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DRAFT

A Device for Quick and Reliable Measurement of Wire Tension

Abstract

A method is described for measuring the tension of a wire. It is based on the well-known technique of inducing mechanical oscillations in a wire by passing an A.C. current through it while it is immersed in a magnetic field. It differs from previous methods in that it uses a short current pulse to excite harmonic oscillations in the wire and then captures and analyzes the "ringing" waveform in a personal computer. The advantage of this method is its robust ability to complete a measurement in a few seconds with a minimum of operator intervention.

1 Introduction

When building a large wire chamber system a quick and reliable method of measuring wire tension is needed. This is quite often done by applying a magnetic field and then determing the mechanical resonant frequency of the wire by studying the properties of the EMF induced as the wire moves through the field. In the absence of damping, the wire tension is related to the fundamental frequency by:

$$f = \frac{1}{2L}\sqrt{\frac{T}{\rho}},$$

where f is the frequency of the fundamental mode, L is the length of the wire, T is the tension and ρ is the linear mass density.

Various devices for for measuring wire tension using this effect have been described in the literature [1, 2, 3, 4, 5, 6]. These devices have found the wire's resonant frequency by detecting either the phase shift or amplitude dependence between a driving oscillatory current and the induced EMF. Both methods suffer the disadvantage that in searching for the resonant frequency, one must scan many frequencies in the range where the resonance is expected. The scanning process can be quite time consuming, often taking several minutes. If the wire is so slack that its resonant frequency falls below the range of frequencies scanned, there is a danger of mistaking a higher harmonic for the fundamental, thus greatly overestimating the wire tension.

Our method eliminates the need to scan a range of frequencies by, in effect, plucking the wire with a brief (3 ms) pulse of current and then observing the oscillating voltage induced by the wire's vibrations. The waveform is captured and analyzed by an IBM compatible PC computer equipped with a data acquisition board. The operator is only required to hit one key on the PC keyboard and a tension measurement is produced a few seconds later. The waveform is also displayed and can be checked by the operator to insure that it looks as it should.

This method most closely resembles that used by a commercially available wire tension meter manufactured by KFKI in Hungary, which finds the resonant frequency by synchronizing a series of excitatory pulses with the natural resonance of the wire [7]. The KFKI device, while quick, is still susceptible to the problem of mistaking a harmonic for the the fundamental when the wire is slack.

Our technique was initially developed to be used on a large straw chamber system for the SSC and was subsequently refined and used to check the tension in the wires of the 2500-tube straw chamber system built for experiment E787 at BNL.

2 Apparatus

A block diagram of the apparatus is shown in Fig. 1. The wire under test is immersed in a transverse magnetic field produced by a large "C" magnet. The field intensity had a full width at half maximum of about 30 cm and was about 380 Gauss at its peak.

