A Technique of Direct Tension Measurement of a Strung Fine Wire

K. Lang, J. Ting, V. Vassilakopoulos

Department of Physics
The University of Texas at Austin
Austin, Texas 78712-1081

November 28, 2021

Abstract

We present a new technique of direct measurement of wire tensions in wire chambers. A specially designed circuit plucks the wire using the Lorentz force and measures the frequency of damped transverse oscillations of the wire. The technique avoids the usual time-consuming necessity of tuning circuit parameter to a resonance. It allows a fast and convenient determination of tensions and is straightforward to implement.
1 Introduction

Many techniques of measuring wire tensions in wire chambers are extensively covered in the literature [1] − [16]. Here, we are presenting a new scheme of performing this task inspired by the principle of generating sound by vibrating strings in an electric guitar. In our novel circuit the plucking is accomplished by forcing a voltage pulse through a wire placed in a static magnetic field. A plucked wire strung in a chamber undergoes damped transverse oscillations with frequencies given by the formula:

\[ f = \frac{n}{2L} \sqrt{\frac{T}{\rho}} \]  

(1)

where \( f \) is the frequency of oscillations, \( L \) is the wire length, \( \rho \) is the linear density of the wire, \( T \) is the tension force stretching the wire, and \( n \) is the order of the harmonic. Frequency of these transverse oscillations can be directly measured by analyzing a waveform of the induced Faraday current.

The main difference between the method presented here and all other techniques known to us is that our circuit offers direct measurement of vibrational frequency (up to a calibration factor) without a usual necessity of tuning the instrument to the resonant frequency of a wire. Once a wire is placed in a magnetic field and is connected to the circuit, the period of oscillations - thus the tension - is determined automatically. This new technique allows the tension measurements to be performed significantly faster than using other methods. We have conducted many tests validating this technique using wires with lengths ranging from 5 cm to 100 cm. Our measurements were done in various conditions and show an excellent agreement between the expected and measured oscillation frequencies. In the following sections, we first briefly review the basic principles of the most commonly used setups for measuring wire tensions, and then describe in detail our technique and performed tests.

2 A Brief General Overview

The development of various wire chambers since early 1970’s and the task of manufacturing reliable long-lived high-quality instruments motivated many different approaches to measuring tensions of wires. Over the years several types of methods have been developed differing in employed physics principles. They range from the most obvious and commonly used electromagnetic
and electrostatic techniques to optical measurements. In this section we give a brief overview of various methods.

A straightforward but somewhat cumbersome way of determining the tensions may be accomplished by measuring the sagitta of a horizontally strung wire. A known weight hung in the center between the two wire-end supports displaces the wire by a distance which depends on the force stretching the wire. This distance may be measured by an electro-mechanical position transducer such as a small differential transformer [1, 2].

Usually, more indirect methods are employed in which the wire is first forced to vibrate and then these vibrations are used to determine the tension. The wire “excitation” can be produced mechanically by gas jets [3], sound waves, or most commonly by electromagnetic or electrostatic forces. The most popular electromagnetic methods use the Lorentz force to generate wire oscillations. Short bursts of sinusoidal or triangular current wave are driven through the wire placed in a magnetic field. By adjusting the frequency of the bursts, the resonance of the wire can be reached. At that point the amplitude of the oscillations, hence the induced emf, reaches the maximum, and the driving and induced waveforms have the same phase [4, 5, 6, 7, 8, 9]. The determination of the resonant frequency is usually accomplished by displaying the driving and the emf waveforms on an X-Y scope. For the lowest and typically the strongest resonance the resulting Lissajous figure becomes a straight line. If induced signals are large, it is also feasible to detect higher harmonics instead of the fundamental emf frequency of the resonance [5].

In the electrostatic methods the wire is forced to oscillate through the Coulomb force. Applying a high voltage sine wave of variable frequency to an electrode, usually an aluminum plate placed alongside the wire, generates mechanical vibrations [1, 2, 11, 12, 13]. To increase the coupling forces, some methods use two electrodes exactly out of phase with the wire in between [1]. Other techniques, instead of plate electrodes, employ parallel neighboring wires as drivers [13]. As before, at the resonance the wire reaches maximum amplitude and exhibits the same phase as the driving waveform. These techniques do not employ magnetic field, thus there is no emf and the determination of the resonance can be done visually, if the wire is visible [1, 2], or indirectly by observing the waveform generated by the change of capacitance between the wire and the electrode [2, 3, 16].

