APPLYING FIBER SUPPORT TECHNOLOGY TO SMALL SATELLITE SYSTEMS

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Abstract

Cryogenically cooled components in infrared instruments designed by Utah State University's Space Dynamics Laboratory traditionally have been mounted on glass-epoxy composite (G-10) cylinders for thermal isolation. Ensuring adequate mechanical stiffness to withstand typical launch loads often compromises the desired thermal isolation and conduction parasitic heat loads become a concern. Beginning with a senior design project in the Mechanical and Aerospace Engineering Department, a new approach to rigidly supporting cold components using high performance fibers in tension was initiated. The development effort included consideration of several candidate fibers for tensile strength, shear strength, creep, and thermal conductivity as well as a technique for attaching and tensioning the support strands.

A support system designed, fabricated and tested for application on the SABER instrument utilizes strands of Kevlar 49 in a bicycle-wheel-spoke like arrangement to support a focal plane assembly (FPA) cooled by a miniature pulse tube refrigerator. The first resonant frequency of the Kevlar supported assembly has been measured to be greater than 600 Hz in all axes. This compares with typical values of 50 to 70 Hz for a similar assembly supported by concentric G-10 cylinders. In addition to an order of magnitude increase in the mechanical stiffness, the Kevlar system reduced parasitic conduction heat loads by almost two orders of magnitude. Calculated conduction loads through the Kevlar strands total less than 1 mW as compared to 85 mW for the G-10 supports. This dramatic reduction brought total parasitic heat loads to within the limited cooling capacity of the miniature refrigerator and made possible the SABER instrument with its very stringent power and mass constraints. Further applications for this technology are currently being designed.

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Nomenclature

FIST	Fiber Support Technology
MLI	Multi-Layer Insulation
MTS	Mechanical Testing System
SDL	Space Dynamics Laboratory
SABER	Sounding of the Atmosphere using Broadband Emission Radiometry
USU	Utah State University
FPA	Focal Plane Assembly
MAE	Mechanical and Aerospace Engineering
A	Area
d	Diameter
E	Modulus of Elasticity
F	Force
k	Thermal Conductivity
K	Dynamic Spring Constant
L	Length
q	Heat load
e	Strain
s	Stress
w	Natural Circular Frequency

I. Introduction

A major challenge faced by those developing cryogenically cooled components for space applications is to provide both adequate mechanical support and thermal isolation. Achieving the thermal isolation objective is often in direct conflict with the mechanical support requirements. Precisely locating and rigidly supporting cooled components under harsh dynamic conditions, such as those experienced by a rocket ride into space, from a mechanical point of view requires very massive and strong support structures. From a thermal stand point, the structure should be small with minimal cross-sectional areas to reduce the parasitic heat transfer.

Traditionally, cold components developed by Utah State University/Space Dynamics Laboratory (USU/SDL) have been supported by concentric composite G-10 cylinders(See Figure 1).

This approach has two limitations that are becoming more serious in the new "smaller, faster, cheaper" environment of the 90's.

The first resonant frequency of these types of support systems, depicted in Figure 1, is roughly 60 Hertz. Higher values are desirable to avoid the risk of resonant response during launch.

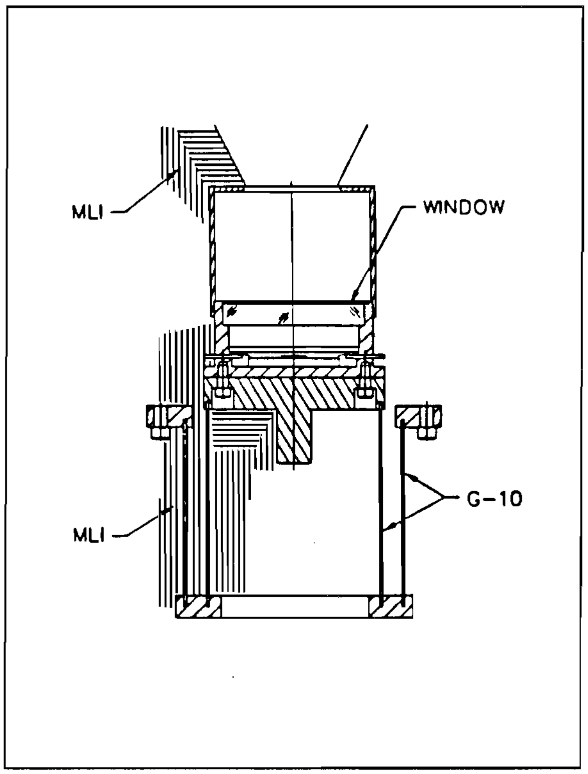

Figure 1 Traditional G-10 Support Method

Also, the parasitic heat load due to conduction through the G-10 support system has a significant impact. For systems using expendable cryogen as the heat sink, mission life is limited. In systems using mechanical coolers, the cooling capacity may be exceeded. For some time cryogenic systems engineers at USU and SDL have discussed the possibilities of supporting cold components with tension strands in an arrangement something like the spokes in a bicycle wheel. A group at NASA Ames [1] reported development of a thermal isolating support bench that used Kevlar strands in tension. As an MAE senior design project in the spring of 1993, two student teams accepted the task of further developing Fiber Support Technology (FIST) by employing ultra-low thermal conductivity fibers (e.g., Kevlar, Vectran) in tension to provide adequate mechanical support and thermal isolation of system components

Two prototypes, very different in appearance from the NASA Ames fixture, were designed, constructed and tested with promising results in the Fall of 1993 and Winter of 1994.

