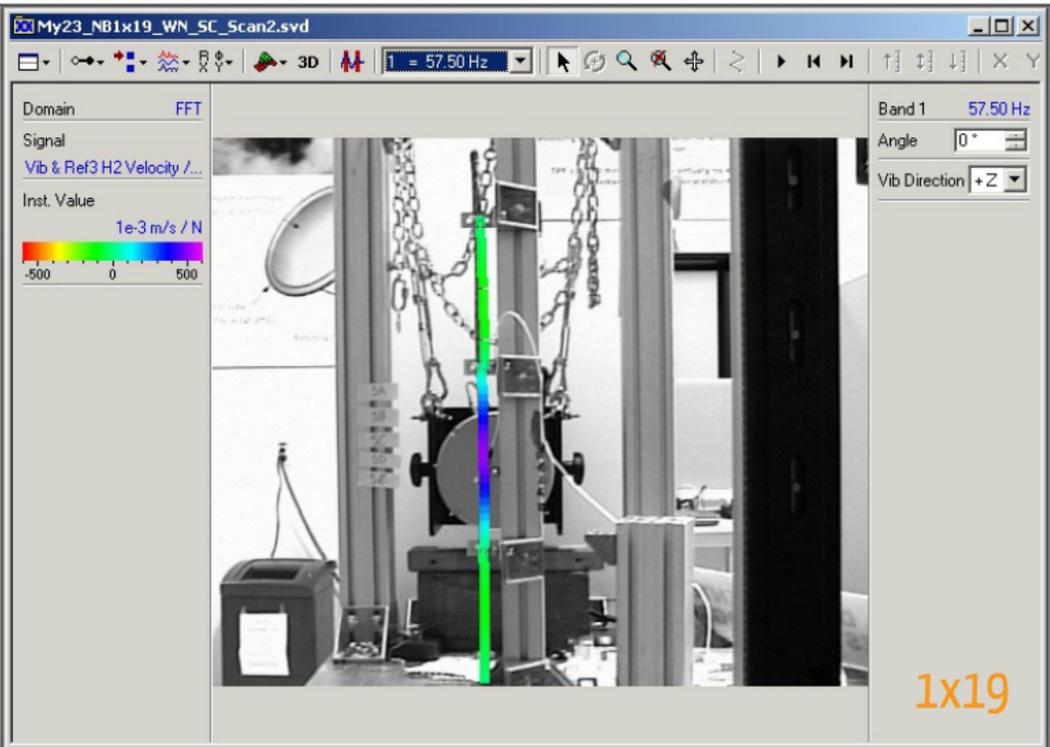
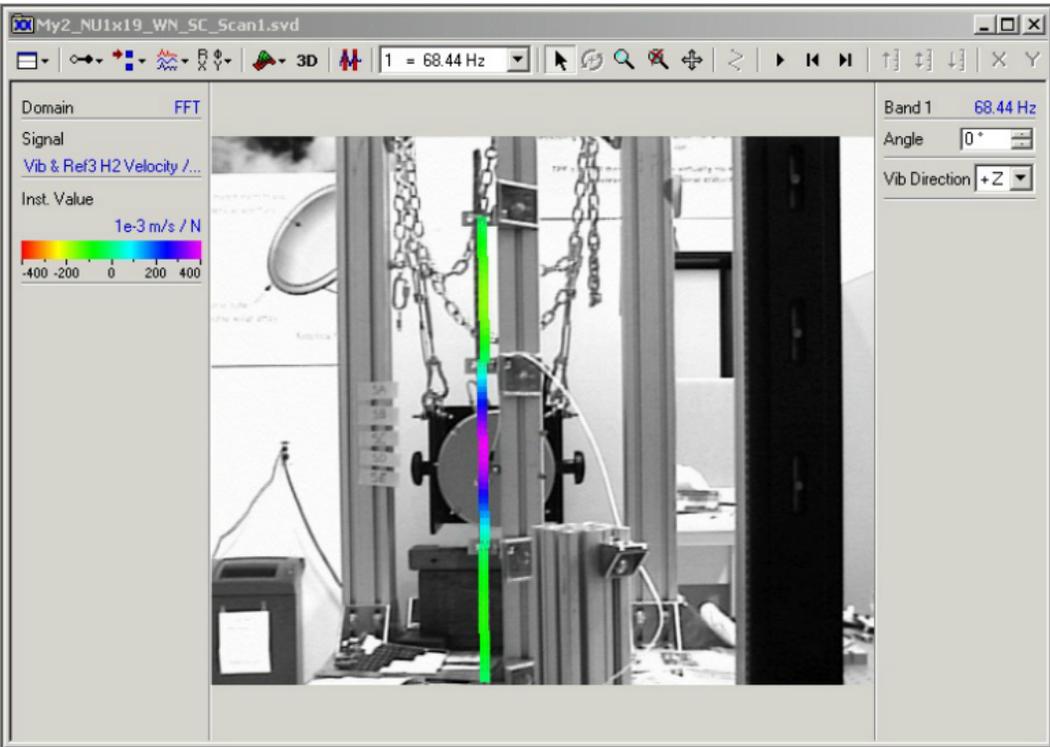
3D **3 = 117.2 Hz** **Angle -10°** **Vib Direction +Z**



