An experimental design for the characterization of fused silica fiber lifetimes in air and vacuum conditions

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Abstract

The aLIGO test masses are suspended by fused silica fibers, which are under a stress of approximately 800MPa. Increasing the stress of the suspension fibers would increase their violin mode frequency and decrease their vertical bounce mode frequency; this could be a possible means of noise reduction for gravitational wave detectors in the future. With limited data on fused silica fiber lifetimes, this experiment seeks to provide a setup for fiber characterization under air and vacuum conditions. Since fused silica fibers have long lifetimes under low stress, fibers are expected to be tested under extreme stress—approx. 4GPa.

1 Introduction

The initial LIGO (iLIGO) gravitational wave detector design was unsuccessful in observing gravitational waves. After the implementation of many hardware upgrades to the detectors—one of which being a redesigned test mass suspension system [1]—it was possible to identify gravitational wave events.

The iLIGO suspension system consisted of a single test mass suspended by steel fibers, which proved inadequate in reducing seismic and thermal noise. The advanced LIGO (aLIGO) suspension redesign included a quadruple pendulum architecture, in which the steel fibers were replaced by fused silica fibers. The transition from a single- to quadruple-pendulum suspension meant greater passive seismic isolation, as each pendulum segment above the test mass works to isolate it. Further, replacing the steel fibers with fused silica fibers reduced thermal noise, as the mechanical loss of fused silica is less than that of steel. [2]

It is advantageous to tune hardware so that its noise is outside a detector's region of interest. In a pendulum system, there are two characteristic modes: the violin mode and the vertical bouncing mode. As it relates to aLIGO's suspension, the fused silica fibers act as a pendulum system when coupled with a test mass. Increased stress on the fibers would not only push the violin mode above the detector's scope, but also bring the vertical mode below the detector's sensitivity. An argument for the relationship between mass and the vertical mode's frequency follows:

$$Y = \frac{\frac{F}{A}}{\frac{L}{\Delta L}}$$
$$F = \frac{YA}{L}\Delta L$$

Analogously, $F = kx$. The vertical mode is then described by

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{\frac{YA}{L}}{m}}$$

As mass increases, the vertical mode decreases in frequency. Secondly, if we consider the pendulum's vibrational mode to be a wave along the fiber, we can deduce that the fundamental frequency of the violin mode is

$$f_0 = \frac{1}{2L}\sqrt{\frac{mg}{\mu}}$$

Thus, the violin mode's frequency scales with the mass of the pendulum.

Since the frequencies of each of these modes is related to mass, it is intuitive to simply increase the size of the test masses in detectors; however, there are upgrades that would be more practical. One such would be to increase the stress of the suspension fibers by making them thinner. This would maintain the current suspension system design, and would only require the installation of new fibers. This is not to say there are no advantages to increasing the size of the test masses; a larger test mass would be particularly beneficial in reducing radiation pressure noise, among other things.

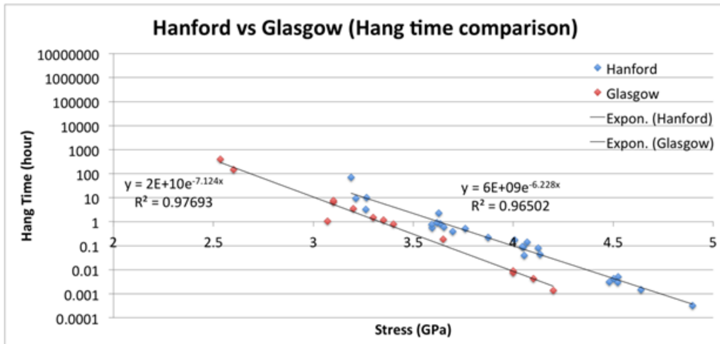

Figure 1: Fiber lifetimes under varying stress. Note that the offset of data sets comes from a difference in the fiber profilers at the two sites.

2 Current data

Data outlining the behavior of fused silica is limited, particularly in vacuum and high-stress conditions. A 1966 paper by Proctor et al.[3] tested many factors in preparing and experimenting with fused silica fibers, and offers essential knowledge. It must be noted, however, that the means of fiber preparation has changed substantially over time. For the purposes of this project, the paper showed that fibers in vacuum are able to last substantially longer than their in-air counterparts. Both LIGO Hanford and the University of Glasgow [4] have carried out in-air fused silica fiber stress corrosion experiments, which were used as a basis for this project. In his work, Toland collected fiber lifetime data as a means to characterize the relationship between fused silica fiber production via fiber-pulling machine and fiber lifetimes

By choosing a desired hang time from Toland's work (Figure 1), a stress could be estimated from the collected data; the appropriate fiber dimensions could then be worked out.

