FLARE LAr TPC WIRE EXPERIMENTS

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ABSTRACT

FLARE (Fermilab Liquid ARgon Experiments) is an initiative to construct several liquid argon detectors to further exploit the two Fermilab neutrino beams, the operational Booster beam, and the recently completed NuMI beam. A new FLARE R&D program has been established to meet the technical challenges of the 4 mil diameter wires to be used inside the detectors. Presented is a write up of some initial research and experimentation done in response to meet the mechanical and technical challenges of tensioning and stringing the wires and the survivability during the cool down phase of the experiment.

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INTRODUCTION

Fermilab's recent major investments in neutrino physics, the construction of two intense neutrino beams spanning energies from 0.5 GeV to 20 GeV, opens many doors to a variety of new neutrino experiments. The goal of FLARE is to further utilize the potential of Fermilab's neutrino beams, with a series of experiments [1]:

- A large, 15 kton class, LAr detector in the off-axis NuMI beam.
- A small, 40 ton class, LAr detector for the Booster beam or the near NuMI hall.
- Another dedicated LAr detector to search for neutrinoless double beta decay.

All of these use the recently developed detector technology of the Liquid Argon Time Projection Chamber (LAr TPC). ICARUS has already demonstrated the technical aspects for the success of a 500 ton class LAr detector with their construction and operation of the ICARUS T600 detector [2]. The FLARE R&D program is therefore acting as a technology transfer to further establish credibility of technical claims and cost estimates.

The operating principle of the LAr TPC is based on the fact that in highly purified LAr, free electrons produced by the ionization of argon atoms can be transported practically undistorted by a uniform electric field over distances of several meters [2]. Detection of the free electrons is done with planes of wires stretched perpendicular to the net path of the electrons. The 4 mil wires to be used in the 15 kton detector will approach 100 feet and will be spaced 5 mm apart. Planes will be orientated at different angles to create a wire mesh. In total there will be approximately 6 planes made up of nearly 300,000 wires [1]. Once strung and tensioned into place, the concern is that during a cool down, the increase in tension in the wires due to thermally contracting faster then the supporting vessel may cause the wires to yield or break. Even one broken wire can short out an entire plane and deem a major portion of the detector unusable [1]. For the proposed 15 kton detector, broken wires cannot be accessed and replaced without a large amount of downtime and cryogenic loss, both in volume and purity. It is economically impractical to consider such repairs a possibility. Therefore the mechanical and technical challenges of tensioning and stringing the wires and the survivability during the cool down phase of the experiment require, in its own right, extensive R&D to ensure both feasibility and reliability.

What follows are various small wire experiments developed to begin to meet the challenges of the cool down phase of the experiment and to understand the behavior of the Stainless Steel 304V, 4 mil diameter wires.

Properties of the Detector Wires

The 4 mil wires are made of Stainless steel 304V; a fully work hardened vacuum treated stainless steel. Manufacture specifications indicate a yield point of 3.5 lbf, a breaking point of 4 lbf, a density of 0.286 lb/in^3, and a Young's modulus 28.5×10^{6} psi [3]. The actual diameter of the wire was measured and found to be 3.85 mils. In addition, unlike many stainless steels, 304V is magnetic.

FEASIBLITY AND ACCURACY OF DETERMINING TENSION VIA FREQUENCY MEASUREMENT

First, an initial test was performed in which a sample of wire was tensioned, inside a fixed 11.26" length, to a desired 2 lbf and then dunked into liquid nitrogen to see if the wire would break. Liquid nitrogen was used rather then liquid argon because it is a conservative alternative, since it is colder and induces a larger tension increase, and is readily available. A detailed explanation of the procedure for tensioning and dunking the wire sample is described in a later section. The wire sample successfully survived cool down, but it was not visually clear whether the wire had gone beyond its elastic limit and permanently deformed. Therefore, it was desired to have an accurate method for measuring if and how much the wire had yielded during cool down. In theory, by measuring the wire's natural frequency of vibration, before and after a thermal cycle, it could be determined whether the wire had yielded or not.

An initial experimental setup was developed to verify that tension could be accurately calculated by measuring the fundamental frequency of vibration and vise versa, using equations derived from classical mechanics.