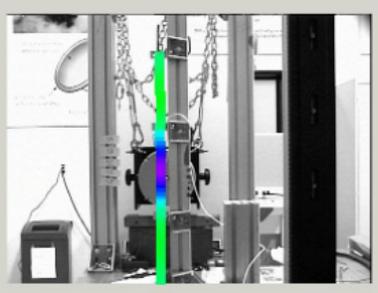
My24_NB1x48_WN_SE_Scan5.svd

3D **3 = 107.8 Hz** **Angle 0°** **Vib Direction +Z**



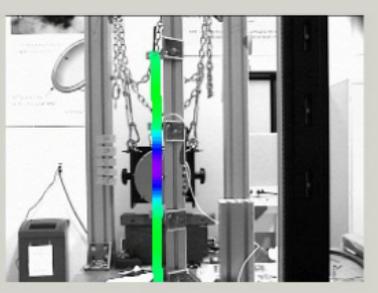


Band 1 41.25 Hz
 Angle 0°
 Vib Direction +Z

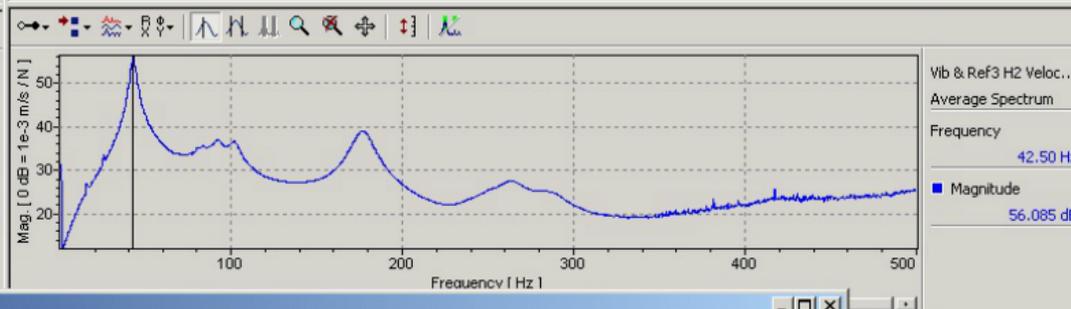
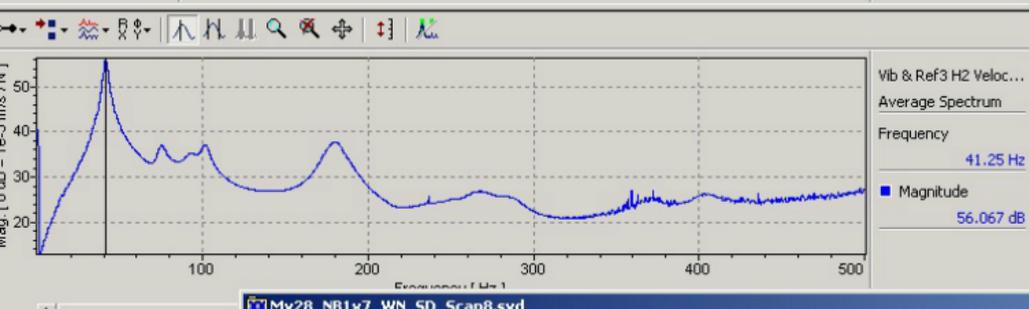


Domain FFT
 Signal Vib & Ref3 H2 Velocity /...
 Inst. Value m/s / N

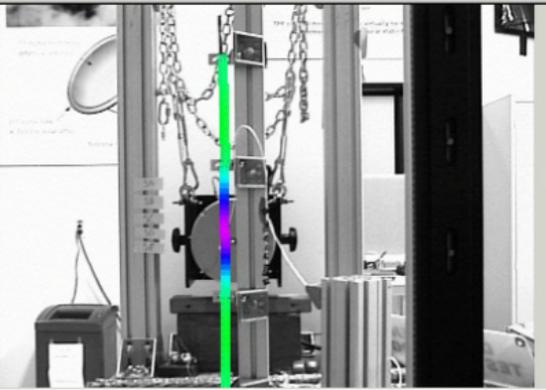
Band 1 42.50 Hz
 Angle 0°
 Vib Direction +Z



