Proceedings of The National Conference
On Undergraduate Research (NCUR) 2014
University of Kentucky, Lexington, KY
April 3-5, 2014

Building a Straw Detector for the Muon g-2 Experiment

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Abstract

Serving as an integral component of particle physics, the anomalous magnetic moment of an elementary particle is often used as a precision test of the widely accepted Standard Model of particle physics. While the theory successfully predicts the magnetic moment of certain particles such as the electron, recent measurements conducted at Brookhaven National Laboratory indicate that the experimental observation of a muon's *g-factor* deviates from the theoretical value by 3.4 standard deviations. This unexpected outcome has caused quite a deal of excitement in the particle physics community as the divergent value suggests the possible existence of physical laws beyond the scope of the Standard Model. Seeking to confirm or debunk this possibility, Fermi National Accelerator Laboratory will run a higher precision iteration of the *Muon g-2* project which will deliver the definitive experimental value of the muon's *g-factor* on the order of .14ppm. In order to attain this desired level of precision the implementation of a high resolution straw-tube drift chamber will be used as the primary particle tracking source. This cutting-edge particle detector will be subject to a high vacuum environment and certain quality control procedures have been designed in an attempt to minimize the possibility of a critical failure (i.e. contamination of the regulated vacuum environment). Northern Illinois University is involved in this quality control procedure and will oversee the assembly of the straw-tube tracker modules. Creep, leak, resistivity and other tests vital to the assembly of the prototype drift chamber have already been put into action with successful results. One of these methods includes the study of a non-contact approach for measuring the tension of the Mylar straw-tubes. By vibrating the straw-tube inside of a known magnetic field with the use of a loudspeaker, the tension of the straw-tube can be approximated by the relationship of the resonant frequency and the set tension. Further collaboration between Fermilab and Northern Illinois University hopes to automate these quality control systems and implement them during the proton test beam runs in 2014.

Keywords: Straw Tracker, Muon g-2, Tension Measurement

1. Introduction:

Often referred to as the heavier cousin of the electron, the muon is a second generation elementary particle with a rest mass roughly 207 times greater than that of the electron.[1] As a result of this additional mass, the muon is not inherently stable and only has a rest frame lifetime of 2.2 μs.[1] Although a few microseconds may seem quite brief, it is actually more than enough time to perform experiments regarding the muon's interaction with other particles and fields.

One of these experiments is the *Muon g-2 Experiment* (E-989). Building on the results from an older muon experiment (E-821) conducted at Brookhaven National Laboratory; the new *Muon g-2 experiment* will measure the anomalous magnetic moment of the muon to a groundbreaking degree of precision (.14ppm).[2] The outcome of this experiment will not only yield the most precise measurement of the muon's magnetic moment, but it will also shed light on the measured value published by E-821, $a_{\mu}^{exp} = 116592089 \times 10^{-11}$, which differed from the theoretical value predicted by the Standard Model, $a_{\mu}^{SM} = 116591802 \times 10^{-11}$, by 3.4σ.[2] Should the new experiment at Fermilab yield a value that diverges from the Standard Model by 5σ (deviation required for a scientific discovery), the discovery of new physics, or physics beyond the Standard Model, would definitely gain credence.[2]

1.1 *g-2*

Before moving on to the specifics of the tracker, it is important to first detail what is being measured. Serving as the ratio of a particle's magnetic moment to its angular momentum, the gyromagnetic ratio (*g*) is analogous to the magnetic moment of an elementary particle.[3] Utilizing standard electrodynamics, the classical magnetic moment of a particle rotating around an axis can be approximated through the following equation,

$$\boldsymbol{\mu} = \frac{1}{2}qvr \tag{1}$$

Substituting in angular momentum, $L = mvr$, we get the following value,

$$\boldsymbol{\mu} = \frac{qm}{2}\boldsymbol{L} \tag{2}$$

Applying these principles to quantum mechanics, one would expect that spin ½ particles (e.g. electron, muon, etc.) would have an angular momentum of,

$$\boldsymbol{\mu} = \frac{e}{2m}\boldsymbol{s} \tag{3}$$

however, considering that the spin of a particle is not comparable to the classical example above, but a phenomenon of quantum mechanics, it becomes clear that the introduction of a gyromagnetic ratio (*g*) is necessary. Thus, the magnetic dipole moment becomes,