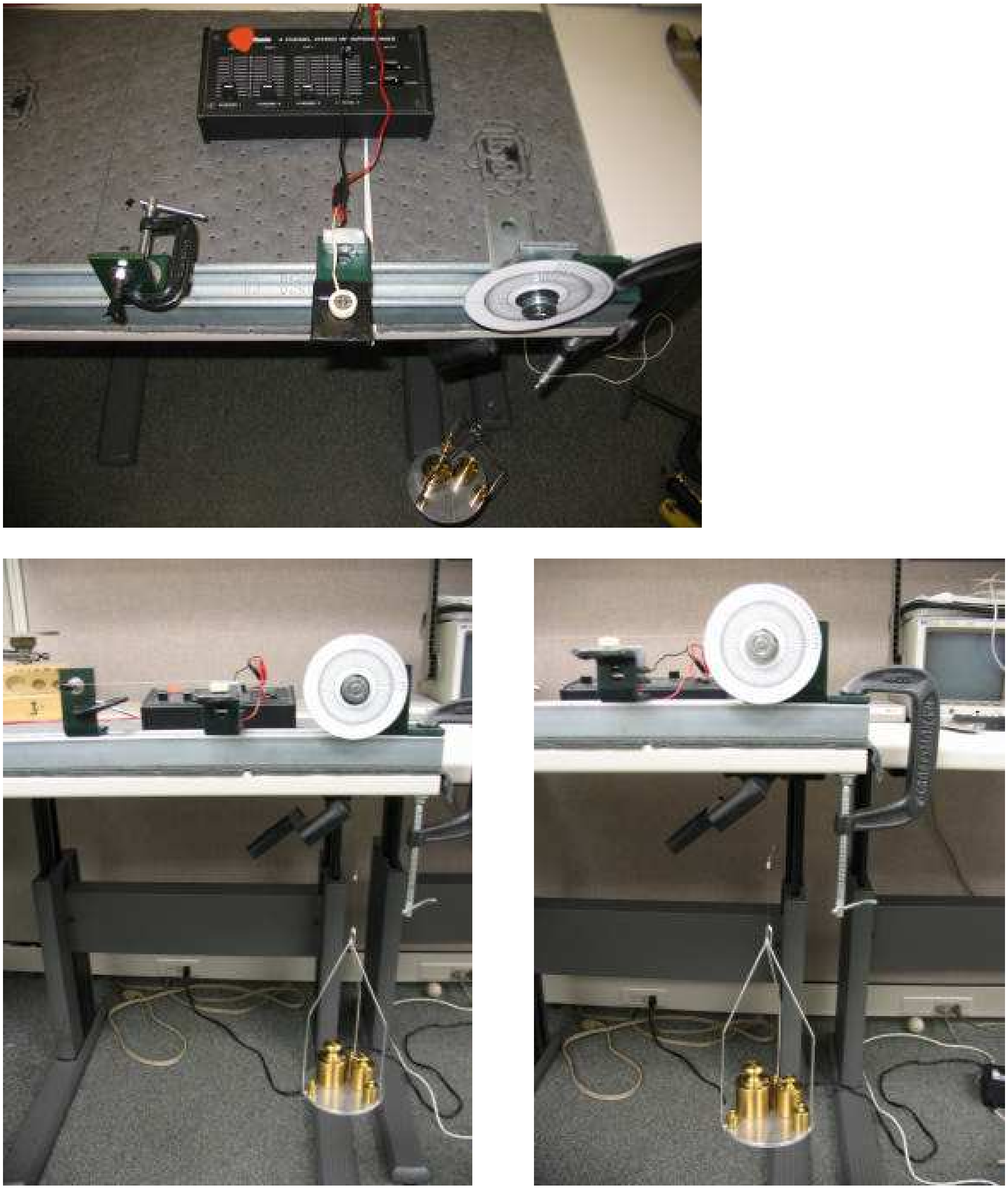


FIGURE 1: Experimental Setup

Experimental Setup

See FIGURE 1 for photographs of the experimental setup. A 24” sample of wire is prepared first by creating a loop at one end using a tapered pin and hole. The opposite end is c-clamped to one end of the apparatus and wrapped one full turn around a 0.25” diameter cylinder. The wire is then pulled horizontally to the opposite end, where it is guided around a ball bearing wheel. A 4.5 oz mass holder is hooked to the loop and hangs freely. The wheel effectively transfers the vertical force of the mass holder to horizontal tension in the wire. The length of the horizontal wire is measured as the distance between the horizontal tangents of the two ends and is 12.036”. An electric pickup, acquired from a disassembled microphone is mounted underneath the wire, halfway between the two ends. The pickup signal is first amplified and then sent to a computer. The audio software DC FIVE is used to record and analyze the signal.

In addition, to measure the axial deformation of the wire, a dial marked in 1 degree increments is mounted behind the wheel and a needle is mounted perpendicular to the curvature of the wheel.

Experimental Procedure

With the 4.5 oz mass holder connected to the end of the wire the dial is zeroed. An initial frequency measurement is taken by plucking the wire and recording the signal. Next, 3.5 ounces is added to the mass holder to give a total tension of 0.5 lbf. The wheel's angle of rotation due to the added tension is recorded and the new frequency of vibration is measured. The tension is then increased by 0.5 lbf increments until the total weight reaches 3 lbf. Then, until the wire breaks, the tension is incremented by 0.125 lbf to avoid excessive shock and premature failure of the wire. Frequency and rotation measurements are taken after each additional weight increment. The procedure is repeated for multiple samples of wire. It is important that the wheel freely turns and does not stick; else the weight of the mass holder will not be fully transferred to horizontal tension in the wire. In addition, to optimize the signal quality, the distance between the pickup and the wire should be minimized.

Methods of Calculations

From classical mechanics an equation for frequency can be derived.

$$f_n = \frac{1}{2 \cdot L}\sqrt{\frac{T}{\mu}} \tag{1}$$

Where, f_n is the natural or fundamental frequency of the wire, L is the length of the wire, T is the tension of the wire and μ is the linear density of the wire. In the feasibility experiment described above, when the wire is tensioned, the diameter decreases and the length stays constant, therefore the linear density changes. The above equation is rewritten in terms of volumetric density (ρ) and diameter (d).

$$f_n = \frac{1}{d \cdot L}\sqrt{\frac{T}{\rho \cdot \pi}} \tag{2}$$

In an attempt to account for the change in diameter due to the applied tension, Poisson's ratio is used in combination with the equation for deflection, derived from Hooke's law.

$$\nu = \frac{\varepsilon_d}{\varepsilon_l}, \delta = \frac{T \cdot L}{A \cdot E} \tag{3}$$

Where, Poisson's ratio ν is 0.3 for stainless steel, ε_d is the lateral strain of the wire, ε_l is the axial strain of the wire, δ is axial deformation, A is the cross sectional area of the wire, and E is Young's modulus.

The deflection equation (3) is valid for tensions within the elastic region (tensions below the yield point). However, it is shown in a later section that there is a negligibly small change in Young's modulus beyond the yield point and equation (3) can still be used without any significant loss in accuracy.