Generally, the electrostatically coupled signal is small so that sensitive balanced bridges need to be used for measurements [2, 14]. In a balanced impedance bridge, the signal is fed back by an amplifier in a circuit analo-
gous to that of a crystal oscillator \[15\]. In this way, the non-linear impedance of the wire guarantees that the circuit oscillates at the natural mechanical resonance frequency of the wire. However, as it is in a typical bridge oscillator, the values of the components have to be tuned very close to the resonance or the circuit will not oscillate.

It should be pointed out that in all the above methods the circuits need to be tuned to the resonant frequency of the wire in order to measure the tension. In most cases this is time consuming and requires careful adjustments of the driving pulses and sensing circuitry. The technique which we are proposing here evades these deficiencies. Our circuit directly determines the resonant frequency by analyzing the characteristic damped oscillation waveform. The measurement does not require any tuning, is fast and robust.

### 3 Circuit Concept

The circuit which we designed is conceptually very simple, as illustrated in Figure 1. It consists of an impulse current source, followed by a signal amplifier and a frequency detector. An optional acoustic amplifier was added to further facilitate the measurements. The principles behind the circuit are the Lorentz force to excite the wire mechanically and the Faraday law to induce a signal on the wire vibrating in a magnetic field. We have primarily tested it using a straw tube wire chamber, but it could be used for most wire chambers. We found that a conductive straw, acting as a Faraday cage, provides a better noise immunity. Our reference description below refers to a wire strung in a 5mm-diameter copperized Mylar straw tube \[17\].

To measure the oscillation frequency the far-end of the wire is shorted to the ground potential. Both the current excitation and the induced signal readout are done from the near-end. A permanent magnet is placed near the mid-point of the wire. At the excitation stage a current pulse (of magnitude of the order of tens of milliamperes) is forced through the wire. It does not flow through the detection circuit because the analog switch S1 is open. This current generates a Lorentz force which is both orthogonal to the wire and to the magnetic field, thereby mechanically displacing the wire. After the current is turned off, the wire vibrates with damped harmonic oscillations and ultimately returns to its rest position. The oscillations of the wire in the magnetic field generate a Faraday current with classical exponential decay envelope which flows through the now-closed switch S1, and into the low impedance measuring part of the circuit. It is first amplified, then filtered,
and then the period of the oscillations is determined and displayed on an LCD panel.

4 Initial Circuit Implementation

The translation of this simple idea into a practical device required following all the basic low-noise circuit practices including a solid single point ground and careful shielding. In the initial trials we used a square voltage excitation pulse. The frequency of oscillations behaved erratically as a function of the tension of the wire. The source of this problem was found to be the interference of two out-of-phase oscillations induced on the wire. One was caused by the leading edge of the excitation pulse and another by its falling edge. The resulting oscillation was indirectly modulated by the width of the excitation pulse. The solution was found by changing the shape of the excitation pulse - a square was replaced by a saw-tooth waveform current. Using a smoother leading edge the initial displacement of the wire is slower, while the releasing is sudden - mimicking plucking of a guitar string.

Another problem found was that for wire oscillations in the frequency range of the order of 60 Hz the interference with the AC power led to some-
what erratic behavior of the circuit. This problem was solved by placing the power supplies and the transformers beneath the circuit box, and by adding a ferrous magnetic shield plate in between.

5 Detailed Circuit Description

The circuit, shown in block diagrams in Figure 2, can be divided into several main functional blocks: Free Running Pulse Generator, Pulse Shaper, Controlled Voltage Source, Analog Switch, Difference Amplifier, Clipping Amplifier, Low Pass Filter, Zero Crossing Detector, Binary Counter, Cycle Gate Generator, NAND gate, Decade Counter, LCD, Free Running Crystal Clock, and Scope Synch. Below we discuss the functions of each part and refer to the detailed circuit schematics shown in Figure 3.

The Free Running Pulse Generator Z1 is a 555 timer chip wired as a free running astable multi-vibrator oscillating at about 1 Hz. The Pulse Shaper changes the fast rising edge of the rectangular pulse into a slowly rising exponential with the $R_6C_4$ time constant. The trailing edge remains fast, as shown in Figure 4. The Controlled Voltage Source changes the reference voltage pulse into a power voltage source. The peak wire voltage can be adjusted up to 10:1 ratio by varying R28. This adjustment improves the signal-to-noise ratio. We typically used peak voltage of 18 V, which corresponds to 62 mA current for the 20 $\mu$m diameter gold-plated tungsten wire which we used [18].