$$\boldsymbol{\mu} = g\frac{e}{2m}\boldsymbol{s} \tag{4}$$

From this equation we can now derive the dimensionless *g-factor* (synonymous, but different from the *g-ratio*) for a muon,

$$\boldsymbol{\mu} = g\frac{e}{2m_{\mu}}\boldsymbol{s} \tag{5}$$

where **μ** is the magnetic moment from the muon's spin, m_{μ} is the mass of the muon, **s** is the spin angular momentum and *e* is the charge of the muon. Alternatively, for reasons that will become clear in the section below, the *g-factor* of the muon can also be displayed as a_{μ}, or the anomalous magnetic moment of a muon,

$$a_{\mu} = \frac{g-2}{2} \tag{6}$$

Here it should be noted that 2 is subtracted from *g* due to the fact that the value of *g* is approximately, but not exactly, 2.[1, 3, 6]

1.1.1 *measuring the g-factor*

The process of measuring the *g-factor* begins with a beam of protons slamming into a dense target and producing pions. These pions decay and yield muons which are then fed into a large magnetic storage ring (Figure 1) where they travel at relativistic speeds until each muon decays into a pair of neutrinos and a positron.[1,6] Being much lighter than its parent particle, the positrons drift towards the inside of the storage ring and interact with the straw tube trackers and calorimeters stationed along scallops on the inside wall of the ring (Figure 2). Through the information obtained from the direction of the emitted positrons, the spin vector (difference between Larmor frequency and cyclotron frequency) of the precessing muons can be extrapolated through the following formula,

$$\boldsymbol{\omega_a} = \frac{e}{mc}\left[a_\mu \boldsymbol{B} - a_\mu \frac{\gamma}{\gamma+1}(\boldsymbol{\beta}\cdot\boldsymbol{B}) + \left(a_\mu - \left(\frac{m}{p}\right)^2\right)\boldsymbol{\beta}\times\boldsymbol{E}\right] \tag{7}$$

where e is the charge of the muon, m is the mass of the muon, a_μ is the muon's anomalous magnetic moment, p is the momentum of the muon, **B** and **E** are the magnetic and electric fields used to store the muons and γ is the Lorentz factor.[1]

While the equation above may look a bit complex, it should be noted that by setting the muon's velocity to be perpendicular to the magnetic field, as well as setting filters on the calorimeters to only accept positrons emitted by "magic momentum" muons ($p_{magic} = \frac{m}{\sqrt{a}}$ so that the third term becomes $(a_\mu - a_\mu)\boldsymbol{\beta}\times\boldsymbol{E}$), the second and third terms are effectively canceled out, thus yielding the much simpler reduced formula for $\boldsymbol{\omega_a}$,

$$\boldsymbol{\omega_a} = \frac{e}{mc}(a_\mu \boldsymbol{B}) \tag{8}$$

and finally, solving for our desired variable a_μ,

$$a_\mu = \frac{mc\boldsymbol{\omega_a}}{e\boldsymbol{B}} \tag{9}$$

Given that the m, c and e are all well measured constants and that the magnetic field (**B**) within the storage ring is extremely uniform, all that is needed to find the anomalous magnetic moment of the muon is the precession frequency ($\boldsymbol{\omega_a}$) which can be derived from the information obtained by the tracked positrons.[1]

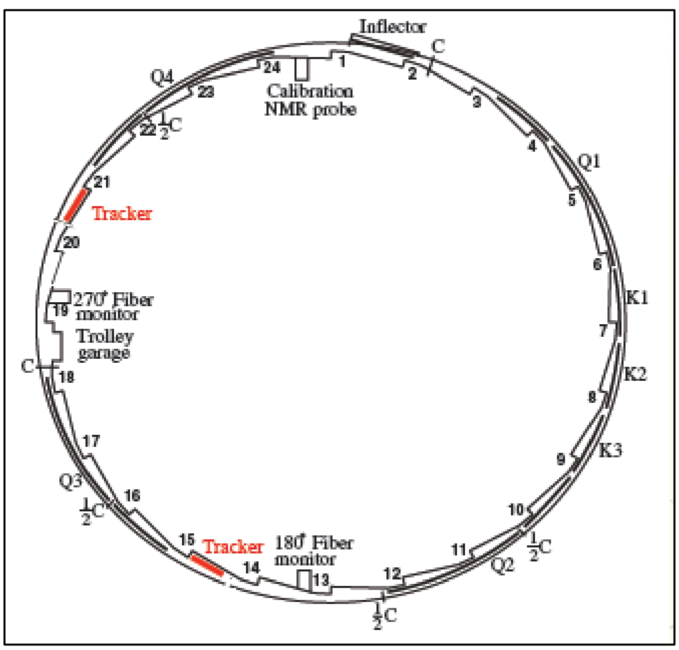

Figure 1. Muon storage ring[1]