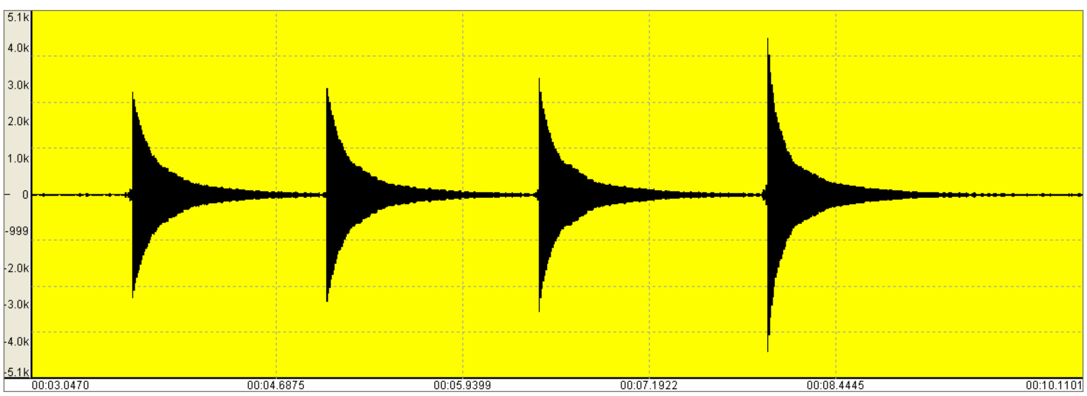
As weight is added to the mass holder, the wheel turns as a result of axial deformation. The wheel's angle of rotation is measured and is directly converted to deformation of the wire.

$$\delta = r \cdot \theta \tag{4}$$

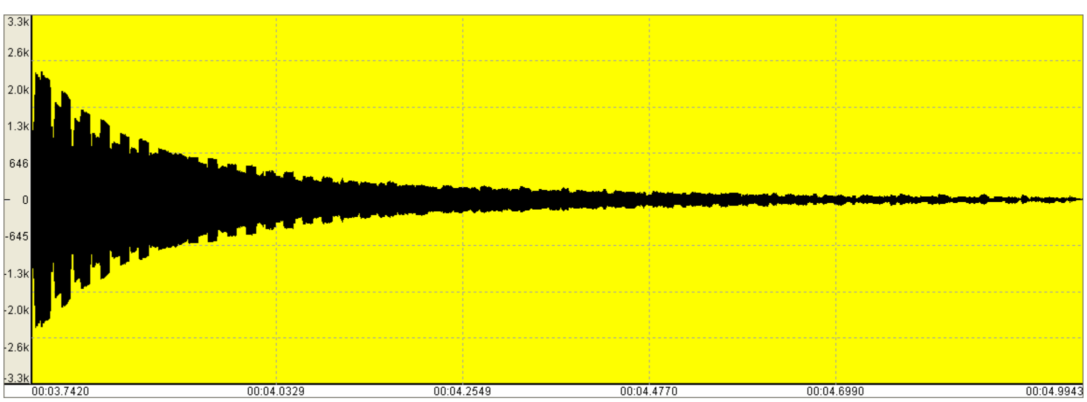
Where, r is the wheel radius and θ is the angle of rotation in radians.

Results

An example of the raw data is shown in FIGURE 2. In FIGURE 4 (a) there are four separate forced oscillations or plucks recorded. They are noted by the sudden increase in amplitude followed by a gradual damping back to zero. Each individual signal is analyzed using the FFT spectrum analyzer. Depending on which section of the signal is analyzed the fundamental frequency is seen to vary slightly, having differences anywhere from 0 to 1 Hz. A section of the signal, near the end of the oscillation, similar to FIGURE 2 (d) is analyzed, rather then a noisier section near the beginning of the oscillation seen in FIGURE 2 (c). FIGURE 2 (e) is an example of a FFT spectrum analyzer read back. The peak at 774.5 Hz is noted and recorded as the fundamental frequency of this signal. Each individual oscillation is analyzed and an average fundamental frequency is taken. A Blackman window type was used with a resolution of 0.04 Hz.



(a)



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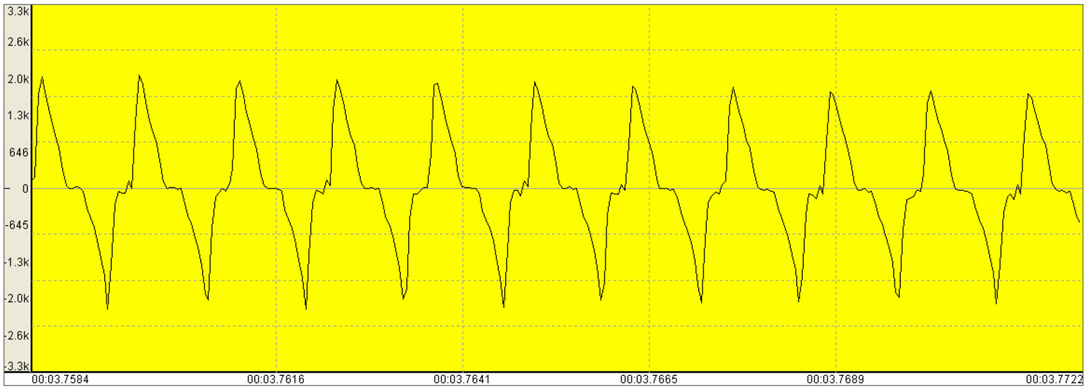
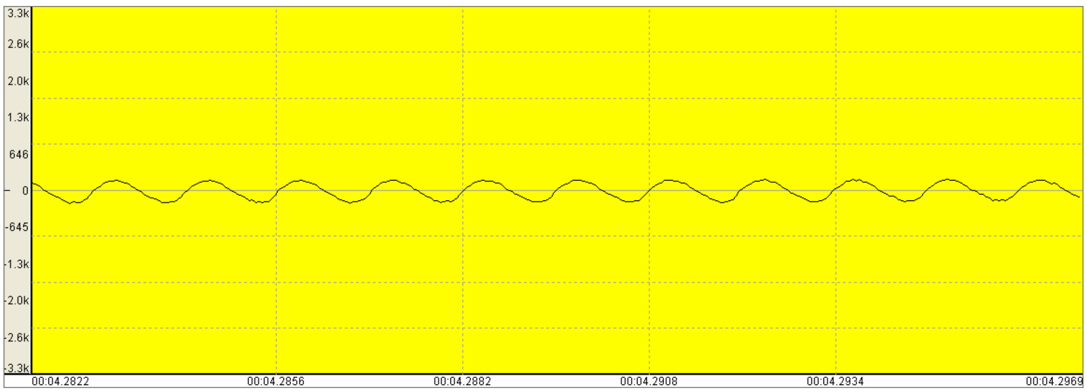