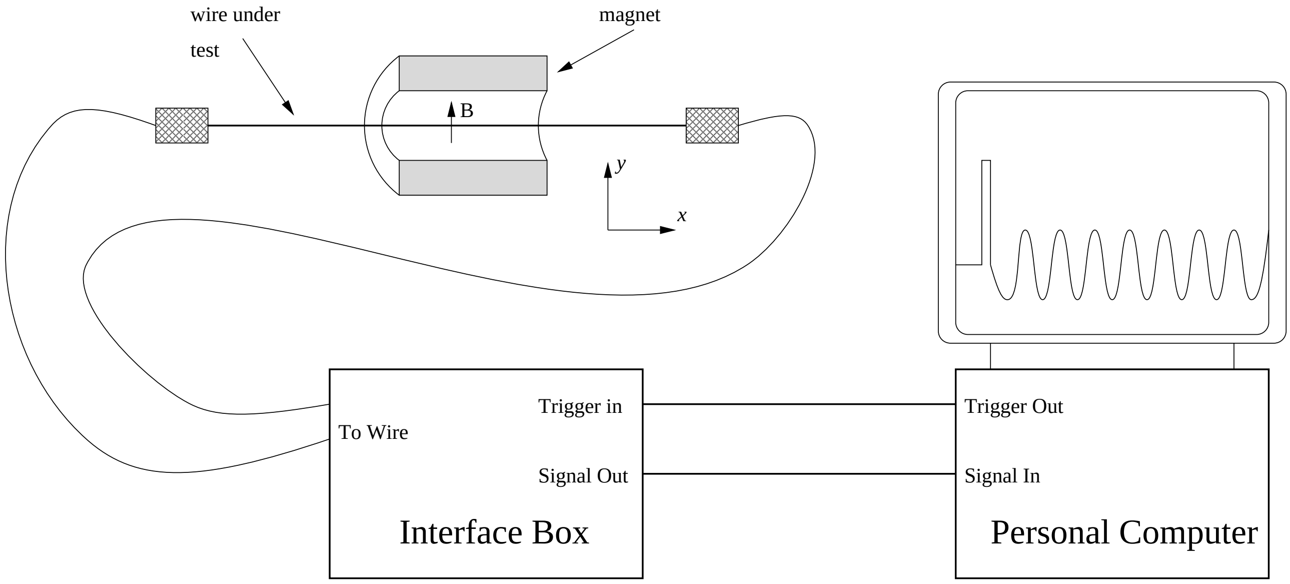

Figure 1: Block diagram of tension-measuring apparatus.

The operator initiates the tension measurement by striking a key on the keyboard of the PC. This signals the data acquisition board [8] to start taking data and sends a TTL trigger pulse to the Interface Box. A circuit diagram of the interface box is shown in Fig. 2. The interface box receives the trigger from the computer and generates a short (3 mS) high-current (46 mA) square pulse on the wire. The 50-μF blocking capacitor insures that even if the 74123 one-shot gets stuck in the high state, the current-source transistor will not stay on, thus protecting the wire from large DC currents. The current pulse sets the wire to oscillating at its fundamental frequency thus producing an EMF at this same frequency. The induced signal is amplified by the LF411 op-amp (gain adjustable between 400 and 4000) and sent back to the computer.

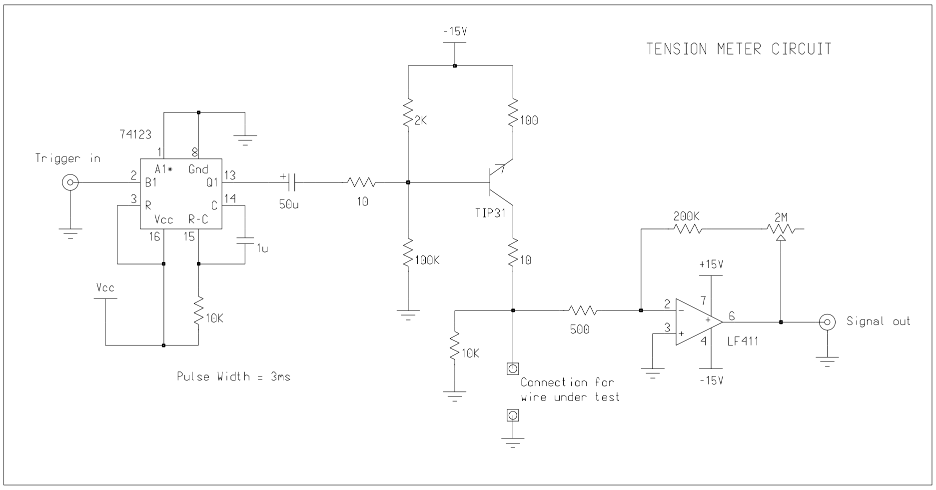

Figure 2: Circuit diagram of interface box.

The signal is then digitized by the data-acquisition board. Typically, 1024 samples were taken at a sampling frequency of 2 kHz. The digitized signal is analyzed by means of a Fast Fourier Transform algorithm, REALFT [9], to produce a frequency-space spectrum. The peak-frequency location is defined as the contents weighted average of the frequencies of the five bins on either side of the highest bin. The whole process takes about fiveseconds on a 286 PC and would certainly be faster on a more modern computer.