II. Application to SABER

A possible application for the USU FIST technology was already being discussed. SDL was proposing to build an infrared limb scanning instrument called SABER in a teaming arrangement with NASA LaRC. SABER's detectors had to be cooled to below 75 K. A desired mission life of 2 years or more together with rather stringent mass constraints precluded the use of an expendable cryogen as the heat sink. Power constraints also eliminated standard size mechanical refrigerators with roughly 100 W input power requirements. A miniature stirling Cycle refrigerator developed by TRW for the Brilliant Pebbles program was proposed provided a reduction in total parasitic heat loads to less than the miniature refrigerators cooling capacity of 250 mW at 72 K could be achieved. The major contributor to the FPA parasitic heat load was 85 mW conducted through the concentric G-10 cylinders supporting the focal plane. We then conceptualized a design to utilize FIST mounting on the SABER FPA.

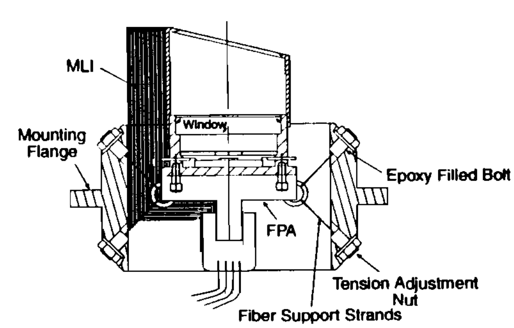

Figure 2 Fiber Support Technology Scheme

III. Support Structure

The support structure consists of four basic components; A warm outer support mechanism, a cold inner support plate (disk), fiber fasteners, and fiber woven into appropriate size strands. The support structure, base lined for SABER, is shown in Figure 2. Size and configuration constraints of the outer and inner support structure are imposed by the system in general.

IV. Fiber Selection

The backbone of FIST is the fiber. It provides the necessary thermal isolation as well as the mechanical rigidity for the system. To date, Carbon, Graphite, Glass, Kevlar, Vectran, Spectra, and Nomex fibers have been considered. Metals are also of interest because of their excellent mechanical properties, and may find application when slightly larger heat loads can be tolerated.

For the SABER instrument, several fibers were considered but Kevlar 49 was chosen for supporting the cold FPA and the chilled telescope within the spacecraft because of its light weight, high tensile strength, and low creep characteristics when compared with the other fibers, in addition to its extremely low thermal conductivity of (.04 W/m-K) [2,3].

Fiber Testing

Ultimate strength, shear strength, and creep were of the most concern, hence, tests were performed to verify data on these mechanical properties as provided by the fiber manufacturers.

Ultimate Strength Test

Kevlar 49 strands were put through a series of tension tests to verify the ultimate strength. Both ends of the strand were wrapped numerous times around a large radius so as to minimize shear loads. Multiple tests were performed on an MTS machine and data collected electronically by a computer. All specimens failed mid-strand thus verifying no significant shear loading at the end connections was present. Figure 3 shows the ultimate strength of the Kevlar 49 strands selected for SABER.

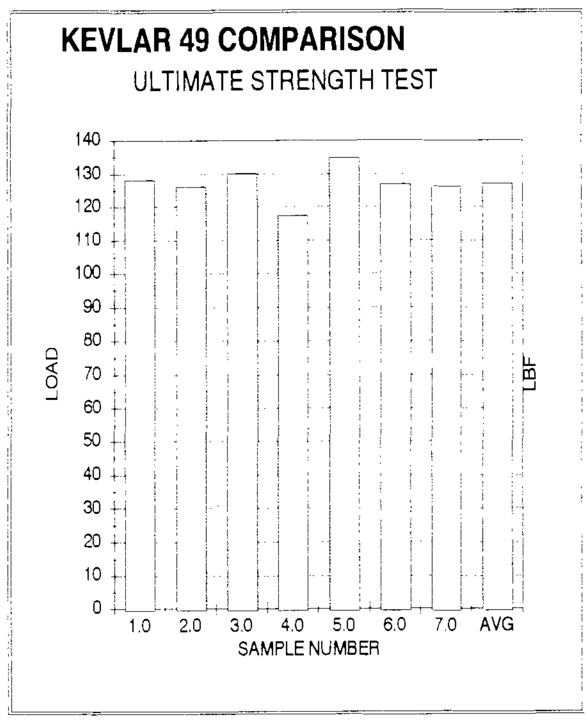

Figure 3 Kevlar 49 Ultimate Strength Test Results

technology evolution by modifying feed housing length and adding or subtracting standardized modules or custom snap-in elements as required.