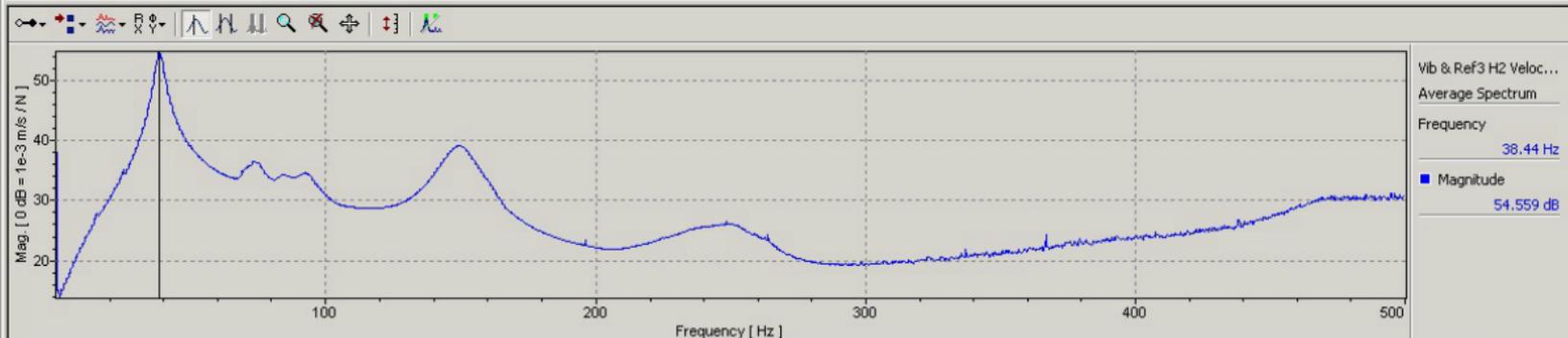
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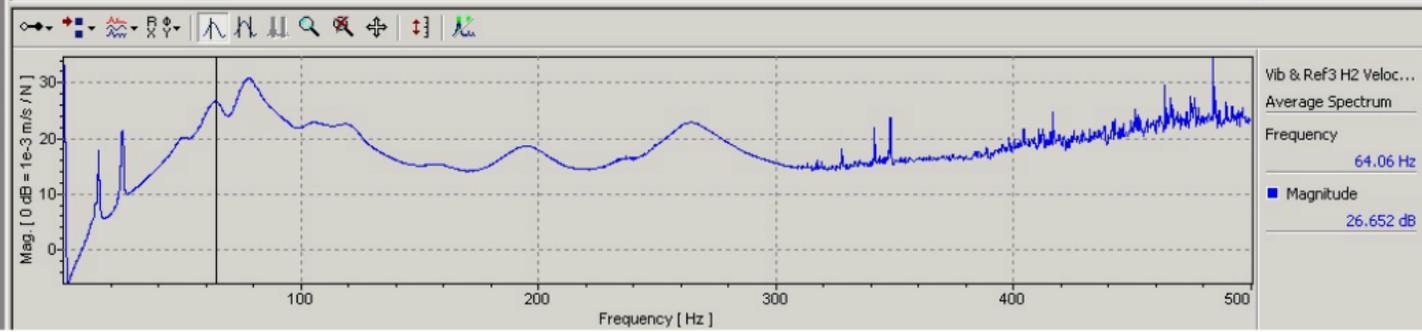
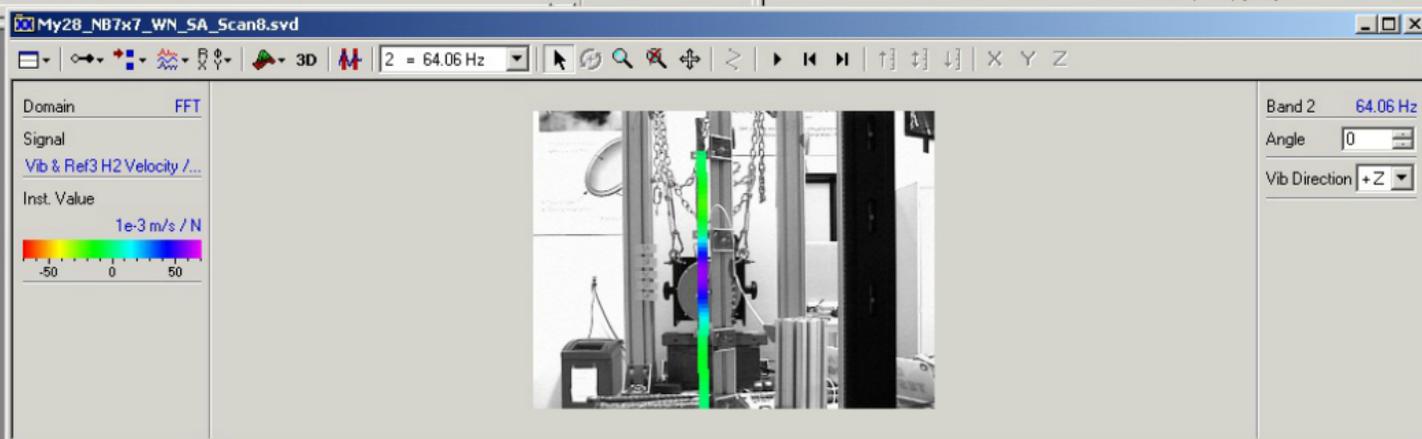