1.2 Straw Tracker

One of the main changes to the *Muon g-2 Experiment* will be the introduction of a straw tube tracking system. The basic setup of a straw tracker consists of several stations of Mylar straws (Figure 3) positioned on the interior wall of the muon storage ring (Figure 2). As the muons decay inside of the storage ring they will emit charged particles (e.g. positrons) which will drift towards the center of the ring and traverse the straw tube modules (Figure 3). Upon passing through a single straw tube, the charged particle ionizes the gas inside of the straw, thus creating free electrons which drift to a wire running inside each straw and create an electrical signal. This signal is then registered as a "hit" which can then be digitized, analyzed by a tracking algorithm and ultimately traced back to the origin of the decaying muon (thus providing the information to calculate the g-factor as detailed in the section above). The use of these straw trackers will be invaluable to the *g-2* project as they will account for over 50% of the improvement in precision over E-821.[4]

1.2.1 tracker specifications

Considering that straw trackers come in a variety of different shapes and sizes, it is important to review a few of the technical specifications of the drift chamber to be used in the *g-2* project. The individual straw tubes used in the tracker modules are 5mm in diameter and approximately 12 cm in length (the final length has not yet been decided) and are made of a Mylar material coated with thin layers of gold and aluminum.[8] The inside of the straws is filled with a mixture of argon and carbon dioxide gas (80:20) pressurized at 1atm and each individual straw has a single 25 µm thick wire running concentrically through its interior.[8] These straw tubes are then arranged in a "staggered" geometry pattern which optimizes hit detection and glued into their corresponding tracker (modules vary in size from 8, 16 and 32 straw count).[5] Finally, the straw trackers, complete with accompanying electronics are placed inside of the large muon storage ring in a formation similar to the setup in Figure 2.

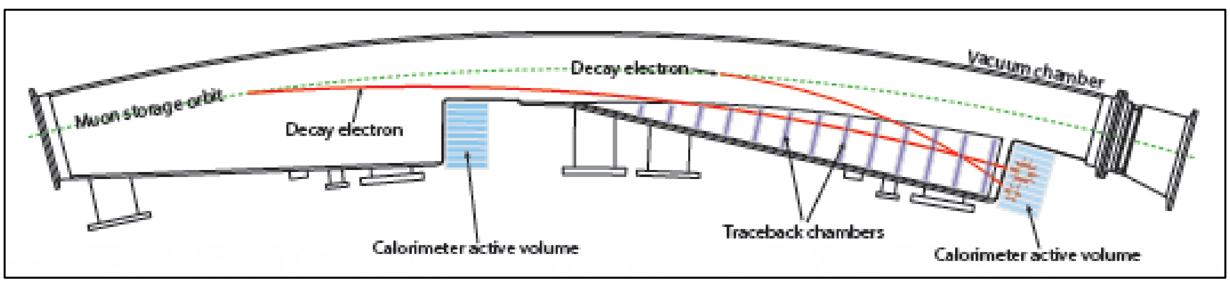

Figure 2. Arrangement of straw trackers and calorimeters inside of the muon storage ring.[7]

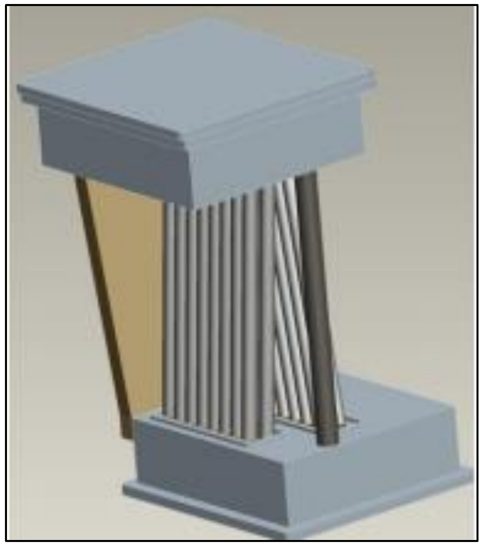

Figure 3. Straws tracker module (32-type).[8]