Micromachined Components

Like any filter, bandwidth, roll-off, and insertion loss are driving requirements. Traditional stripline and waveguide filters are large, even at the millimeter wave frequencies. Evolution of semiconductor etching processes over the last few years has yielded a host of micromachined components ranging from electro-mechanical actuators to simple filters. Micromachined filters provide performance comparable to traditional counterparts with reduced production cost and dramatic reductions in size and weight. Filter parameters are tightly controlled by the masking and etching process, so variations in critical performance parameters over time and between filters of a given design should be minimal. This stability enables automated production and test with minimal tuning. Micromachined filters use proven silicon etching and deposition techniques to reduce microwave filter size by up to 75%, resulting in smaller electronics packages.

A typical micromachined filter is shown in *Figure 3*. The planar structure combines standard silicon etching and metal deposition techniques with emerging membrane technology to produce filters with integral shielding cavities etched into the two laminated substrates. The center silicon wafer is etched through. The resulting sandwich resembles a waveguide filter in performance at 25% of the volume.

Other micromachined components are possible including magic-T's, couplers, dividers, and phase-shifters. These components are combined with the MMIC receiver components on GaAs substrates using either flip-chip or conventional wire bonding techniques.

Application to Ocean Surface Winds

The SeaWinds scatterometer is an example of current-generation wind sensing instruments. As shown in *Figure 4*, the SeaWinds instrument

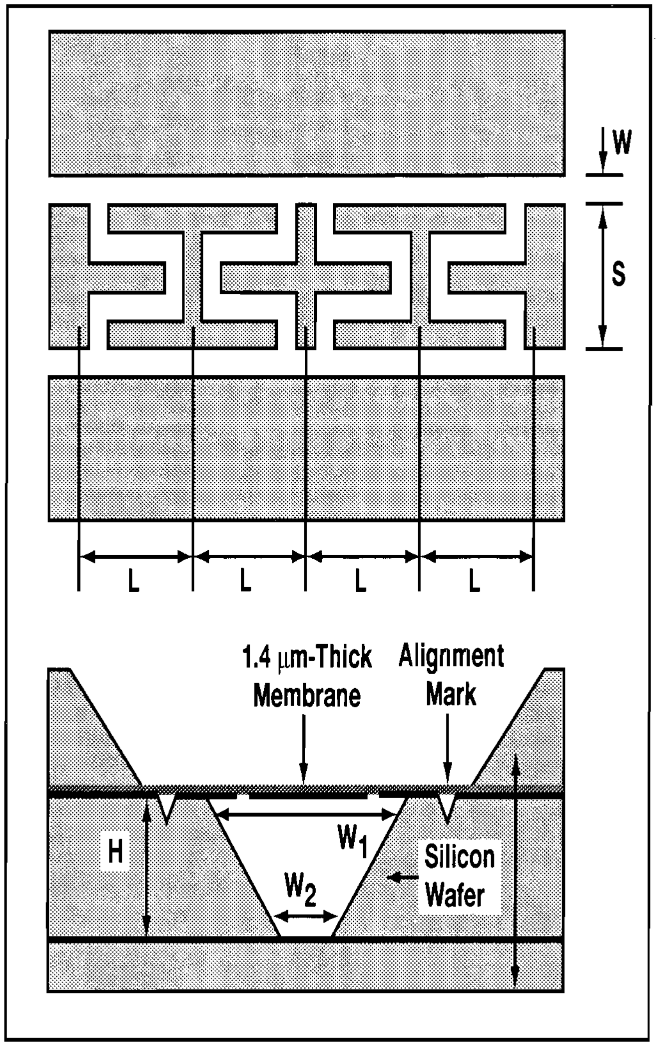

Figure 3. Micromachined Filters

is mounted on a nadir-facing panel of the ADEOS II spacecraft and consists of a rotating antenna subsystem, the Scatterometer Electronics (SES) and a Command and Data System (CDS). The complete instrument weighs in at 176.8 KG and draws 234 Watts of prime power. Thermal control components make up nearly a third of the instrument mass, while the TWTA accounts for half of the power consumption.

Recent work by JPL, Marshall Space Flight Center, and others, has shown that wind vectors can be derived from a passive scatterometer. The passive scatterometer uses dual-channel radiometers operating at selected frequency bands to derive the required Stokes parameters for ocean thermal emission. Processing of this data along the circular scan of the instrument