The Analog Switch consists of a pair of FET switches Q3 and Q4. Q3 controls the signal path. Q4 switches a DC reference pedestal. When both are closed at the same time, the switching transients are canceled out by the Difference Amplifier Z5. It is followed by an AC amplifier Z6, which slightly differentiates the signal in order to balance it around ground, and also clips large signals to prevent the saturation of the op amp. The clipping is provided by a pair of back to back 10 V zener diodes CR2 and CR3.

The Low Pass Filter lets through only the fundamental frequency (below 200 Hz) and attenuates all higher harmonics. Depending on the application this filter may need to be adjusted or removed. The Zero Crossing Detector transforms the exponential decaying sine wave, as shown in Figure 3, into a series of logic pulses. The period of the oscillations is measured by a Free Running Crystal Clock. The time window selected for the period measurement is produced by the Cycle Gate Generator and begins at the 5th and ends with the 12th cycle. Thus, 8 complete cycles are gated through
and measured by the Crystal Clock. The CMOS Decade Counter with its 6-digit LCD is a modified “Red Lion” counter where only the 4 most significant digits are used. This arrangement yields good low noise results. A typical reading of about 2011 counts has a ± 2 counts uncertainty. For further convenience we have also added an audio amplifier which translates the measured frequency to a speaker sound.

The Crystal Clock runs continuously at a measured frequency of 32,770 Hz (2 Hz higher than the nominal 32,768 Hz). The frequency of the wire oscillations, $f$, (to be used in formula 1) is determined by a simple expression:

$$f = \frac{32,770}{N_{\text{count}}/8} \text{ [Hz]}$$

where $N_{\text{count}}$ is the number of clock counts within the measuring time window and it is displayed on the LCD panel, 8 stands for the number of cycles within the measuring time window, and 32,770 is the effective frequency of the clock.

The “Red Lion” counter and the LCD require a 5 V power supply. All other logic units use 15 V CMOS primarily for good noise immunity and the capability of direct interface with power MOSFETs.

### 6 Test Results

To determine the functioning of the circuit many measurements were conducted with a variety of circuit parameters and wire conditions. In most tests we used a gold-plated tungsten wire with a 20 µm diameter and a measured linear density of $\rho = 61 \, \mu g/cm$ [18]. For our tests the wire was secured at different tensions by soldering it to two vertically spaced fixed points. The wire was first soldered at the top fixed point, then a weight was attached to it and after the wire stabilized it was soldered to the bottom fixed point which was also electrically in contact with a BNC signal connector. Every time the weight changed the solder was made to re-flow. The conversion of the measured periods into frequencies was done “offline”, but if desired it could be hard-wired into a computer or a microprocessor to convert the direct readings into frequencies or tension.

First, we experimentally verified that the strength of the magnetic field changed only the amplitude of the signal and not its frequency, even when the signals were very large and thus heavily clipped. The position of the magnet along the wire did change the harmonic content of the signal, but
Figure 2: A block diagram of the designed circuit to directly measure wire tensions.
Figure 3: A detailed schematics of the designed circuit to directly measure wire tensions.
Figure 4: An oscilloscope trace showing the shape of the wire plucking excitation pulse.

Figure 5: The oscilloscope trace of the induced signal from the oscillating wire. The signal is not exactly damped sinusoidal due to short range of the magnetic field.

Figure 6: The oscilloscope trace of the signal from the Cycle Gate Generator. The gate is spanning exactly 8 periods (5th through the 12th) is measured to detect the number of zero-crossings.
not its fundamental frequency, and therefore the results were essentially the same. When the magnet is placed at mid-way along the wire the fundamental frequency dominates, the signal-to-noise ratio reaches the highest value, therefore this magnet position was kept throughout the measurements. It should be also pointed out that the induced emf is not exactly sinusoidal but rather has a somewhat square-wave shape as shown in Figures 3. The cause of this effect is the relatively short range of the applied magnetic field as compared to the length of the wire. The triangular wave shape is the result of the differentiation of the square wave. When a single magnet was replaced by a pair of separated magnets along the wire, the signal became much more sine-wave like. Figures 4, 5, and 6 show typical synchronized oscilloscope traces of the excitation pulse, the induced damped emf, and the standard time window for zero-crossing measurement.