(c)



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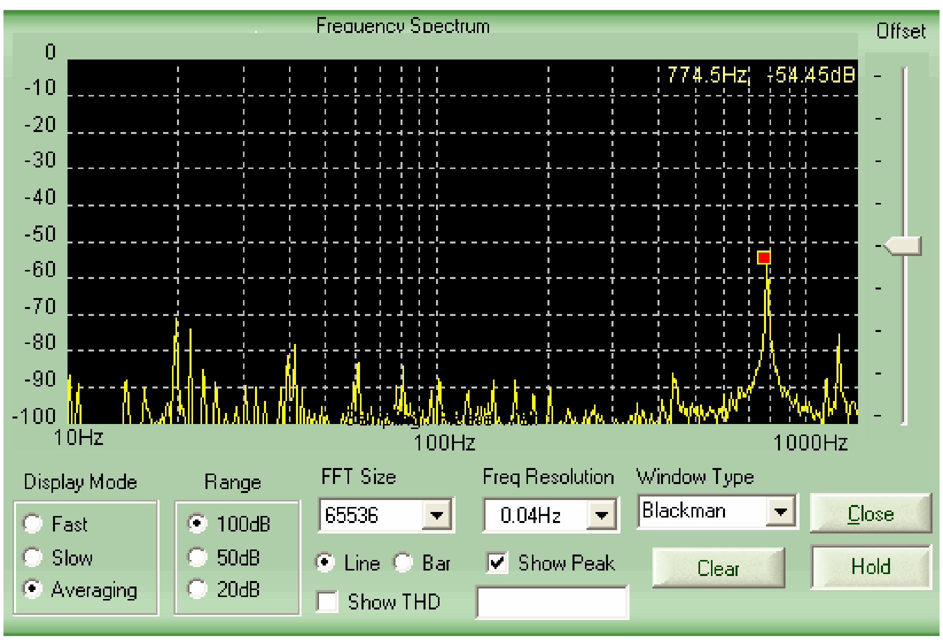


(e)

FIGURE 2: (a) Entire recording of four separate forced oscillations of the wire. (b) Close up of one entire signal. (c) Close up of very beginning of signal, shortly after forced oscillation. (d) Close up of signal near the end. (e) FFT Frequency Spectrum of the signal.

The average fundamental frequency is then used to calculate the corresponding tension using equations (2) and (3) described above. The calculated tension versus the measured frequency is graphed on the same plot as a theoretical curve for tension versus frequency in FIGURE 3. The experimental data agrees very well with the theoretical data and any error is indiscernible from the graph. The experimental percent error was calculated for each of the 31 data points and the Root Mean Square of all 31 percent errors was found to be 0.375. Predictions were not consistently over or under the actual tensions expected.

The angle of rotation for each of the data points was converted to axial deformation using equation (4) and graphed versus tension in FIGURE 4. There is a small change in Young's Modulus around 3.5 lbf, which corresponds to the manufacture specified yield point.

With confidence that the vibrating frequency of a wire can be measured accurately and the corresponding tension predicted, the liquid nitrogen cool down tests could continue.