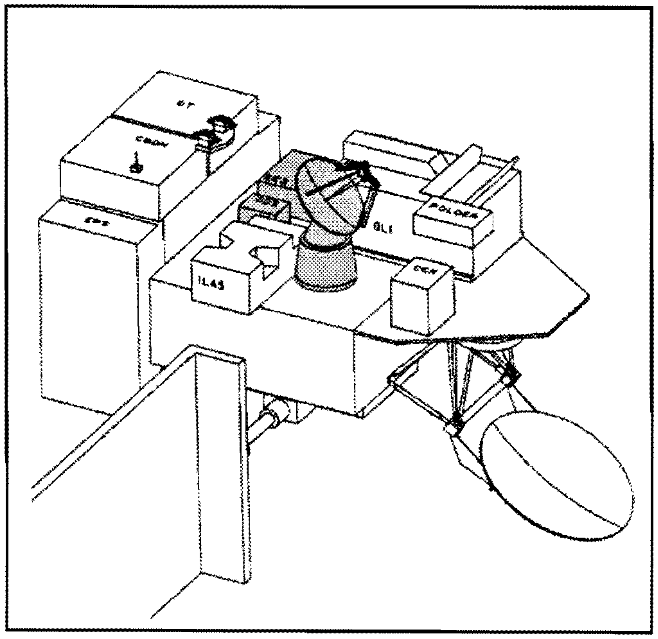

Figure 4. The SeaWinds backscatter radar wind vector sensor

yields the wind direction and velocity. Frequency bands of interest for this instrument are 19 and 37 GHz. Some extraction algorithms under study use 22.5 GHz as well. Including this band is beneficial because it allows measurement of water vapor.

For 800 km altitude scanning at an incidence of 54 degrees, a reasonable reflector mechanical assembly is possible that produces a 2500 km swath at 25 km resolution. A projected reflector diameter of 86 cm results for the 19 GHz band. The Integrated Feed/Receiver is small enough to be integrated into the scanning antenna subsystem without adverse impact on the mass properties. Sampling and control functions are performed in the post-detect electronics. This allows the data to be transferred through slip rings or roller contacts, rather than transferring RF through a rotating waveguide joint as is done on the SeaWinds instrument. *Figure 5* summarizes the weight and power advantages of the miniaturized wind vector radiometer over just the SeaWinds SES component. This assessment assumes SeaWinds-like digital components and does <u>not</u> include weight or power advantages of integrating other instrument components into MCMs.

Power Comparison (Watts)		
Module	SeaWinds (SES)	Proposed PS
TWTA	140	N/A
Tx Chain	17	N/A
Rx Chain	9	< 8
Processor	10	< 10
	176 Watts	< 18

Weight Comparison (Kg)		
Hardware	SeaWinds (SES)	Proposed PS
TWTA	40	N/A
RF Group	12	< 3
Digital Group	7	< 7
Thermal Control Subsystem	31	≤ 3
	90 Kg	< 13 Kg

Figure 5. Advantages of an Integrated Passive Scatterometer over SeaWinds

Other radiometer applications including ocean surface temperature measurement and atmospheric moisture sounding also benefit from the reduced size and weight of the Integrated Feed/Receiver subsystem.

Application to Altimetry

Future extension of the technology to include transmit/receive isolation will enable significant reductions in size and weight of active RF instruments like radar altimeters for sea height sensing and backscatter cross section measurements. Similar application of these technologies will also enable significant size and weight reductions of microwave and millimeter wave communications systems.

The GFO instrument consists of a fixed-aperture Ku-band radar altimeter and a 2-frequency, 4-channel water vapor radiometer to allow correction of the radar data. Incorporating integrated feed/receiver technologies would allow the current feed and waveguide assemblies to be replaced with a single assembly incorporating the radiometer and radar receiver front-ends. A simpler transmit-only waveguide would connect the SSPA to the feed. Application of MIC and MCM technologies to the SSPA could allow migration of the final drive stage to the integrated feed and further simplification of the instrument.

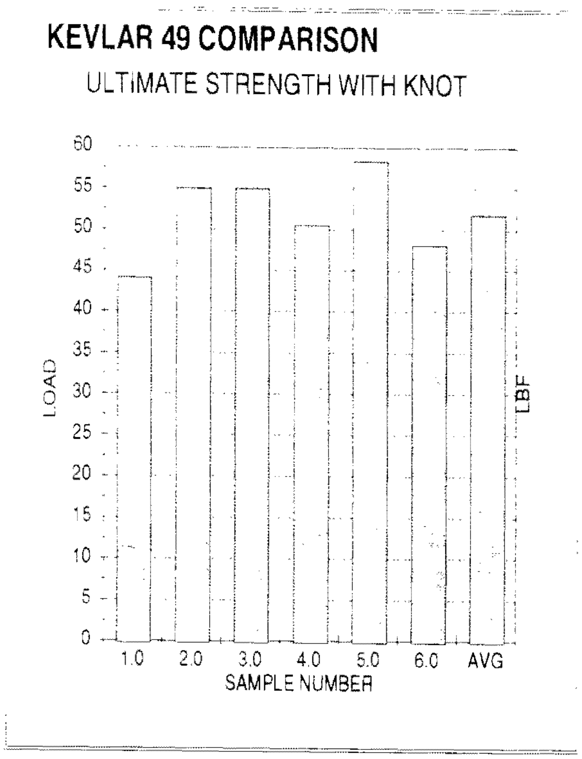

Figure 4 Kevlar 49 Shear Strength Test Results

<u>Shear Strength Test</u>

Tests similar to the ultimate strength tests described above but with a knot tied in the Kevlar at mid-strand to induce a shear load were performed. All specimens failed at the knot, verifying that shear loading was dominate in this configuration. Figure 4 shows the loads at which the Kevlar 49 strands with the knot present failed. Comparison with Figure 3 shows approximately a 50% reduction in load carrying capability due to the presence of the knot. This fact made the design of the strand fasteners an interesting and challenging task which will be discussed in a following section.