3 Methods

Properly manufactured fused silica fibers can survive under low stress for periods many times greater than the human lifespan. To maximize the possible data collection, a high stress was chosen as to ensure a fiber would not last long in air. Once a desired hang time of roughly 30 seconds in air is achieved, a similar fiber would be tested in an identical setup under vacuum. The final setup is shown in Figure 2. This combination of in-air and vacuum tests expedites data collection, as a fiber of different dimensions can be characterized in air while another is being tested in vacuum.

Using the Hanford-Glasgow data, a stress of 4.1GPa was chosen. The test mass was weighed at 12.28kg, which included the fiber mounting piece. From

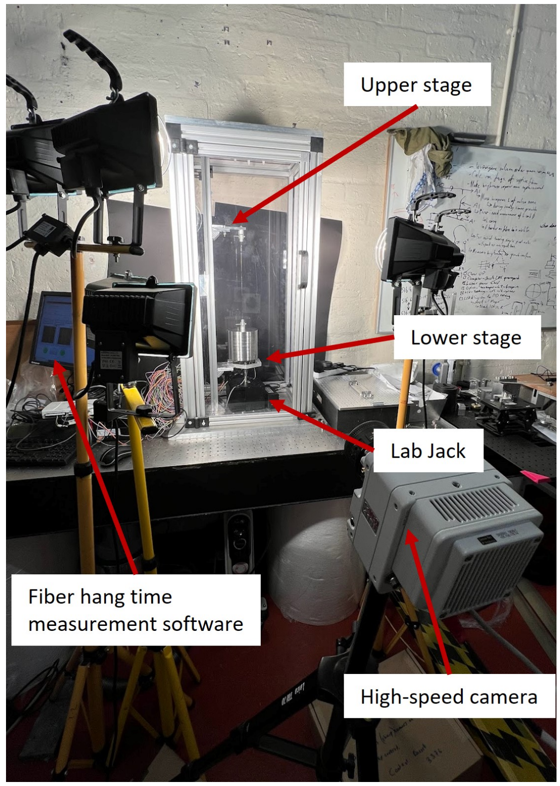

Figure 2: Fused silica fiber lifetime experimental setup

this, the desired fiber radius was found:

$$\text{Stress} = \frac{Force}{Area}$$
$$4.1 \times 10^9 = \frac{12.28 \times 9.81}{\pi r^2}$$
$$d = 2r = 193.4 \mu m$$

With a known stress, the amount the fiber would stretch could be estimated as a linear function of the fiber's length. This estimation follows:

$$\text{Young's modulus} = \frac{Stress}{Strain}$$
$$72 \times 10^9 = \frac{4.1 \times 10^9}{\Delta L} \times L$$
$$\Delta L = .056944 \times L$$

To measure a fiber's lifetime, an apparatus that consisted of an upper stage to mount the fiber from and a lower stage to catch the test mass after failure (see Figure 2). To bring the mass from a neutral to suspended state, a motorized jack was used.

The jack used is a Thorlabs MLJ150(/M) Lab Jack, to which a post and base were attached to hold the test mass above the lower stage during fiber loading.

On the base, a switch was created using two pieces of copper tape (see Figure 3). When the mass is sitting on the jack, it acts to close the switch since it is made of a conducting material. When the mass is hanging, the switch will open, which will start the timer. Two switches were mounted on the lower stage, the closing of either will end the timer. Putting the two switches in parallel ensures that the timer will end in the event of a switch failure. Figure 5 fully describes the circuit layout. After stretching, the mass should sit at least a centimeter above the lower stage; this is to ensure that the mechanical switches are not falsely triggered. This setup was made identical in both the in-air and vacuum systems as to ensure consistency in data collection.

Unfortunately, due to time constraints there were no vacuum tests done. However, this setup can be used to characterize fused silica fiber behavior in the future.