The parameters of the interface box were chosen with the E787 straw chamber wires in mind. If the system were to be used with a different chamber, a number of changes would be desirable. The driving pulse should be shorter than one half the period of the fundamental. For the E787 chambers the period of the fundamental is approximately 12 ms, so the driving pulse duration was chosen to be 3 ms. For shorter-period wires, this duration would need to be reduced. The E787 wires were also quite low resistance (30 Ω), so they presented a low output-impedence source to the op-amp amplifier. This allowed a low input impedence of 500 Ω to be used. For wires of higher resistance, a higher input impedence would be necessary so that the signal is not reduced by voltage divider losses in the wire. In fact, it would probably be desireable to add a “buffer” stage between the wire and the amplifier to minimize this effect. Higher wire resistance must also be taken into account with regard to the transistor current source. The maximum voltage across the wire that the transistor can produce is about 14 V which will limit the driving current for a high-resistance wire.

3 Performance

It is shown in the Appendix that the amplitude of the induced signal is given by:

$$V = \frac{2I\tau F^2}{\rho L}.$$

Definitions of the variables and their values for the system as used for the E787 straw chambers are shown in Table 1. The field integral F is defined by

$$F \equiv \int B_y(x)dx.$$

For example, the large magnet used for the E787 chambers had a field of approximately 300 G over a distance of about 30 cm, giving a field integral of approximately 9000 G-cm = 0.009 Tesla-meters.

Table 1: Parameters of the tension measuring system as used for E787 straw chambers.

Parameter	Value
Driving Current (I)	46 mA
Driving Current Duration (τ)	3 mS
Effective Magnetic Field (B_{eff})	.029 T
Magnetic Field Length (l)	.3 m
Field Integral (F)	8.93 $\times 10^{-3}$ T-m
Wire Length (L)	1.15 m
Wire Linear Density (ρ)	3.7 $\times 10^{-5}$ kg/m
Wire Tension (T)	1.47 N

With the parameters given in Table 1, the expected signal amplitude is 5.2×10^{-4} Volts. Figure 3 shows a waveform produced by an E787 straw chamber being checked with the system. The typical amplitude was 3×10^{-4} Volts, in reasonable agreement with the prediction given the simple assumptions that went into the calculation. Histograms of repeated tension measurements for two different wires are shown in Fig. 4. These show that the "statistical error" of a single measurement is approximately 0.5%. The day-to-day variation of the mean of a large number of measurements is of the order of 0.3%.

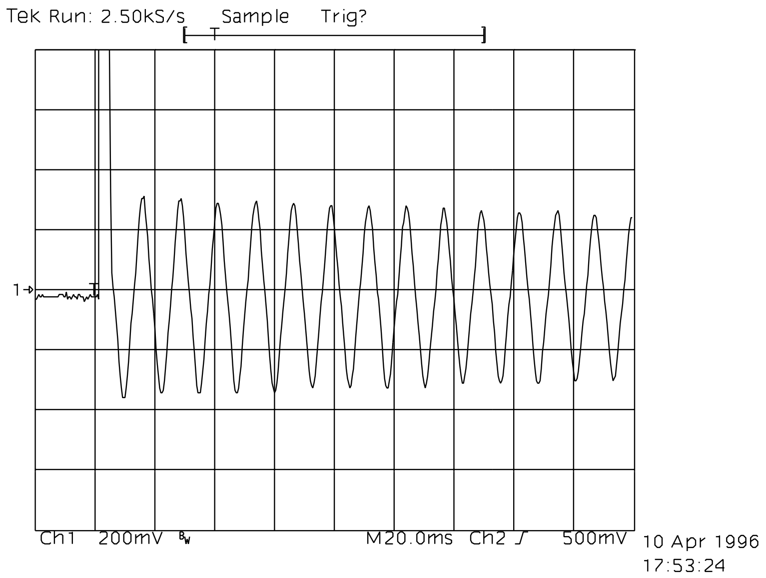

Figure 3: Tension measurement waveform from E787 straw chamber. The large driving pulse and the signal due to the ringing of the wire are visible. Electronic gain was 1000.