2. Methodology and Materials

2.1 Quality Control Tests

In order to ensure that the straw trackers run accordingly, several quality control tests have been devised to aid during the production phase of the tracking modules. Properties including resistivity, tension measurement and creep have been tested on the Mylar straw tubes as well as tungsten wire by the NIU Muon *g-2* team; however, this paper will focus only on the two methods used to study the behavior of straw tension.

2.2 Straw Tension Tests

The tensioning of the straws inside of the tracker module serves not only to mitigate the expansion of the straws once inside the vacuum environment of the storage ring, but to also to keep the tubes from stretching or deforming during production.[5] In a method similar to the wire tension tests, an indirect method of tension measurement was devised in which a tensioned straw suspended in the middle of a large c-magnet is vibrated by a loudspeaker, thus creating a measurable EMF (Figures 4 and 5). The loudspeaker sweeps through various frequencies (0-2000 Hz) and the resulting signal is read by an oscilloscope. This signal is then processed via a NI LabView data acquisition VI and the largest V_{pp} amplitude, which correlates to the resonant frequency, is collected (Figure 6).

While it might seem feasible to check the resonant frequency with an equation used to approximate the tension in a solid wire,

$$F = \frac{1}{2L}\sqrt{T/\rho} \tag{10}$$

it turns out that due to the straw length being too short, modeling the tension of the straw using the equation above would yield erroneous results.[10]

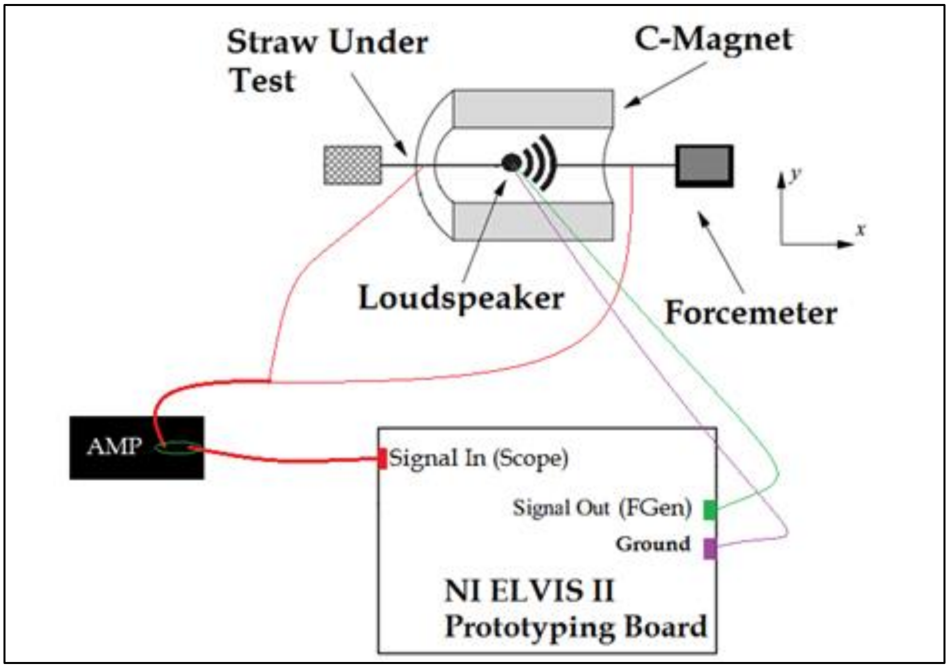

Figure 4. Setup for indirect straw tension test (acoustic method)