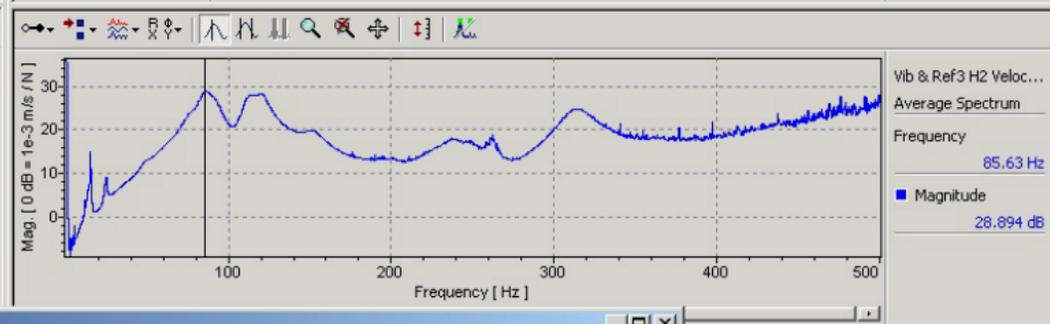
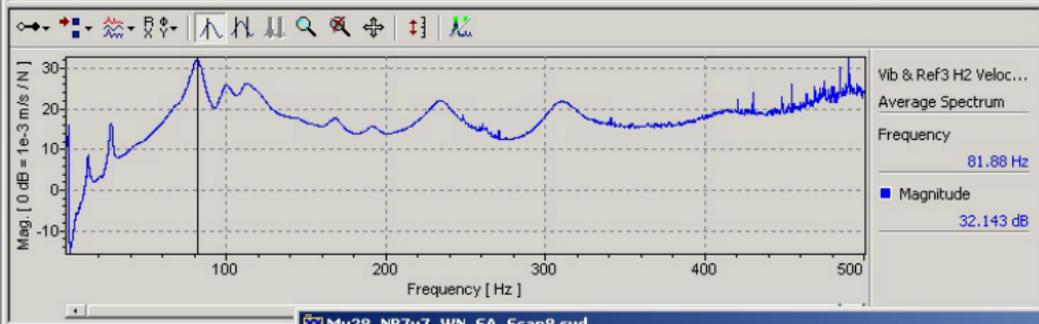
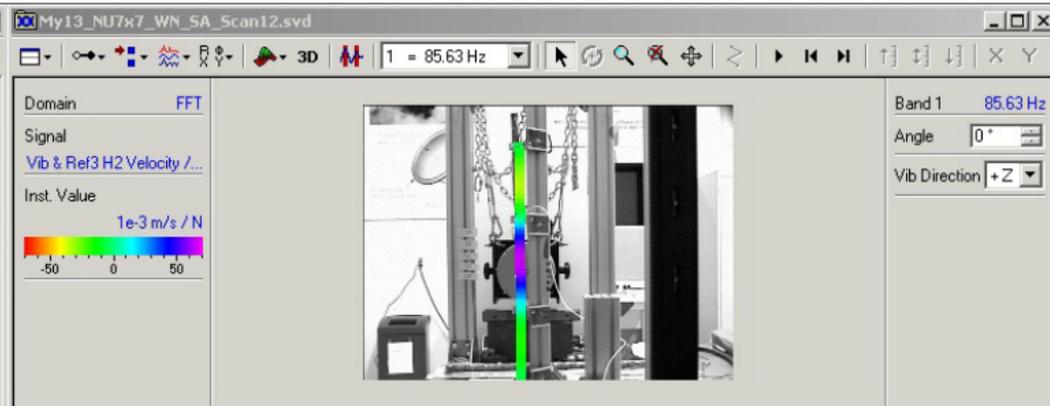
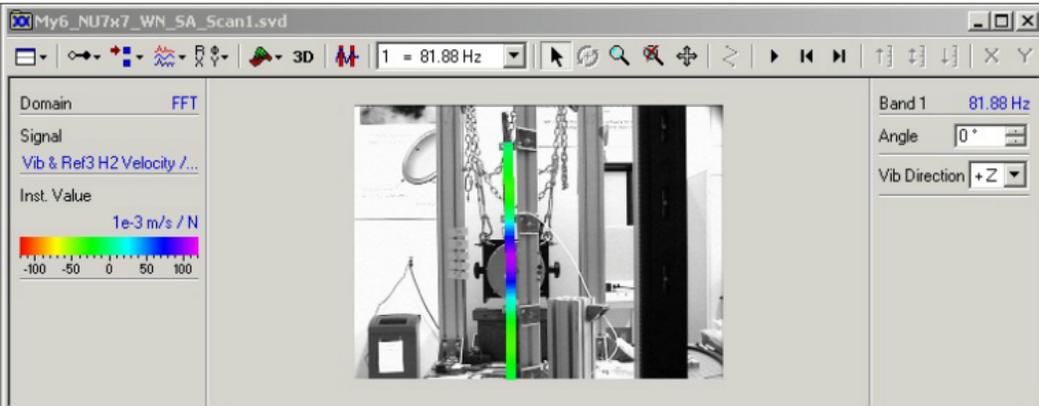
Band 1 38.44 Hz
 Angle 0°
 Vib Direction +Z