<u>Creep Test</u>

Dupont, the manufacturer of Kevlar 49, claims that creep is a logarithmic function of time and is virtually gone after approximately 3 weeks [3]. To verify this, an 8m length of Kevlar strand was loaded to approximately 65% of its breaking strength and creep was measured over a period of 9 months. As can be seen from our test results in Figure 5, almost all creep does indeed occur within the first 3 weeks following loading. Retensioning of the Kevlar strands after this time could be part of a creep management strategy. In the SABER application with strands of approximately 1" in length and the

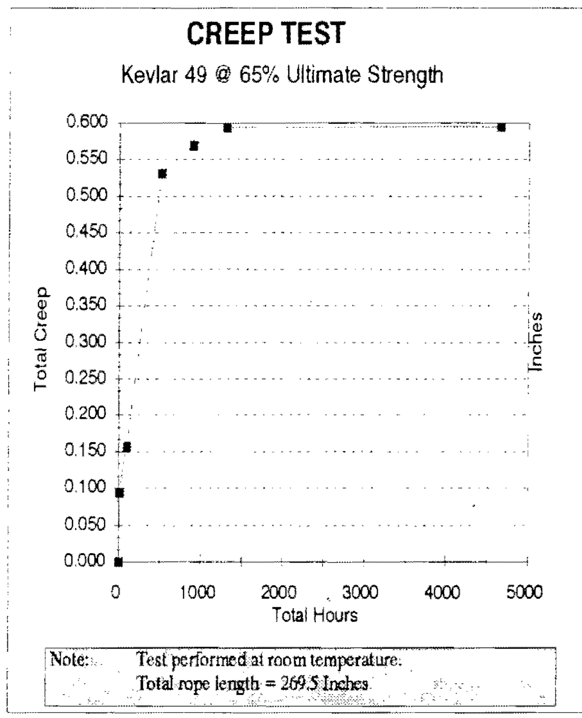

Figure 5 Creep Test Results

tensioning design used, as expected total creep of 1.5E-4 in. is not regarded as a problem.

V. Fiber Fasteners

It became clear from the shear tests described earlier that care had to be taken not to induce shear loads on the fiber when fastening the Kevlar strands to the support structure. Due to the extremely small size of the SABER instrument, the luxury of using large radius fasteners was not possible. An alternative way of fastening the Kevlar to the fiber fasteners, while maintaining the mechanical strength of the fiber support, had to be developed.

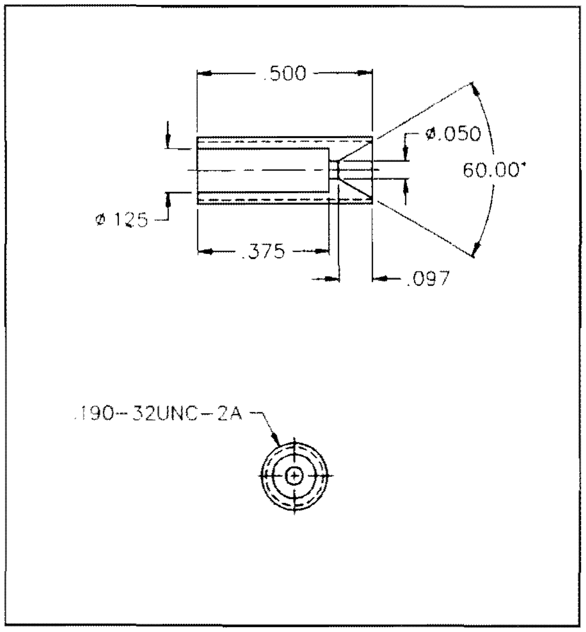

Figure 6 Fiber Fastener

Figure 6 shows a fastener designed to accomplish this task. Upon examination of the fastener, it can be noted that the fiber is always under tensile loading. The longitudinal shear force between the glue interface and the fiber does not adversely effect the load carrying capacity of the fiber as does the transverse shear due to a knot. The strength of the fastener system, while dependent upon the glue-fiber interface, is considerably stronger than a fiber compromised by a tie off or knot scheme.

Fastener Testing

Initial test results indicate the load carrying capacity of the fasteners exceeds the ultimate strength of the fiber. Further testing is planned but initial results indicate success.

VI. Tensioning Scheme

In order to maintain the precision alignment required on the FPA, the Kevlar strands must all be nearly equally tensioned so as not to induce any tilting, or bending of the optical bench. We considered several ways to accomplish this task. Load cells, tuning by frequency, and other methods were all considered. We chose to use spring loaded Belleville washers over these other methods because they not only provide a know load to within 5-15% but they also take up any slack in the Kevlar which might be induced by creep or thermal expansion. This method is also very simple.