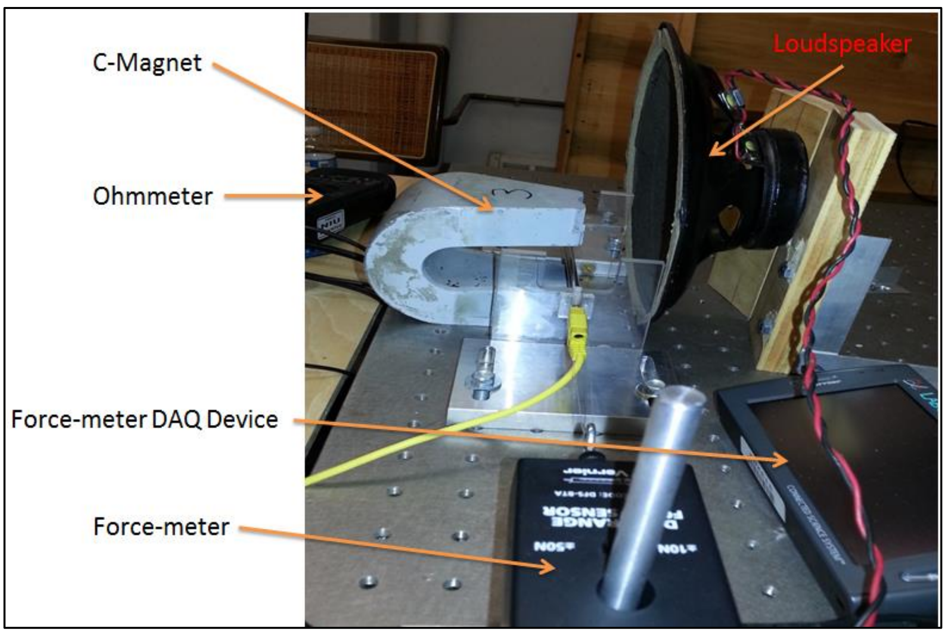

Figure 5. Close up of indirect straw tension test

Figure 5. One should take note that the loudspeaker and NI ELVIS II prototyping board (not pictured) were supported by wooden surfaces in attempt to mitigate the effects of radio frequency interference.

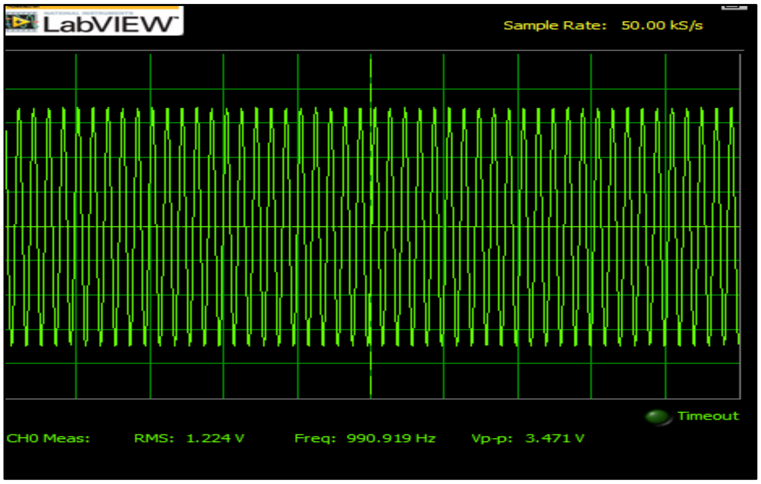

Figure 6. Oscilloscope reading displaying a resonant frequency signal for a straw tensioned at 3N

Figure 6. This image was taken using the integrated oscilloscope function of the NI Elvis II data acquisition tools.[9] The 3.471 Vpp is representative of the observed signal when vibrating a straw tube at its resonant frequency. Not pictured are the various harmonics along with the flat intervals preceding and following the resonant frequency.

As a result of the aforementioned phenomenon, another direct tension method was devised as a means of checking our experimental method for accuracy. This setup was quite simple as it was composed of a forcemeter being fastened to one end of the straw and utilizing a stretching rack to slowly increase the straw-tube's linear displacement. This method, like the indirect tension method, also utilized an ohmmeter to measure the resistance of the straw in between trials (increase in resistance signaled the deformation and destruction of the straw tube).