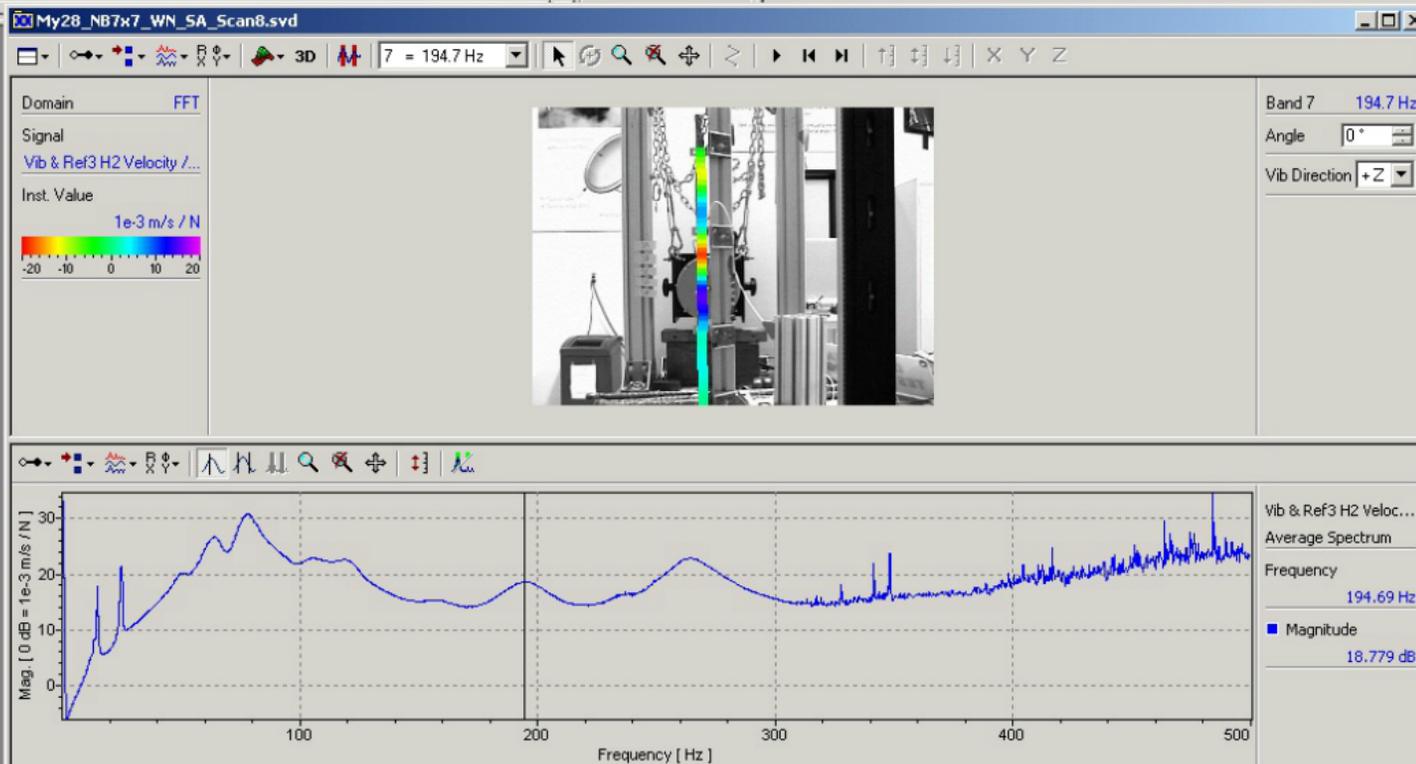
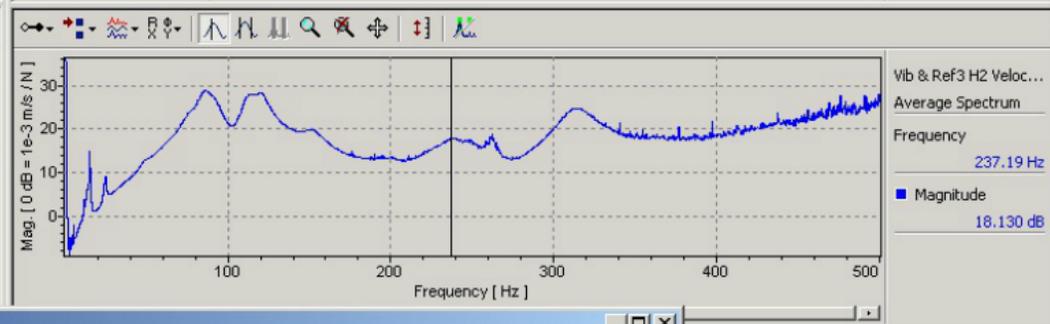
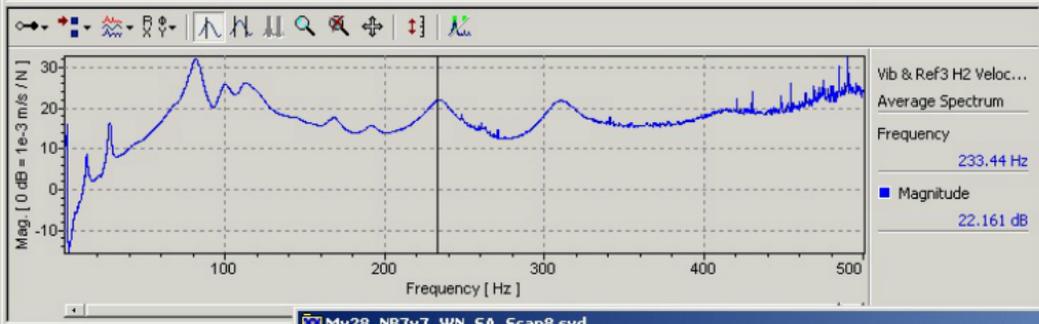