4 Low-Field Performance

While building the E787 straw chambers we had the luxury of using a large magnet which produced very large signals. If this system were to be used in a large cylindrical chamber, such a large magnet would not be practical. In fact, the field integral F would probably be about a factor of 10 smaller - yielding signals 100 times smaller. It is therefore interesting to know how well the system would perform with a much lower field.

The wire tension was repeatedly measured at four different values of the field integral F to see the effect this had on signal size and tension-measurement precision. This was done by moving the chamber farther away from the magnet, thus reducing the field and the field integral. While it is actually the length of the magnetic field, l, that would be smaller in a cylindrical chamber setup, it is the integral of the field that controls the signal size so reducing the intensity of the field will have the same effect. The field was measured at several points along the wire with a Bell Model 4048 Gaussmeter and the results averaged to produce an estimated field integral. The values of field integral were 11.7, 20.2, 34.8 and 89.3 Gauss-meters. For comparison, the maximum field integral of a small 1-inch "C" magnet is approximately 20 G-m.

A Tektronix TDS744A digital oscilloscope was used to measure the amplitude of the signal. The range of fields spanned about an order of magnitude corresponding to about a factor of 100 in signal size. The results are shown in Fig. 5. The signal size shows the expected strong dependence on field. The measured tension shows a slight dependence on field of about 0.6%. And, most strikingly, the width of measured tension distribution - which corresponds to the precision of a single tension measurement - depends quite strongly

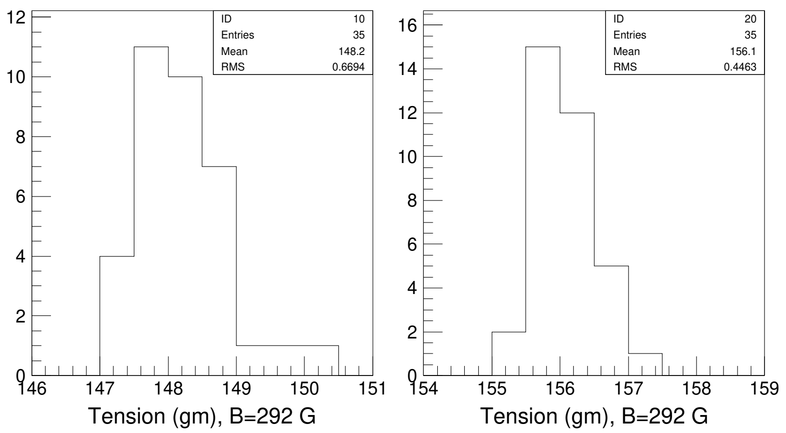

Figure 4: Histograms of repeated tension measurements for two different wires in the E787 Straw Chamber production configuration.

on field. This is due to the much smaller signal-to-noise ratio which is produced at the lower fields.