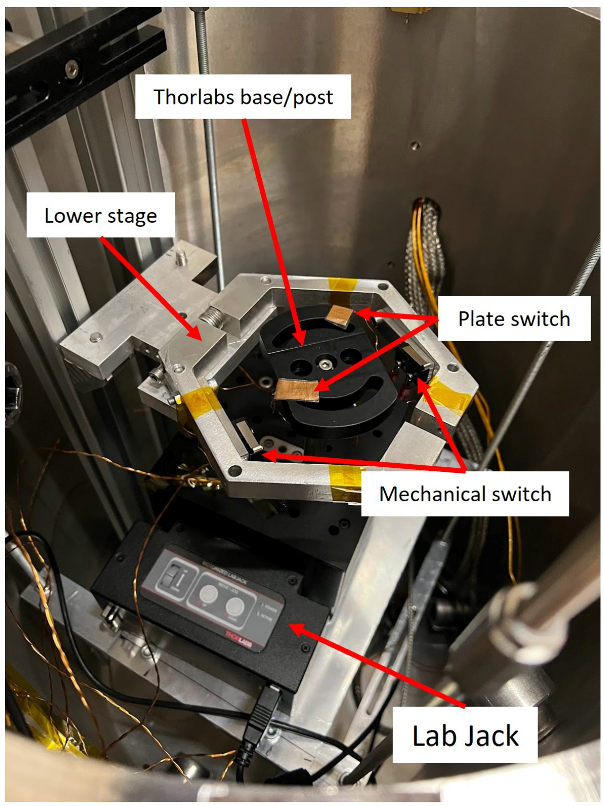

Figure 3: Vacuum system lower stage

4 Electronics and software

Measuring a fiber's lifetime can be split into three sections:

1. Apply stress to fiber
2. Start timer
3. End timer

Controls for all three of these steps were implemented via a LabVIEW VI (see Figure 4). A National Instruments USB-6211 analog digital converter was used to measure the voltage across both the plate and mechanical switches. One plate switch is sufficient, as an operator would have a reasonable idea of when to manually start the timer if the switch failed. Lastly, A Thorlabs Kinesis .NET plugin was used to control the Lab Jack within LabVIEW.

To ensure the ADC does not have a damaging current travel across it, a 5.1kΩ resistor was used as a pull-down. With this, the ADC should receive only 1mA of current.

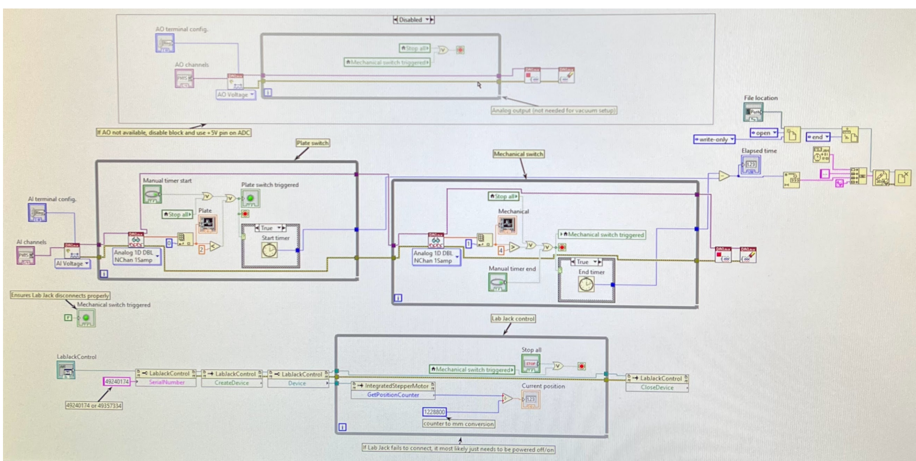

Figure 4: LabVIEW voltage measurement block diagram

5 Fiber production

Fused silica fibers can neither be produced to exact dimensions nor to be perfectly cylindrical. Each fiber must then be profiled to find its effective diameter; this is done by use of the fiber profiler (constructed by the University of Glasgow's IGR) shown in Figure 6.