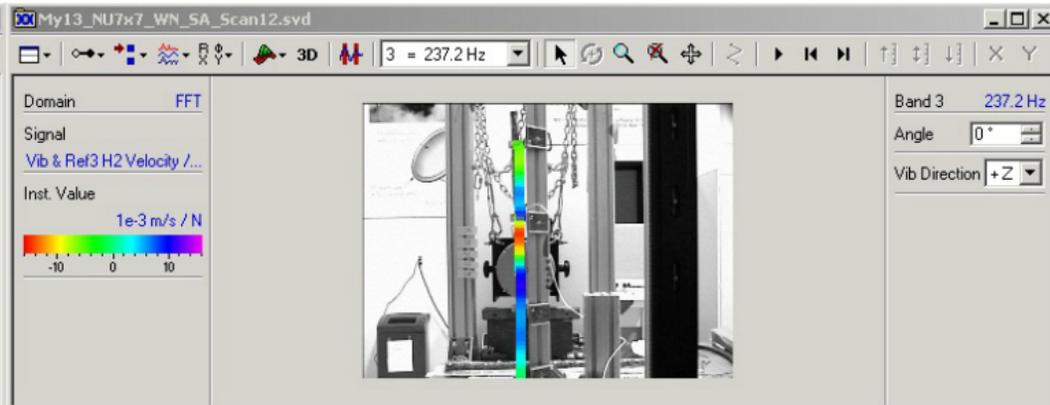
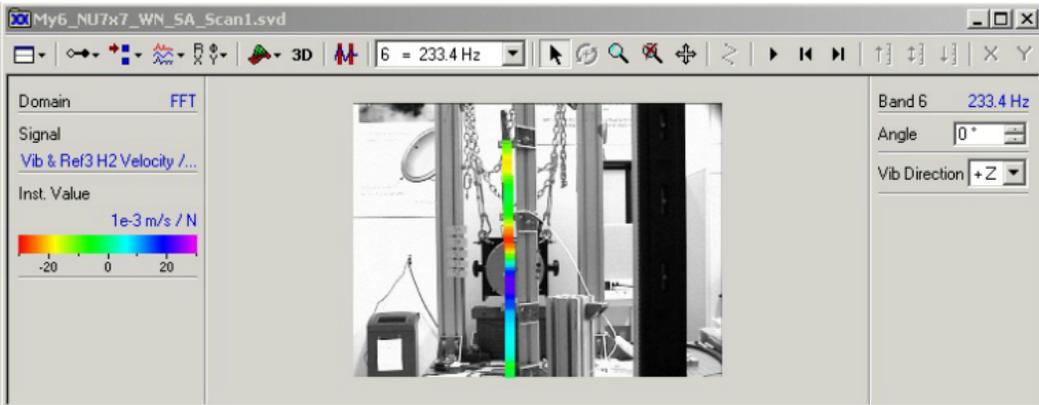
Domain FFT
 Signal Vib & Ref3 H2 Velocity /...
 Inst. Value m/s / N