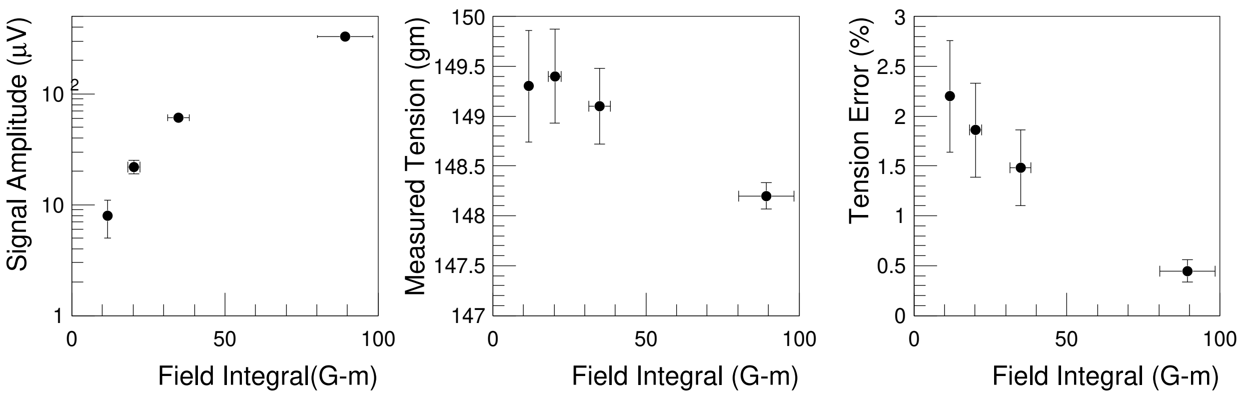

Figure 5: Plots of the measured signal amplitude before amplification, the average measured tension and the width of the measured tension distribution as a function of the field integral.

The signal-to-noise variation can be seen in Figs. 6 and 7. Figure 6 was taken at the high field such as was used for the E787 straw chambers. The two traces are the waveform and its Fast Fourier Transform. The peak at 80 Hz in the Fourier transform is the fundamental frequency of the wire. The peak at 240 Hz is the third harmonic. The second harmonic is missing because it has a node at the center of the wire and thus is not efficiently excited when the magnet is at the center. Figure 7 shows the same two traces for the low-field configuration such as would most likely be used for a large cylindrical chamber. The signal-to-noise ratio is clearly much smaller. Nonetheless, the peak at 80 Hz is still quite evident.

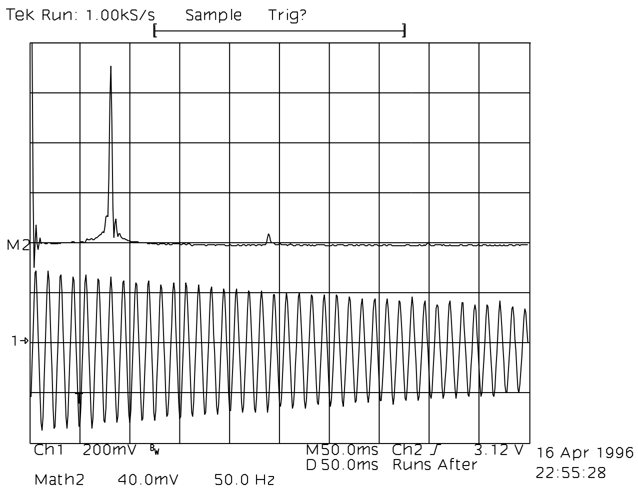

Figure 6: Digital-oscilloscope traces showing the time-domain waveform and its Fourier transform as calculated by the scope. The Fourier spectrum is plotted at 50 Hz/division The peak at 80 Hz is the fundamental frequency of the wire. The field integral for these traces was 89.3 G-m.

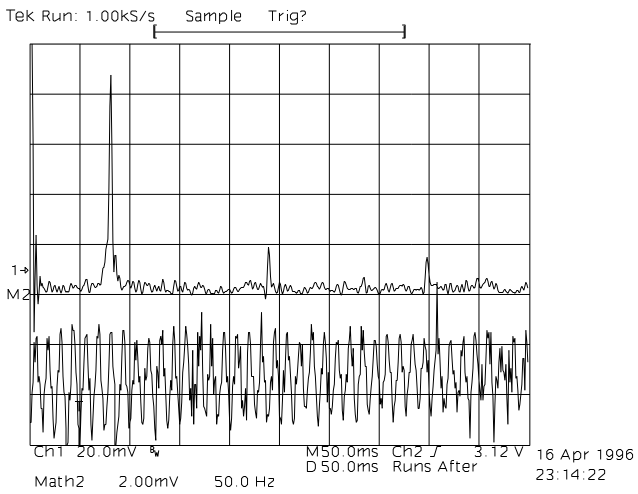

Figure 7: The same traces as in Fig. 6 but taken with a field integral of 19.3 G-m. The fundamental frequency peak at 80 Hz is still very evident, although smaller than in the high-field configuration.