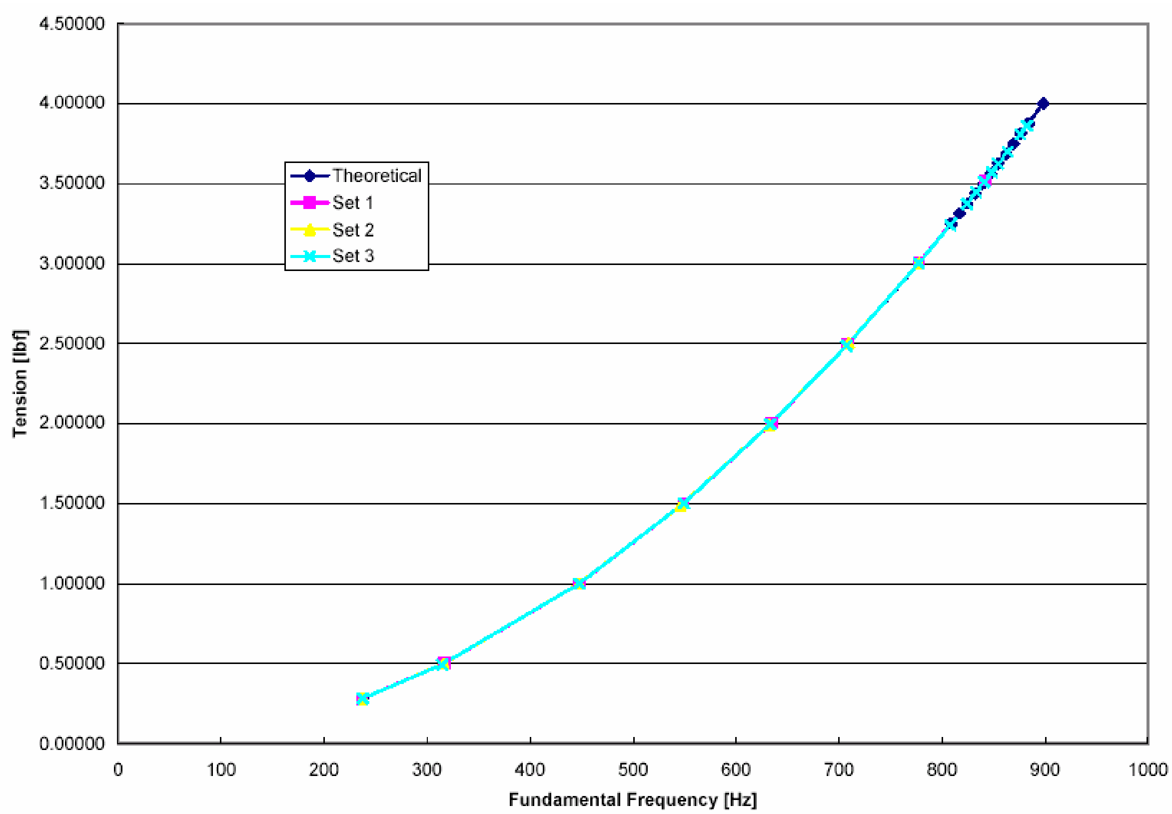


FIGURE 3. Tension vs. Fundamental Frequency

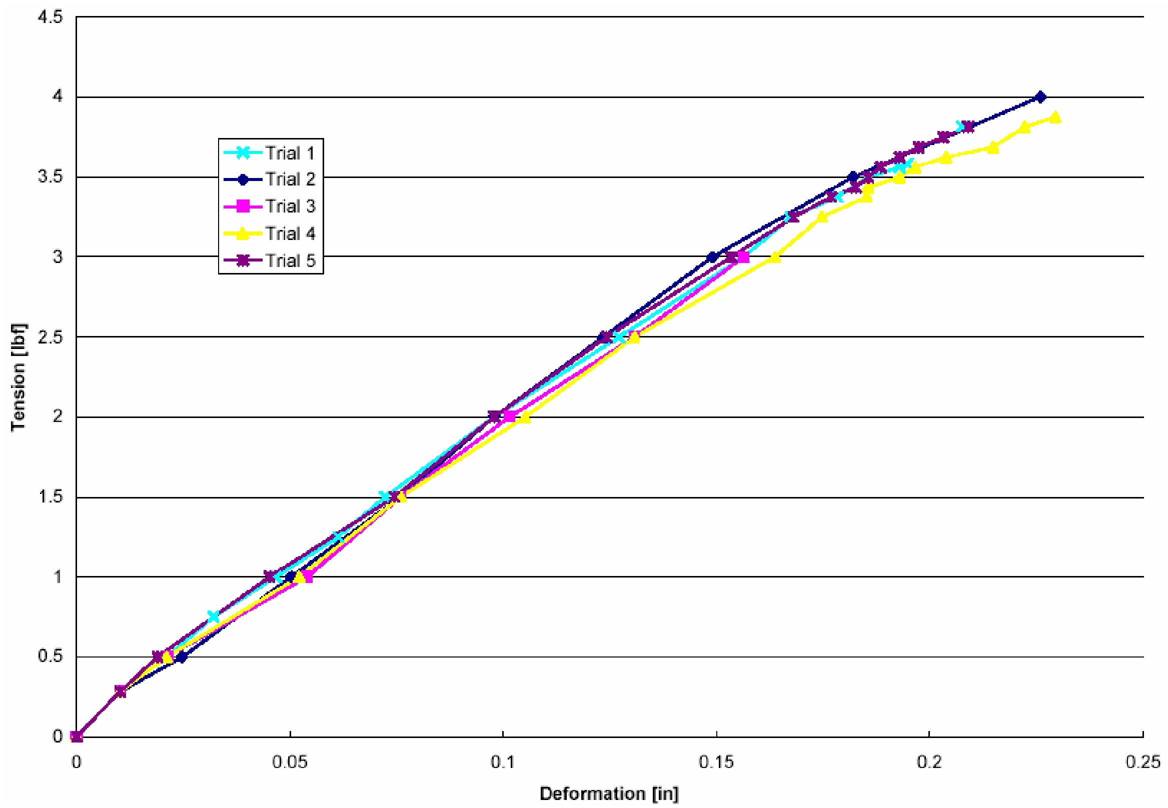


FIGURE 4. Tension vs. Axial Deformation

LIQUID NITROGEN COOL DOWN TESTS

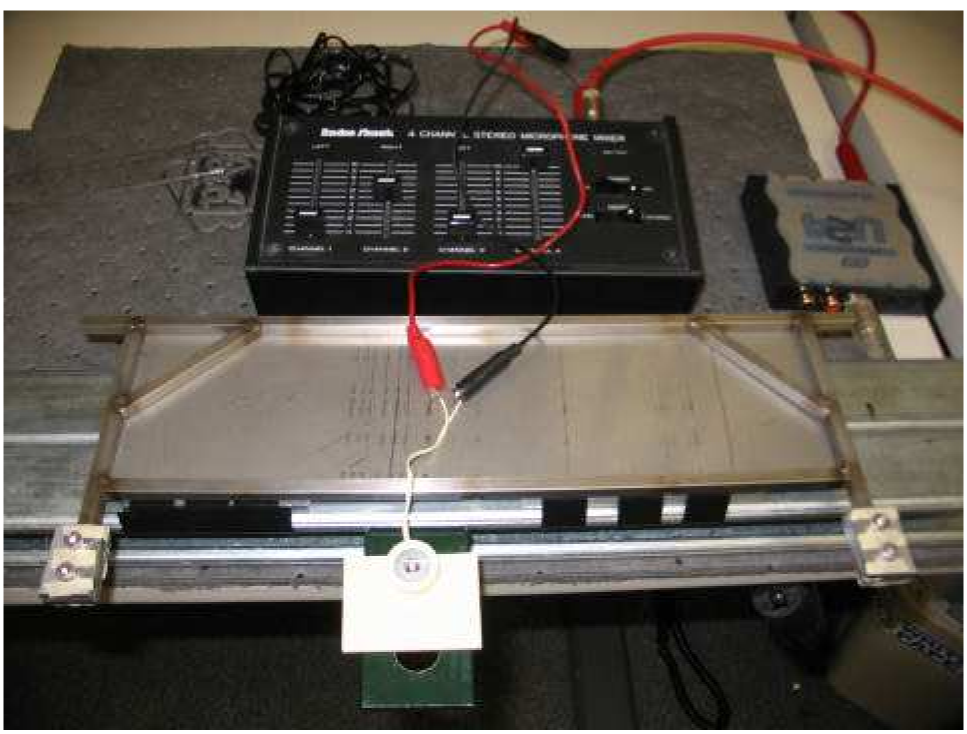
Experimental Setup and Procedure

The wire holder apparatus can be seen in FIGURE 5. A sample of wire is fixed at its ends by screwing two sheets of stainless steel 304A together and pinching the wire. The metal clamps are suspended away from the support structure, so the wire can be submerged without cooling the entire apparatus. Therefore, the wire is rigidly fixed at a length 11.26”.