For verification of Belleville washer performance, during initial testing a load cell may be placed on the opposite end of the Kevlar strand to determine if the accuracy of the washers is predictable.

The Belleville washers selected for SABER provide a tensile force of 50 lbs when compressed .006". this provides a pre-tension on the Kevlar of about 35% of the ultimate strength of the fiber strand. This appears adequate for the launch loads anticipated.

VII. Thermal Analysis

In minimizing the conducted heat through the fiber tension support structure, basic principles dictate minimum thermal conductivity, minimum cross-sectional area, and maximum possible length of the support strand.

The total conductive heat flow for our system was modeled using Fourier's law of conduction (See Figure 7). The total conductive heat flow through one strand is found by multiplying the calculated heat flux based on thermal conductivity and length by the measured cross sectional area of the strand. The total conductive heat load for the system can then be found by multiplying by the number of strands that are used to support the system [4].

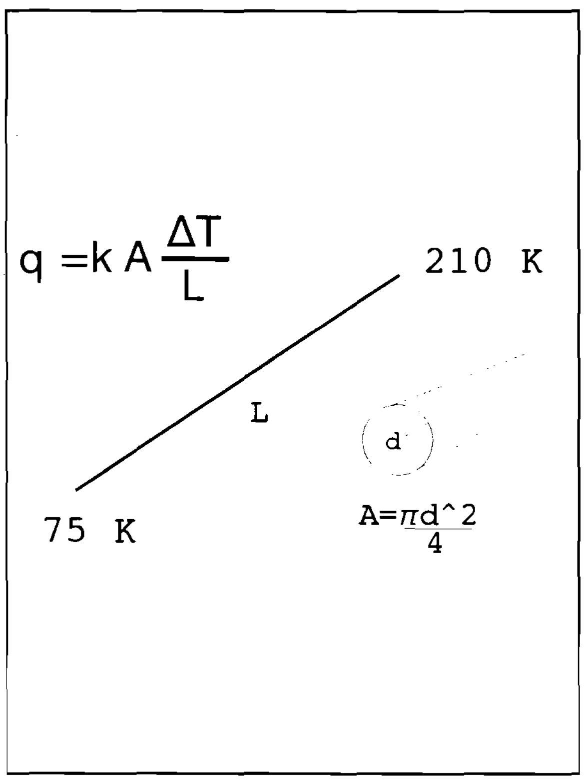

Figure 7 Fourier's Law Of Conduction

Figure 8 illustrates the conductive heat flow expected on the SABER based support structure.

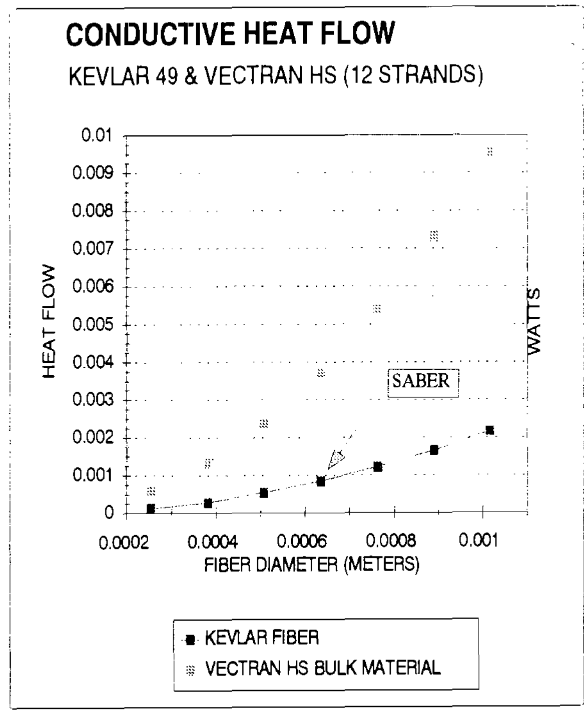

Figure 8 Expected Conductive Heat Load

For comparison purposes, the thermal data for the bulk material of an alternative fiber (Vectran), has been included.

One other area of concern is the parasitic heat load due to radiant heat transfer. These affects are minimized by utilizing multi-layer insulation (MLI) blanketing and/or utilizing low emissivity surfaces. Though blanketing around the strands is a little tricky, with care a very thorough job can be done.

VIII. Dynamic Analysis

During launch, vibrationally induced loads occur. The frequencies of these vibrations typically reach 70 Hz. As a result, the natural frequency of the object being supported by FIST is designed to be over 70 Hz to eliminate the possibility of resonant