While it appears that the SNR should be acceptable even for somewhat smaller fields than were used for the E787 chambers, there are a number ways of improving it if necessary.

Averaging several consecutively measured waveforms together will enhance the SNR because the signal will add coherently while the noise will add incoherently. Another way of improving the precision would be to make several measurements and average them together for each wire. Either of these techniques, however, would lengthen the amount of time necessary for the measurement to roughly 20 seconds. Other ways to enhance the signal include using a higher driving current and using a more exotic permanent magnet material to produce a higher field.

5 Conclusion

The technique described provides a quick and reliable measurement of wire tension. It works best when a large magnetic field of order 100 Gauss-meters is used but also provides an acceptable measurement for more modest fields of 10 to 20 Gauss-Meters, such as would be provided by a one-inch "C" magnet. It therefore appears that a very similar apparatus as was used for the E787 straw chambers could be used for checking the wire tension in a large cylindrical drift chamber such as the one planned for BaBar.

6 Appendix: Expected Signal Size

In order to design the electronics for this system and to determine the feasibility of its use in various configurations, it is useful to have an order of magnitude estimate of the size of the signal produced by the oscillation.

As shown in Fig. 1, the wire is pointing along the x-axis and is a immersed in a transverse magnetic field. The magnetic field is approxmiated by:

$$B_x = 0, \qquad B_z = 0, \qquad B_y = \begin{cases} B & |x| \leq l/2 \\ 0 & |x| > l/2 \end{cases}.$$

Such a field is not too different from the one produced by a "C" magnet.

The driving current used to initiate the oscillation is assumed to be very short on the time scales of relevance and so an "impulse" approximation is used. The wire in the region of non-zero field is assumed to come up to a constant velocity instantaneously. The intial state of the wire is described:

$$q(x, t=0) = 0, \qquad \dot{q}(x, t=0) = \begin{cases} v_0 & |x| < l/2 \\ 0 & |x| > l/2 \end{cases}.$$

where $q(x,t)$ and $\dot{q}(x,t)$ are the transverse displacement and transverse velocity, respectively.

For these initial conditions the amplitude of the fundamental mode is given by [10]: *

$$A_0 = \frac{4v_0}{f\pi^2} \sin(\frac{\pi l}{2L}) = \frac{2v_0 l}{\pi f L}, \frac{l}{L} \ll 1,$$

*Higher frequency odd modes are also excited with an amplitude:

$$A_r = \frac{4v_0}{rf\pi^2} \sin(\frac{\pi r l}{2L}), r = 3, 5, 7...$$

Although in practice the period of these nodes is usually shorter than the driving current duration τ so they are somewhat suppressed.

where f is the fundamental frequency of the wire.

In the impulse approximation,

$$v_0 = \frac{\Delta p}{m} = \frac{F\tau}{\rho l},$$

where Δp is the momentum change, m is the mass of the wire between $\pm l/2$, F is the force produced by the driving current, τ is duration of the driving pulse and ρ is the linear mass density of the wire.

The force due to the driving current I is

$$F = lIB.$$

We then have

$$A_0 = \frac{2IB\tau l}{\pi\sqrt{\rho T}}.$$

And so the EMF due to the fundamental mode is

$$V = \dot{\Phi} = (lB)(2\pi f A_0) = \frac{2IB^2l^2\tau}{\rho L},$$

again assuming $l/L \ll 1$.

For situations where the field is not uniformwe can replace the quantity Bl with the field integral

$$F \equiv \int B_y(x)dx.$$

In terms of this variable we have

$$V = \frac{2I\tau F^2}{\rho L}.$$

7 References

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