1x7



7x7, Mode 1

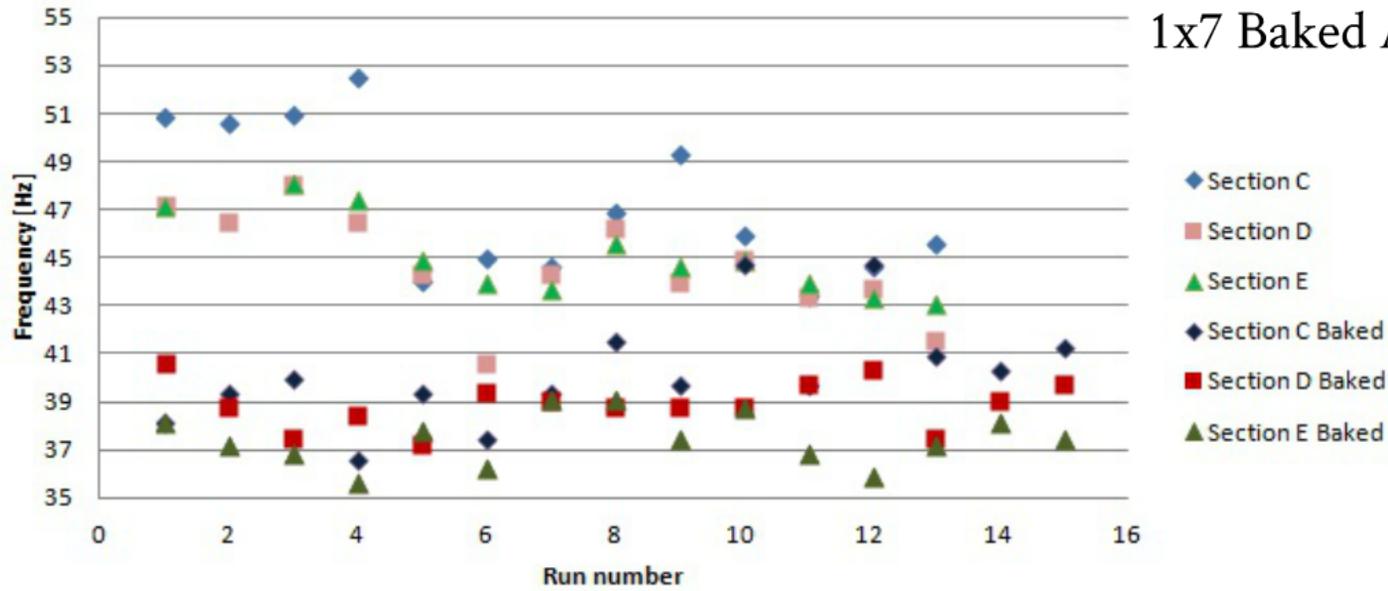


7x7, Mode 2

1 by 7 Cable

1x7 Unbaked Average: 45.73 Hz

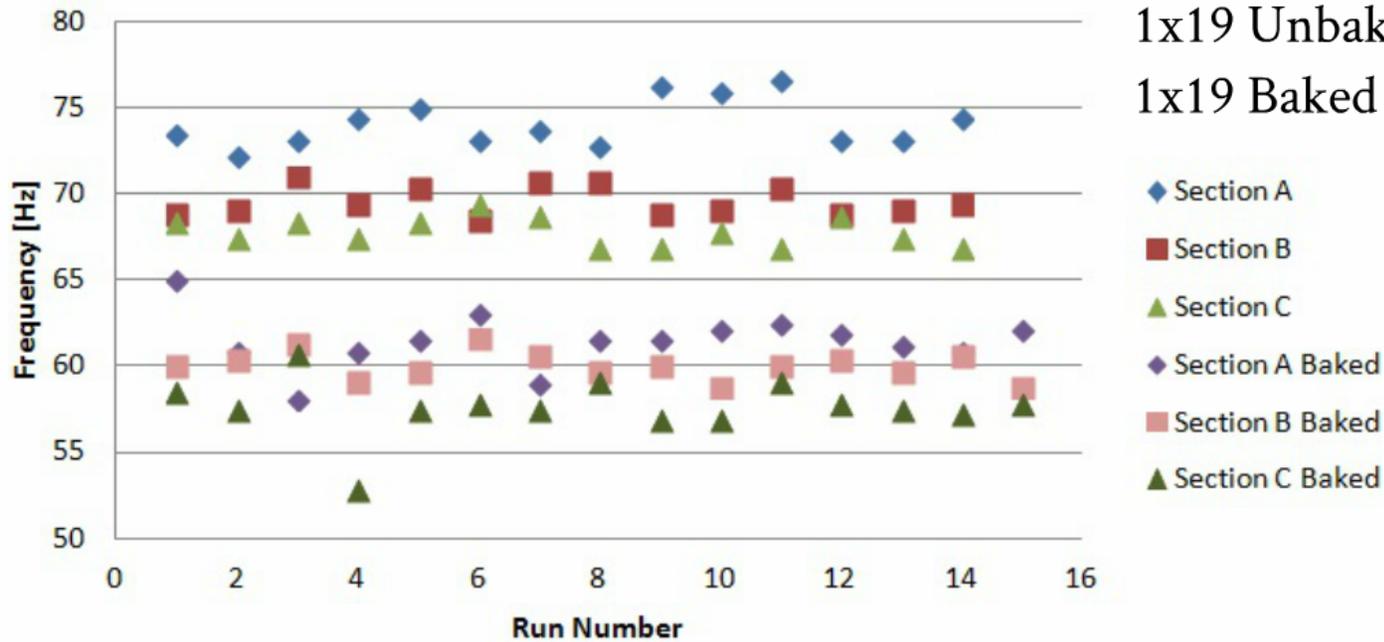
1x7 Baked Average: 38.85 Hz



1 by 19 Cable

1x19 Unbaked Average: 70.49 Hz

1x19 Baked Average: 59.72 Hz



Baked out cables show decrease in natural frequency and increase in damping.

	LASER SCANS	ME SCOPE	
1x7	First Frequency [Hz]	First Frequency [Hz]	% Damping
Unbaked	41.25	41.3	3.49
Baked	38.44	38.5	4.25

1x19

Unbaked	68.44	68.3	4.65
Baked	57.5	57.4	5.5

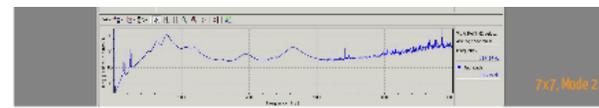
1x48

Unbaked	118.1	118	4.6
Baked	107.8	108	6.87

7x7

Unbaked	81.88	86.5	8.45
Baked	64.06	65.3	5.55

	% Difference Scan	% Difference Scope
1x7	7.05	7.02
1x19	17.37	17.34
1x48	9.12	8.85
7x7	24.42	27.93



CONCLUSIONS, CONTRIBUTIONS, AND FUTURE WORK

- No literature exists on the effect of bakeout treatment on cable stiffness;
this work provides concrete data that bakeout does indeed change the dynamic response of space flight cables
- After a low Earth orbit bakeout, the first and second natural frequencies decreased for all cables between 7 and 28%
- After a low Earth orbit bakeout, damping values increased for all single-strand cables

It is clear that this combination of wire type and bakeout results in a significant reduction in bending stiffness.