First, to tension the wire to a desired tension, the wire holder is installed vertically in a vice grip, as seen in FIGURE 5 (a). A sample of wire around 20” is clamped at the top of the apparatus and hangs between the two pieces of unclamped metal at the bottom. At the end of the wire, a loop is made and the mass holder is hooked to it. The desired tension is then obtained by adding the equivalent amount of mass minus the mass of the holder. Finally, the bottom is tightly clamped and the wire is fixed into place. The mass and holder is then removed from the vice and the wire holder is taken for an initial frequency measurement, as seen in FIGURE 5 (b). The method for measuring the fundamental frequency of the wire is the same as described earlier. The corresponding tension is calculated using equations (2) and (3).

Next, the wire is submerged in an open liquid nitrogen bath for one or two seconds. Once removed, the wire and clamps are allowed to warm up to room temperature. A new frequency measurement is taken and the corresponding tension is calculated. The wire is then removed and a fresh sample of wire is prepared. The procedure is repeated for a range of tensions.

(a)



(b)

FIGURE 5: (a) Wire Tensioning Setup. (b) Frequency measuring Setup.

Calculations

A theoretical increase in tension is calculated using classical mechanics. Noting the wire is at a fixed length and under goes zero total deformation, we can write an equilibrium equation of deformation.

$$\delta = 0 = \frac{T \cdot L}{A \cdot E} - \alpha \cdot \Delta T \cdot L \qquad (5)$$

Solving for T we get the theoretical increase in tension due to cool down.

$$T = A \cdot E \cdot \alpha \cdot \Delta T \qquad (6)$$

The fractional contraction ($\alpha \cdot \Delta T$) from 293°K to 90°K is said to be 0.0027, A is the cross sectional area of the wire and E is Young's modulus. For the 3.85 mil wire we calculate an increase in tension of 0.896 lbf. Note from equation (6) T is independent of the length of wire. It's also important to note that this increase in tension differs physically from increasing the tension in the wire by pulling on its ends and stretching it.

Results

In total, seven trials were preformed, one in which the wire failed. When tensioned initially to 3 lbf and clamped, the actual tension calculated from the measured frequency before cool down was 2.86 lbf. At this tension the wire failed immediately upon cool down. By adding the theoretical increase in tension calculated above, we get a predictive maximum tension of 3.756 lbf during cool down.

By taking the difference between the desired tension, created by the mass before clamping the bottom end, and the actual tension, calculated from the measured frequency after clamping, it was found that the wire always experienced a loss in tension. FIGURE 6 is a graph of the difference in tension due to clamping versus desired tension. In three of the trials the clamp was layered with two sheets of aluminum foil. It appears from FIGURE 6 that the use of aluminum foil slightly helped decrease the loss in tension due to clamping.

The difference in frequency before and after cool down is plotted versus desired tension, actual tension, and max tension in FIGURE 7. Desired Tension is the tension created by the weight of the mass and holder, before clamping the wire into place. Actual Tension is the calculated tension from the measured frequency before cool down. And Max Tension is the predictive maximum tension the wire experiences during cool down. Drops in frequency, ranging from (0 to 7 Hz) are seen to occur for every trial, even at tensions well below the yield tension.

It's believed that the severe stress concentrations due to the clamps pinching the wire at the ends, causes the wire to permanently elongate slightly at these locations during cool down. The change in tension corresponding to the change in frequency ranges from (0.005 to 0.05 lbf) as seen in FIGURE 8. The wire ends were observed through a mini hand microscope and revealed the clamps had permanently deformed the wire. A rough surface with dents and kinks was seen rather then the usual smooth surface observed on the rest of the wire.

Seen in FIGURE 7 the slope goes from positive to negative at the point where the predictive maximum tension indicates the wire has went beyond the yield tension. This is contradictory to what was originally expected. It was thought, the wire would permanently deform and elongate at tensions above the yield tension, thereby causing a decrease in tension and a sudden increase in delta frequency. It's suggested that some residual stress remains in the wire after warm up, resulting in a slightly higher tension then before cool down and thus, a decrease in delta frequency.

Intuitively, it was thought that the wire would act the same way as if the tension was increased by pulling its ends apart, beyond the elastic limit and then releasing the tension by returning the wire back to its original length. The wire would sag more due to the permanent elongation and the wire's overall tension would decrease.

Instead, in our case, there is no deformation in length and the internal stress of the wire is more complex. The entire wire wants to contract inward and increase it's density but the rigid ends do not allow it. As a result, it is believed the large internal forces experienced within the material cause the molecular structure to change permanently and when the wire is warmed back to room temperature, not all of the internal stress is relieved.