The profiler measures a fiber's diameter for many steps along its length. The smallest measured diameter is then used as the fiber's effective diameter, as it

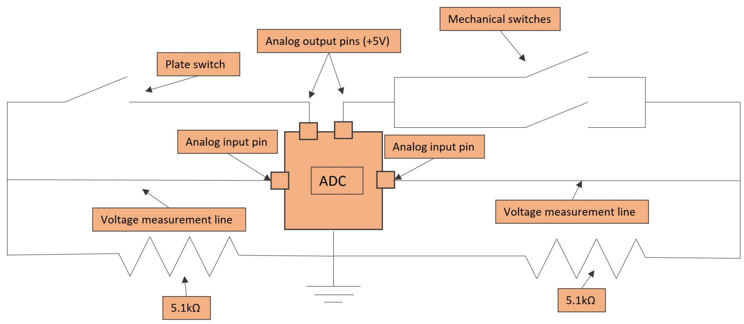

Figure 5: Timing measurement circuit

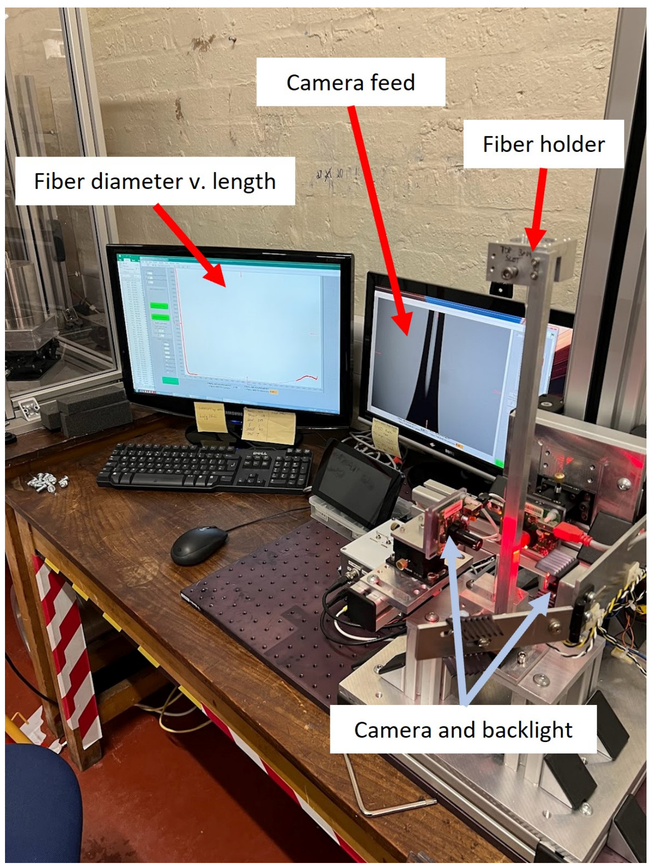

Figure 6: Fiber profiling setup

is expected that a fiber would break at its thinnest point. This is based on the relationship between diameter and stress, as shown in **Methods**.

6 Results

Most of the experiment's formulation was spent marrying hardware and software. It took several weeks to construct a suitable mechanical structure, but once both setups were complete, the next step was to introduce control software. The first major difficulty was finding a compatible combination of software to control the Lab Jack via a LabVIEW .NET container.

Once the Lab Jack control was functional, a National Instruments USB-6211 analog-digital converter was implemented (see Figure 7). For the hardware to be vacuum compatible, enamel-coated copper wire was used inside the vacuum chamber. Unfortunately, some of this coating was stripped off of a section of the wire; when this section contacted the side of vacuum chamber, it shorted the circuit. Suffice it to say neither the USB port the converter was plugged into, nor the converter itself, are in usable condition.