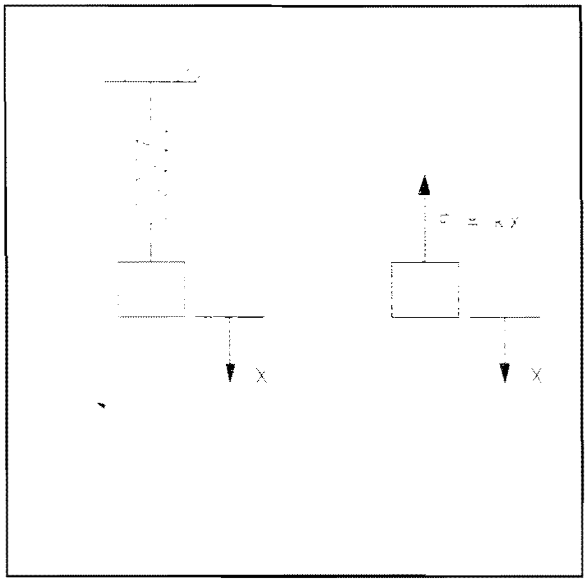

Figure 9 Spring Mass System

response. The Fiber support system can be modeled as a simple spring mass system, as shown in Figure 9. The stiffness constant K was derived from equations 1-5 shown previously.

$$F=KX \qquad \text{Eqn. 1}$$

$$K=\frac{F}{X}=\frac{sA}{X} \qquad \text{Eqn. 2}$$

$$s=\frac{E}{e} \qquad \text{Eqn. 3}$$

$$e=\frac{DX}{X} \qquad \text{Eqn. 4}$$

$$K=\frac{AE}{X}=\frac{AE}{L} \qquad \text{Eqn. 5}$$

The Modulus of elasticity E was obtained from material data by Dupont. The area, A, and length of each strand, L, are determined by system constraints. Summing the forces dynamically in all directions, the natural frequency of the supported object was obtained by a second order linear equation. The following is an illustration of this procedure.

Applying Newtons second law of motion

$$\sum_{n} F=m\cdot\frac{d^2}{dt^2}x \qquad \text{Eqn. 6}$$

Summing Forces about the equilibruim position

$$mg-(mg+kx)=m\cdot\frac{d^2}{dt^2}x \qquad \text{Eqn. 7}$$

$$m\cdot\frac{d^2}{dt^2}x+kx=0 \qquad \text{Eqn. 8}$$

$$w_n=\sqrt{\frac{k}{m}} \qquad \text{Eqn. 9}$$

$$f_n=\frac{1}{2\cdot p}\cdot\sqrt{\frac{k}{m}} \qquad \text{Eqn. 10}$$

Eqn. 10 is valid for a linear spring-mass system. Correction to this equation for the complex angle is done by multiplying Eqn. 10 by a cosine squared correction term.

$$f_n=\frac{1}{2\cdot p}\cdot\sqrt{\frac{k}{m}}\cdot\cos(q)^2 \qquad \text{Eqn. 11}$$

Equation 11 is used to estimate the first natural resonant frequency of the support system. Although these equations were derived for a single direction of motion, they apply to both of the other axes by simply changing the complex angle relative to the other axes. Figure 10 shows the natural frequency of the supported object with .000635 m diameter strands as

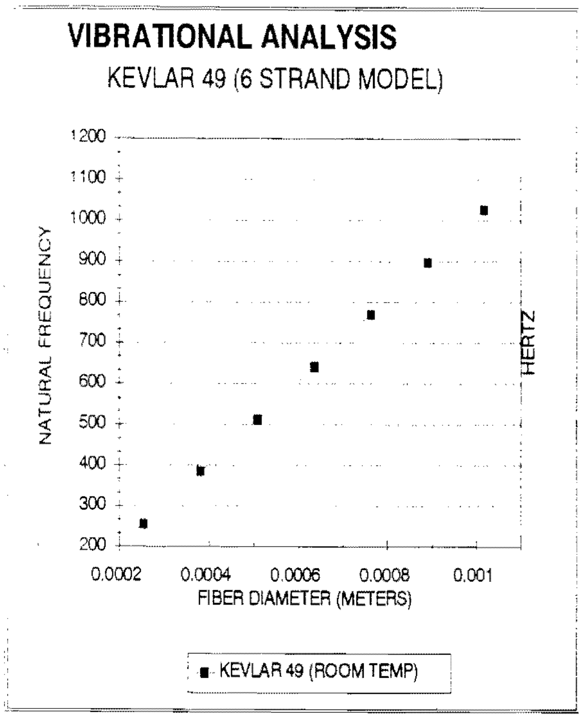

Figure 10 Predicted First Natural Resonant Frequency

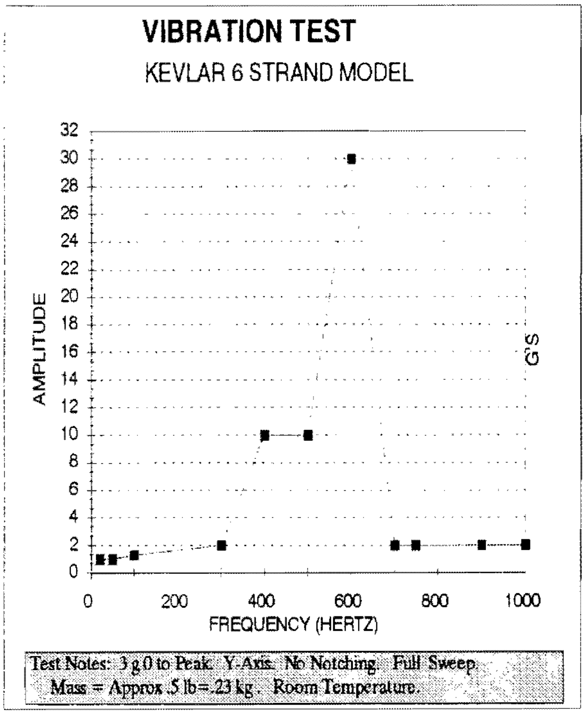

Figure 11 First Resonant Frequency X-Y Axes

used on the SABER FPA having a predicted resonant frequency of 650 Hz. It will be shown in the following section how these predicted values compared to actual measured vibrational data [5].