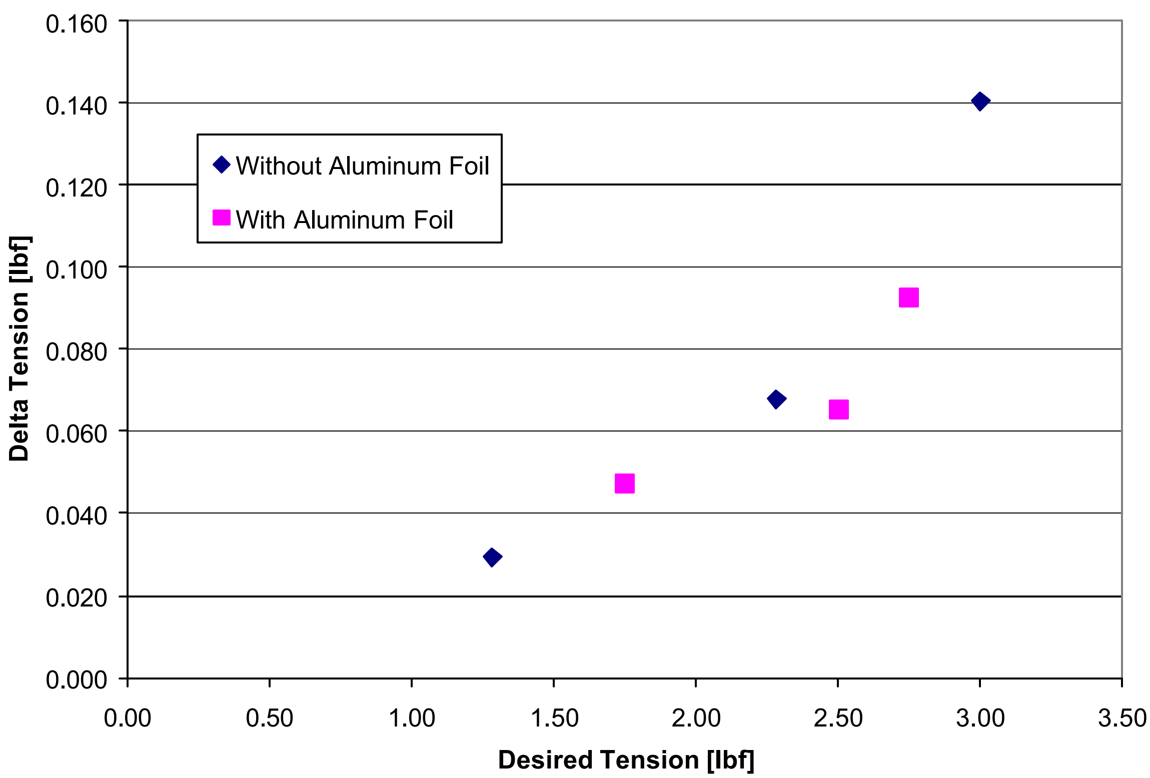


FIGURE 6: Drop in tension due to clamping versus desired tension.

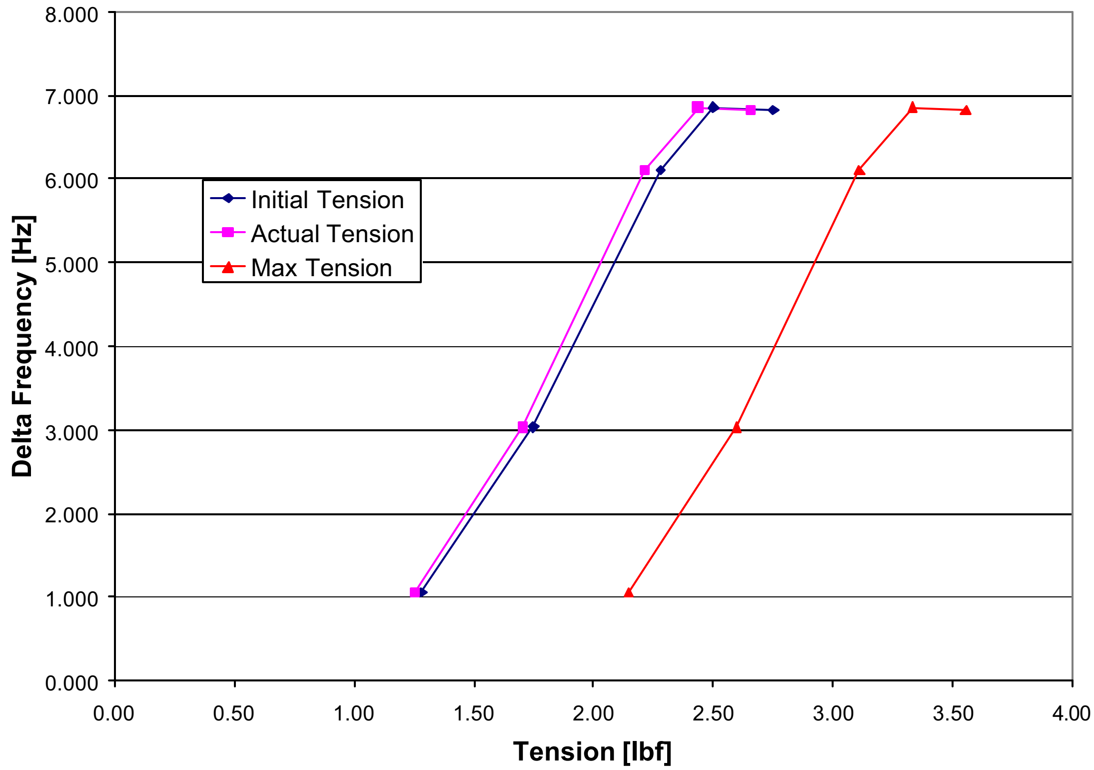


FIGURE 7: Difference in frequency before and after cool down versus tension.