The tension of the wire was measured for a wide range of tensions and up to the breaking force of the 20 µm diameter gold-plated tungsten wire of about 1.2 N. The results are shown in Figures 7(a) and (b). The error bars reflect the uncertainty in the wire density, the wire length, and the standard deviation of 10 readings on the instrument. An excellent agreement between the predicted and measured frequencies has been achieved with the circuit.

We also performed a test to check whether the determination of a period of oscillations depends on the position of the time window used. A special circuit generating a sliding measurement time window was built and is shown in Figure 8. This additional circuit allowed the measurement of the number of zero-crossings between the 4th and the 7th cycle, or between the 7th and 10th, or 10th and 13th, etc., at every 4 cycle intervals. Unfortunately the circuit was too big to fit inside the original circuit box. Its use decreased the signal to noise ratio of the system therefore it was removed after this test. The averages and standard deviations were taken from 50 consecutive readings for each window position. The measurements indicate that the readings are fairly independent of the time window. The standard deviation of the measured frequency increases slightly with the time interval between the beginning of the oscillations and the time position of the measuring window. This is expected because the amplitude of the oscillations decreases with time, and consequently its signal-to-noise ratio worsened. The results of these tests are shown in Figure 9.

In our test we liked the addition of an audio amplifier, as implemented in reference [7], which significantly facilitated the tediousness of the measurements. After a bit of practice, one can detect the abnormalities of the wire like shorts, breakage, or very low tensions just by the sound, and with-
Figure 7: (a) Measured frequency squared of a test wire as a function of tension. The points with error bars were obtained using a 1 m long 20 µm gold-plated tungsten wire. The straight line is the predicted fundamental frequency. The excellent agreement is further illustrated in (b) where the same results are plotted as percentage of deviation from the expected value.

out reading the frequency on the LCD monitor. For a large set of wires the tension measurements can be done fast by first grounding all ends on one side, and then by connecting successively the other end of each wire to the circuit. In our tests it typically took only few seconds per channel to determine the wire tensions.

7 Summary

We have designed and tested a new circuit to measure tensions of wires in wire chambers. Our simple technique of plucking the wire electromagnetically and analyzing the frequency of the induced signal is fast, robust and easy to implement. It offers a direct method of determining the tensions without a time-consuming necessity to tune the circuit to a resonance. Our tests showed better than 1% agreement between the applied and measured tension values.
Figure 8: A circuit for the sliding time window test.

Figure 9: Measured frequency (counts) of a test wire as a function of the time window used. The uncertainty increases if later zero-crossings are used.
References

[1] A. Borghesi et al., Nucl. Instr. Meth. A 153 (1978) 379-381.
[2] M. Cavalli-Sforza et al., Nucl. Instr. Meth. A 124 (1975) 73-82.
[3] R. Stephenson et al., Nucl. Instr. Meth. A 171 (1980) 337-338.
[4] Y. Asano et al., Nucl. Instr. Meth. A 254 (1987) 35-43.
[5] S. Bhadra et al., Nucl. Instr. Meth. A 269 (1988) 33-39.
[6] M. Calvetti et al., Nucl. Instr. Meth. A 174 (1980) 285-289.
[7] M. Coupland, Nucl. Instr. Meth. A 211 (1983) 369-370.
[8] Y. Hoshi et al., Nucl. Instr. Meth. A 236 (1985) 82-84.
[9] T. Regan, Nucl. Instr. Meth. A 219 (1984) 100-102.
[10] K. B. Burns et al., Nucl. Instr. Meth. A 106 (1973) 171-180.
[11] D. Carlsmith et al., Nucl. Instr. Meth. A 364 (1995) 79-89.
[12] L. S. Durkin et al., IEEE Trans. on Nuclear Science, Vol. 42, No. 4, August, 1995.
[13] R. T. Jones, Nucl. Instr. Meth. A 269 (1988) 550-553.
[14] N. J. Shenhav, Nucl. Instr. Meth. A 324 (1993) 551-557.
[15] I. D’Antone et al., Nucl. Instr. Meth. A 317 (1992) 155-160.
[16] Construction process of the Atlas Transition Radiation Tracker uses an audio-speaker for tuning wires to resonant frequency. The resonant condition is detected by measuring the variation of the capacitance between the wire and the straw. S. Oh private communication.
[17] S. Graessle et al., Nucl. Instr. Meth. A 367 (1995) 138-142.
[18] We have used a 20 µm diameter gold plated tungsten wire #821 manufactured by Luma Metall International, Kalmar, Sweden.