Vibrational Testing

Vibrational testing was done to verify the predicted resonant frequency. The test results shown in Figures 11 and 12 were obtained from the SABER model shown in Figure 2.

The test data when compared to Figure 7, matches very closely to the predicted values for this system. It may be noted at this point that the first natural frequency of FIST has been increased to nearly 700 in one axis and over 600 Hz in the other two axes compared to the 50-70 Hz of the conventional method.

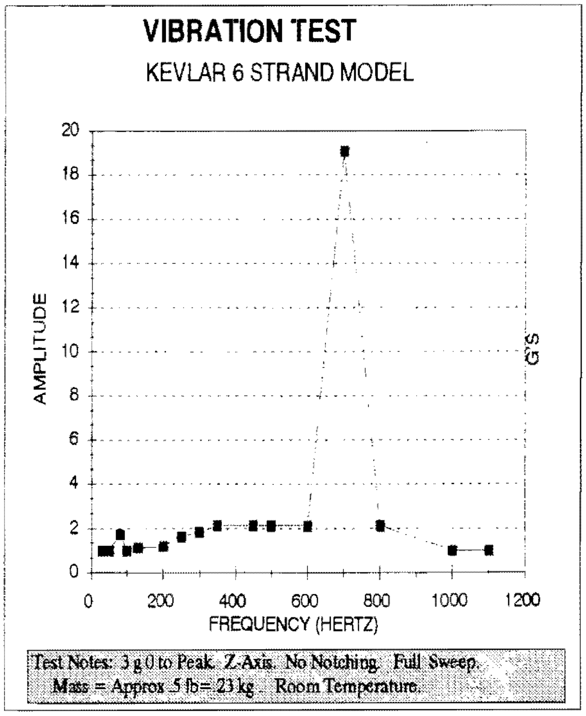

Figure 12 First Resonant Frequency Z Axis

IX. Conclusions

A support structure, utilizing Kevlar 49 strands in a tension support scheme, has been successfully designed and tested. Kevlar 49 was chosen due to its extremely low thermal conductivity and high strength in tension. At the beginning of the project, both creep and attaching the Kevlar were major concerns. Both these issues have proven to be manageable.

The support structure is very rigid. The instrument being supported has a first natural frequency and order of magnitude above the maximum 70 Hz expected during launch. This was verified theoretically as well as with testing.

The heat loads of the system due to conduction have also been reduced nearly 2 orders of magnitude from 85 mW down to less than 1 mW.

FIST has also been baselined to support the chilled SABER telescope inside the spacecraft. Although much larger diameter Kevlar will be used the basic concept behind the design will remain the same as that used on the FPA (See Figure 13).

We feel that FIST can meet conductive heat load and mechanical stiffness requirements, for many applications, and that this will prove to be a valuable technology in the future.

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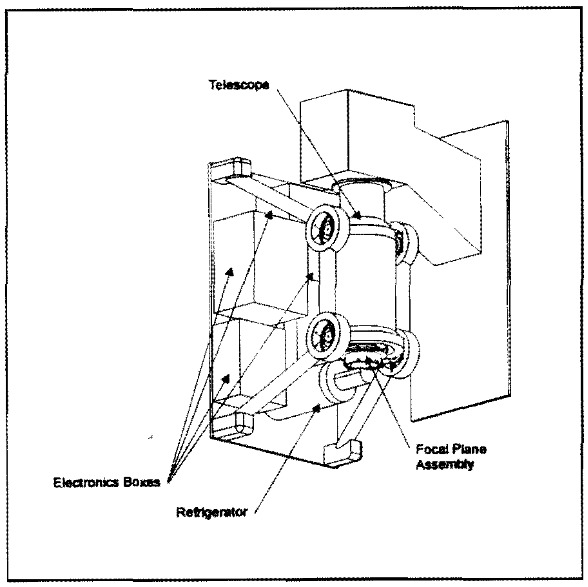

Figure 13 SABER Instrument

Biography

Scott Jensen is a graduate student in Mechanical and Aerospace Engineering at Utah State University. He is currently working on his masters thesis and expects to finish in the Fall of '95. The emphasis of his research is based on cryogenic tension support fixtures. Upon completion of his masters degree, he hopes to obtain his doctorate degree as well. He is currently working for the Space Dynamics Laboratory as a student thermal engineer under the supervision of Dr. J. Clair Batty on a NASA sponsored instrument called SABER. He has been working on this project for about a year and a half.