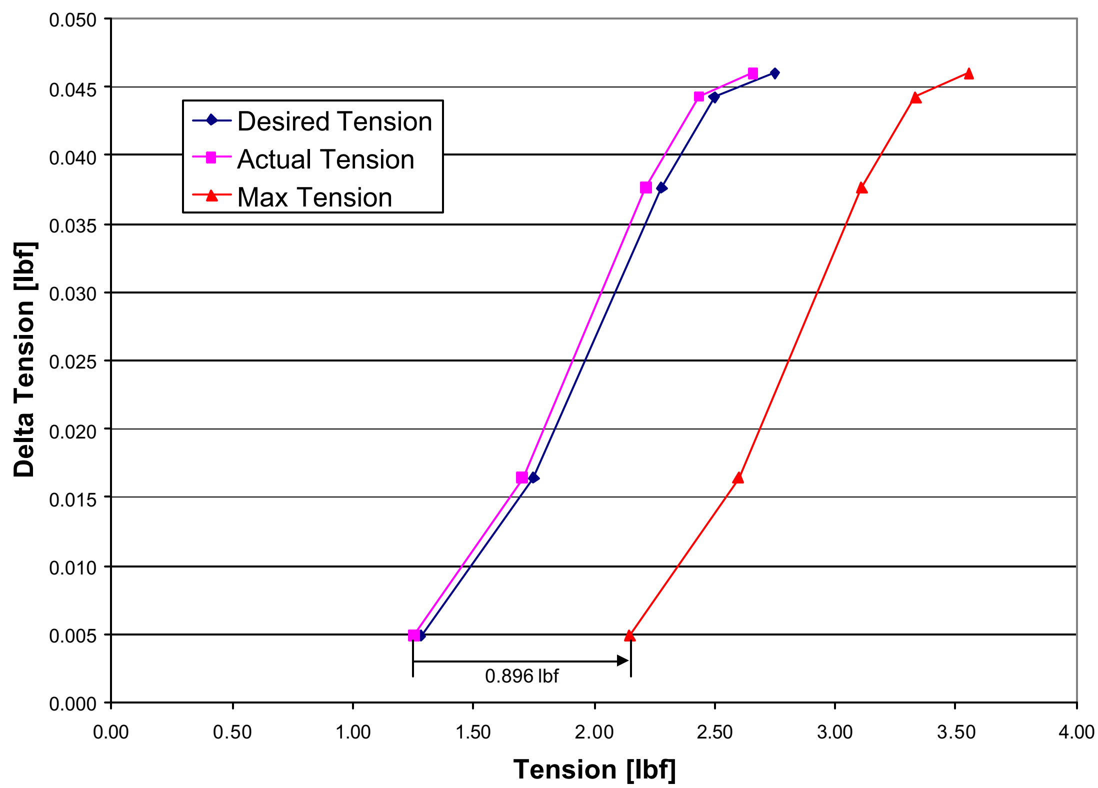


FIGURE 8: Calculated difference in tension versus tension.

CONCLUSION

The tension of a wire can be accurately calculated by measuring its fundamental frequency of vibration. The change in slope may be due to going beyond the yield point, but more tests and research should be done. If possible the diameter of the wire should be accurately measure after each trial.

The tension drop from clamping the ends ranged from (6 to 20 Hz) or (0.03 to 0.14 lbf) and is greater then the tension drop caused by a cool down, (1 -7 Hz) or (0.005 to 0.05 lbf). The method for fixing and tensioning the wires should be carefully considered. More experimentation should be done with various methods of fixing the wires.

FIGURE 9 is a theoretical plot of fundamental frequency versus tension for a 100 ft wire to be used in the final proposed detector. Vortex induced vibrations caused by the natural buoyancy driven currents of the large LAr volume, should be considered. These vibrations could cause the wire to resonate, fatigue and break over time.

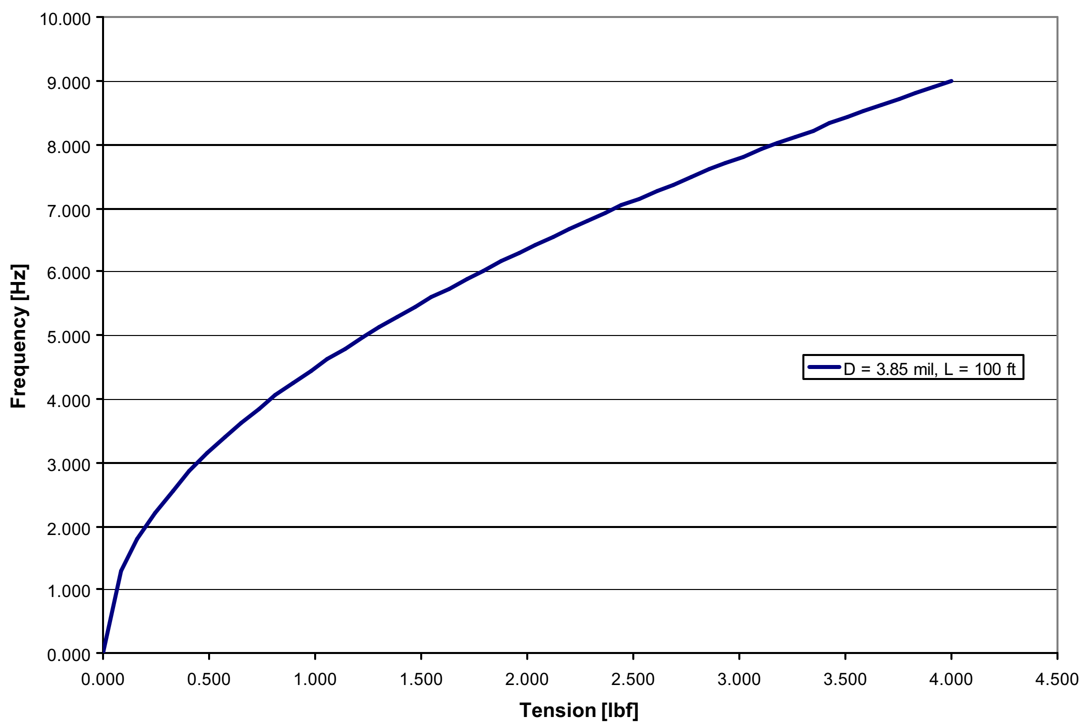


FIGURE 9: Theoretical Frequency versus Tension for 100 ft, 3.85 mil, Stainless Steel 304V, wire.

ACKNOWLEDGMENTS

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