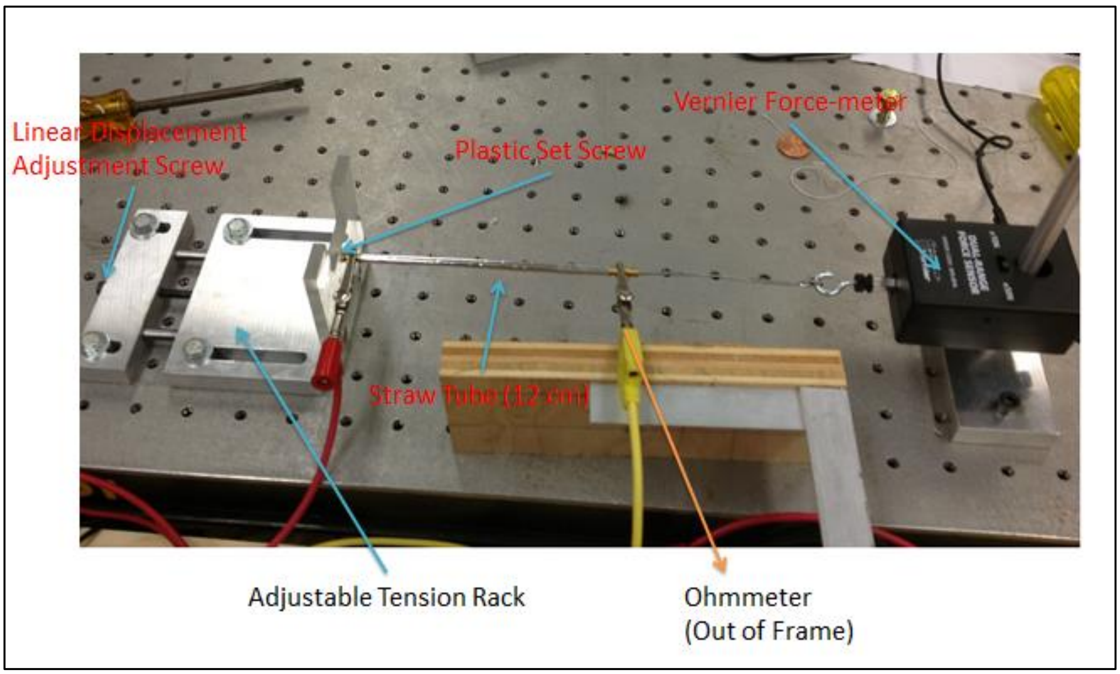

Figure 7. Direct contact tension setup

3. Results

3.1 Direct Contact Tension Tests

The direct contact tension test (forcemeter) was able to successfully observe the relationship between linear displacement and straw tension.

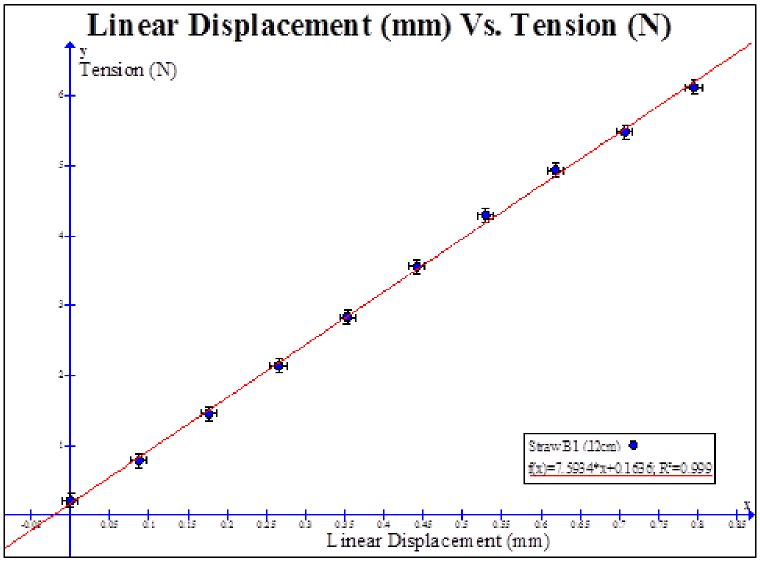

Figure 8. Linear Displacement (mm) vs Tension (N) for a single straw tube

Figure 8. As seen in the figure above it is clear that linear displacement and straw tension share a linear relationship with approximately .1mm change in displacement being proportional to 1N of tension. It should be noted that no readings higher than 6N were performed on the straws as considerable, permanent increases in resistivity (~.5Ω) were observed.