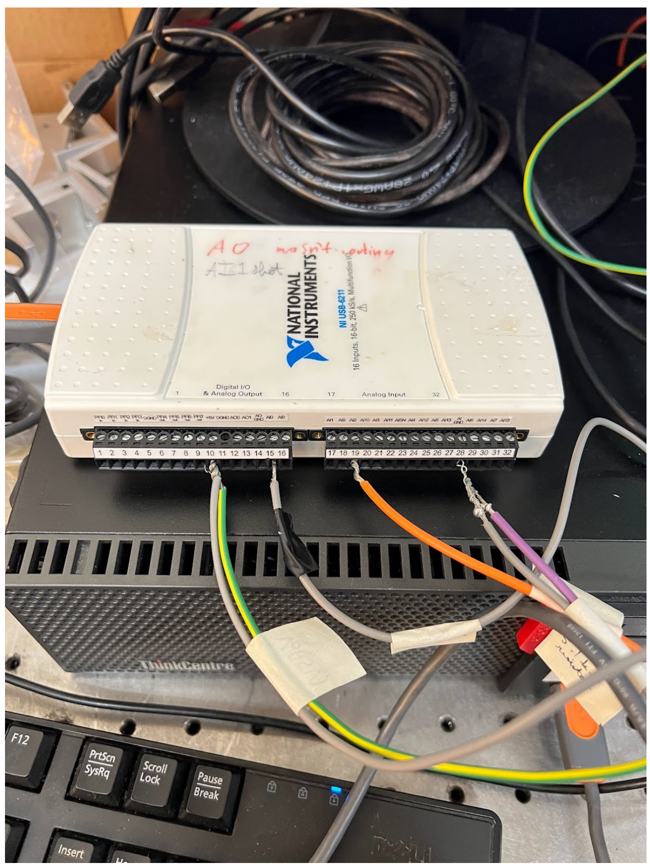

Figure 7: National Instruments analog-digital converter

7 Error analysis

The most significant error in this experiment is related to the fiber production process. Given that the fused silica stock is not an ideal material, it is possible that structural faults could result in a shorter lifetime than is expected, and/or the fiber breaking at a point that is not the smallest diameter. To find where the fiber breaks, a high-speed camera was used.

Each fiber must be moved by hand from the pulling machine to the testing rig, meaning it is possible that fiber damage can occur as a result of improper handling. This may come from an impact while mounting the fiber, contact with the fiber itself, or accidentally applying stress to the fiber during the move. Although possible, these are unlikely; if they were to occur, it is expected that the test not continue since the fiber has been compromised.

Error in measuring the mass's hang time must also be considered. To reduce shock during unloading, the Lab Jack should descend at a speed less than $.5\frac{mm}{s}$. Although there was no testing done on the Lab Jack descent speed, it is intuitive that a slower unloading would reduce the shock on the fiber. Were the Lab Jack to move faster, it is possible that the fiber would experience shock that could shorten the hang time. Further, a slow descent means that the contact between the copper plates would not be broken until the fiber is freely hanging. In other words, the fiber stretches as the mass is being released, which means the timer is started when the fiber is under its maximum stress and at its final length.

Both the start and end timers are controlled by the mass. The copper plate switch was designed in such a way that it triggers as close to the start of the mass's hang time as possible. However, the mechanical switch is only triggered once the mass falls a distance. An estimate for this interval follows:

$$\Delta y = -2cm = v_0 t + \tfrac{1}{2}at^2$$
$$-.02 = 0 + (\tfrac{1}{2} \times -9.8 \times t^2)$$
$$t = \sqrt{.00408} = .06389s$$

Although this interval is non-zero, it is insignificant for any tests with a stress less than 4GPa—see Figure 1.

8 Possible improvements

The most apparent improvement that could be made to this experiment is the machining of parts. All of the hardware used was redundant tooling or Thorlabs optical table equipment. Although made to be as symmetrical and rigid as possible, the experimental rig is limited by its constituent parts.

It is particularly important for the Lab Jack and upper stage to be as level as possible. If they are not, then the mass may swing or spin after its release, causing unwanted stress. Machining parts would improve symmetry, reducing offsets between each stage and the Lab Jack.

Another improvement would be finding the angle the mass is released at. This information would help draw a relationship between the offloading of a mass and the hang time of a fiber. If the fiber's lifetime is affected by motion of the mass, then it would be reasonable to investigate leveling the system further. This would be possible with the inclusion of a second copper plate switch on the Lab Jack.

Lastly, a camera setup in the vacuum system would be a worthwhile upgrade. It is necessary to ensure that the point of failure is known for each fiber; this ensures the glue did not fail, and that the fiber actually broke. Further, triggering the high-speed camera via the LabVIEW VI would mean tests could be left to run without supervision. Presently, the camera needs to be triggered by hand.

9 Conclusion

With limited data on fused silica fiber behavior under vacuum, it is necessary to characterize the fibers if a higher-stress suspension system is to be considered for gravitational wave detectors. Although time constraints denied the opportunity to test fibers, the two setups created will be useful for future data collection if taken up by another researcher. It is expected that fibers will last longer under vacuum, but there is insufficient data to suitably characterize the difference in fiber lifetimes. Moving forward, this experiment offers a ready means of data collection, which is easily upgraded for increased precision in measurements.

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