- Current cable frequency data refers to unbaked cables, which may have a higher frequency than flight-ready cables;
spacecraft designers should keep this in mind if using currently published data

Future work:

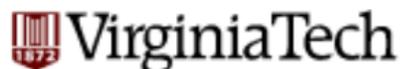
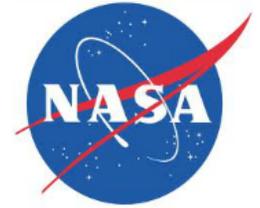
- Different bakeout treatments may have different results
- Different wire coating may have different results; the presence of plasticizers that would outgas would likely cause stiffening after bakeout
- More extensive chemical research could be done to identify the softening mechanisms due to bakeout treatment

Many thanks to the organizations and universities that have supported this research and provided equipment:

- NASA Space Technology Research Fellowship Program
- Virginia Space Grant Consortium
- Air Force Office of Scientific Research
- AIAA San Gabriel Valley Chapter
- Jet Propulsion Laboratory
- Virginia Tech
- University of Michigan
- Southern California Braiding Co.

Advisor: Dr. Daniel Inman, Univ. of Michigan

Mentor: Dr. Greg Agnes, JPL



Effects of Bakeout on Space Flight Cable Stiffness

SEM Student Paper Competition ~ June 3, 2013

Kaitlin Spak

MOTIVATION

Spacecraft cables are critical components of the spacecraft. They are used to transmit data, power, and control signals. The cables must be able to withstand the harsh environment of space, including vacuum, temperature extremes, and radiation. The cables must also be able to maintain their mechanical properties over the long life of the spacecraft.

Current cable designs are based on a variety of materials and construction techniques. However, the effects of bakeout on cable stiffness are not well understood. This research aims to determine the effects of bakeout on cable stiffness and to develop a model for predicting the effects of bakeout on cable stiffness.

Current cable designs are based on a variety of materials and construction techniques. However, the effects of bakeout on cable stiffness are not well understood. This research aims to determine the effects of bakeout on cable stiffness and to develop a model for predicting the effects of bakeout on cable stiffness.

OBJECTIVES

- Determine whether space flight cable stiffness is indeed affected by bakeout, as evidenced by changes in dynamic response
- Observe the effects of bakeout on space flight cables and compare the cables pre- and post-bakeout
- Quantify the dynamic response effects of low Earth orbit bakeout on a set of cables generated for determining the design to natural frequency and for damping

BACKGROUND

CABLE CONSTRUCTION
Cables are constructed from a variety of materials and construction techniques. The cables are typically made of a central core surrounded by a braided shield. The cables are then coated with a protective layer.

CABLE MODELING
Cables are modeled using finite element analysis (FEA). The cables are discretized into a series of elements, and the dynamic response of the cables is simulated.

BENDING STIFFNESS
Bending stiffness is a measure of a cable's resistance to bending. It is determined by the cable's material properties and its cross-sectional geometry.

BAKEOUT
Bakeout is a process used to remove volatile contaminants from a cable. It involves heating the cable to a high temperature for a period of time.

EXPERIMENTAL PROCEDURE

Several cables were tested to observe the overall dynamic behavior and develop the test set up. Cables were excited with a modal shaker and the dynamic response was measured with a laser vibrometer at the driving point. Factors affecting the cable response were investigated and a standard run was developed to ensure future cable tests will be comparable.

Cable type chosen
The cables chosen for testing were 1x17, 1x19, 1x18, and 7x7.

Test fixture designed
A test fixture was designed to hold the cables in a fixed position during testing.

Standard run developed
A standard run was developed to ensure future cable tests will be comparable.

Machine-produced cables undared and tested
Machine-produced cables were undared and tested to compare their dynamic response to that of the hand-made cables.

Most reliable cables determined and baked out at 105°C (E-5 torr) for 72 hours, then re-tested
The most reliable cables were determined and baked out at 105°C (E-5 torr) for 72 hours, then re-tested.

Results compared:
Mode shapes, natural frequencies, damping values

RESULTS: UNBAKED VERSUS BAKED

1x17 Unbaked Average: 45.75 Hz
1x17 Baked Average: 34.85 Hz

1x19 Unbaked Average: 76.49 Hz
1x19 Baked Average: 59.72 Hz

Cable	1x17 Cables		1x19 Cables	
	Unbaked	Baked	Unbaked	Baked
1x17	45.75	34.85	76.49	59.72
1x19	76.49	59.72	76.49	59.72

CONCLUSIONS, CONTRIBUTIONS, AND FUTURE WORK

- No literature exists on the effect of bakeout treatment on cable stiffness. This work provides concrete data that bakeout does indeed change the dynamic response of space flight cables.
- After a low Earth orbit bakeout, the first and second natural frequencies decreased for all cables between 7 and 28%.
- After a low Earth orbit bakeout, damping values increased for all single-strand cables.
- It is clear that this combination of wire type and bakeout results in a significant reduction in bending stiffness.
- Current cable frequency data refers to unbaked cables, which may have a higher frequency than flight-ready cables; spacecraft designers should keep this in mind if using currently published data.
- Future Work:**
 - Different bakeout treatments may have different results.
 - Different wire coating may have different results; the presence of plasticizers that would outgas would likely cause stiffening after bakeout.
 - More extensive chemical research could be done to identify the softening mechanisms due to bakeout treatment.

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