3.2 Indirect contact tension tests

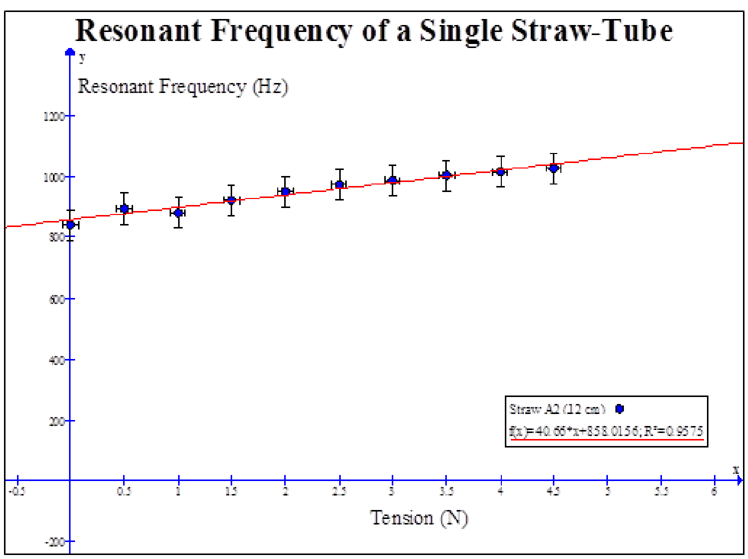

Figure 9. Tension (N) vs Resonant Frequency (Hz) for a single straw tube

Figure 9. Like the direct tension test, the indirect tension test (acoustic method), also produced a linear model that related tension with resonant frequency (i.e. resonant frequency and linear displacement should also be linearly related). Unlike the previous method, however, the acoustic method did not have as high of an R^2 value (.9575 < .9999) due to the presence of a reoccurring "dip" in frequency at the 1N mark. Considering that the resonance behaves linearly before and after that point, we have reason to believe that the dip may be due to a mechanical property of the straw (e.g. yield point), however, more research on a larger sample of straws (the above graph is an average of three straws) would be needed to prove this theory.

4. Discussion

Upon the collection of the straw tension data it became clear that due to the linear behavior displayed by both the indirect and direct tension tests both of these methods could be used to gauge the tension of a single straw tube. As a result of limitations set by the inherit design of the straw tube tracker module (Figure 3), however, it also became apparent that both of these methods would be restricted to perform only certain functions during the various stages of the *Muon g-2 Experiment*.

The direct tension test will most definitely be used during the construction phase of the tracker modules as the invaluable relationship between linear displacement and set tension (.1mm $\propto$ 1N) will allow the straw tracker team to set a tension that will not only account for the expansion of the gas filled straw tubes, but that will also take into consideration the effect of long-term creep (loss of tension due to deformation). Unfortunately, this method will have no use beyond this phase of the experiment as the straws in the tracker module will be glued into place (i.e. performing a pull test with a forcemeter would not be possible).

As for the indirect tension test, the results are inconclusive. While our data (Figure 9) demonstrates that it is possible to approximate the tension in a single straw by observing its resonant frequency, obtaining this data on a stack of tubes, as is the case on the tracker modules, may not be feasible. The main case for this argument is that the sound waves from the loudspeaker would only be able to vibrate the straws on the outer edges and thus obtaining a signal for the innermost straws would be far more difficult due to wave interference. Furthermore, even if the indirect tension method could single out a loose straw during the post-production phase of the experiment, it may prove inconsequential due to the fact that a single straw cannot be replaced as it is glued in place (entire module would have to be changed).

In spite of the aforementioned limitations, it is certain that the devised tension tests will be important during the construction of the straw tube modules and will play a part in the quality control of the experiment. Furthermore, should there be any further design changes before the start of the building phase; it is reassuring to know that we have various means of measuring the straw tension.

5. Acknowledgements

The author wishes to express his gratitude to his faculty mentor Dr. Michael Eads for giving him the support and guidance necessary to complete his research. Furthermore, he would also like to share his appreciation to his NIU peers that assisted him on the project (A. Epps, J. Paschal, and M. Shenk) as well as NIU shop services for their aid in manufacturing many of the parts used in the tension tests. Finally, he would like to thank the NIU Undergraduate Research and Assistantship program for granting him the funds needed to perform this research.

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