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Measuring and Verifying Wire Tension

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Summary

The ATLAS MDT baseline design requires tight control of the wire tension in order to guarantee that the wire position determined by the sagitta under gravity and electrostatic forces be well known. In order to realize this design the wire tension must be precisely determined at the time of manufacturing and, ideally, there should be a method of verifying the tension at the time of construction. The wire must be strung in such a manner that the relaxation time of the wire tension is very long. This memo describes experiences of stringing 50 μm wires in a test setup. A method which precisely measures the wire tension by determining the frequency of vibration is outlined.

Introduction

In order to study the essential characteristics of tensioned 50 μm wires several test setups were used. The intent was to study the properties of strung wires and not be very mindful of the mandates of a rapid production facility. Figure 1 shows the essential features of the setup. A precision optical positioner (Newport Optics - A 462) with ≈ 1 μm control and very small backlash was used to tension the wire. A precision strain gauge (Omega Engineering Model LCF-500G) whose calibration is "NIST traceable" was used to measure the wire tension. The strain gauge was mounted horizontally with loose linkages so that there was negligible pedestal strain.

To independently measure the wire tension, vibrations were excited by means of a sinusodial current in the wire in an external magnetic field. The two determinations of the wire tension were compared. The wire resistance was also measured as a function of tension. Two wire lengths were studied, 76 cm and 309 cm. For the 76 cm studies the setup was an 'informal' rig mounted on a solid lab bench. For the 3 meter studies the entire setup was constructed on an aluminum "U" channel strong-back. Wire lengths were measured to about 1 mm for the 76 cm setup and to about 5 mm for the 3 meter setup.

Data were taken of the correlation of the wire tension, as measured with the precision strain gauge, with the fundamental vibration frequency, as well as the third and fifth harmonics, the wire length and resistance. The history of the tension was recorded for several wires in order to study the wire tension as a function of tension and time. The data gathered by both setups were quite reproducible. Fifty micron diameter gold plated tungsten wire manufactured by Philips Elmet Corp. of Lewiston, Maine was used.

WIRE TENSION TEST SETUP

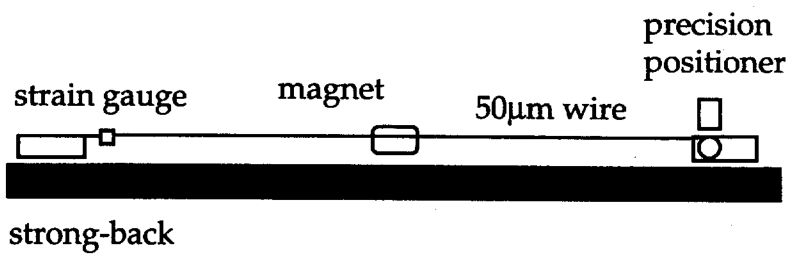

Figure 1. The essentials of the test setup. For the short wire tests, the lab bench and lead bricks served as the strong-back.

Measurement of Wire Tension by AC Bridge

In order to independently determine the wire tension, the mechanical resonance frequency of the wire was measured. The governing equation for small amplitude oscillations is given by:

$$T = (2\,L\,f_0)^2\,\pi\,a^2\,\rho, \qquad (1)$$

where T is the wire tension, L is the length of the wire, f_0 is the fundamental frequency, a is the wire radius and ρ is its density. Useful numbers for a pure tungsten 50 μm wire are $\rho = 1.935 \times 10^4\ kg/m^3$ and $\pi a^2 = 1.964 \times 10^{-9}\ m^2$. The fundamental frequency for a 76 cm wire at 350 grams tension will be roughly 198 Hz. By this equation, a 1% measurement of the wire tension requires knowledge of the wire length, frequency and radius to better by 0.5% [$\delta a \leq 0.13\ \mu m$ - a small tolerance].

For the setup shown in Fig. 1, as the wire is tensioned, the length L increases and the cross section decreases by an amount governed by Young's modulus, Y_m:

$$L = \frac{L_0}{1 - (T - T_0) / Y_m\,\pi a_0^2} \qquad (2)$$

where $Y_m = 35.5 \times 10^6\ Nt/cm^2$ for tungsten. With these two corrections Eq. 1 becomes:

With the length and radius corrections Eq. 1 becomes:

$$T = (2\, L_0\, f_0)^2\, \pi\, a_0^2\, \rho\, (1 + \varepsilon), \qquad (3)$$

with $\varepsilon = \Delta L/L$ and L_0 and a_0 are initial (untensioned) wire length and radius.

A sensitive AC bridge method was employed to detect the oscillation. See Fig. 2. The wire functions as one arm of a resistive bridge which is balanced for driver frequency well away from the fundamental frequency, or equivalently when the magnetic field is removed. When the wire is excited at the mechanical resonance frequency, the wire arm of the bridge is no longer purely resistive and develops an inductance which unbalances the bridge.

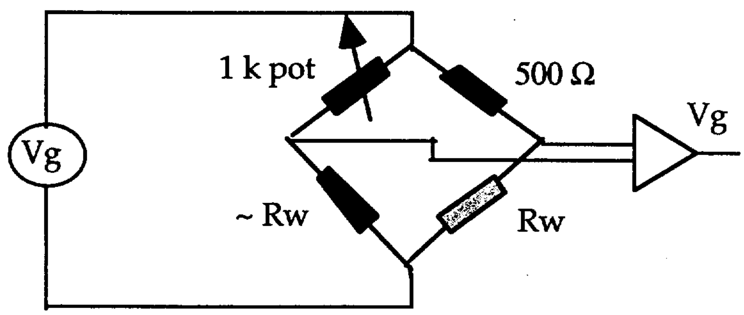

Figure 2. The AC bridge circuit used for measuring the wire resistance. The bridge is balanced with the magnet removed (or off frequency) when the circuit is purely resistive. At resonance, the wire becomes an inductor and resistance in series and the bridge is unbalanced.

At the 200 Hz to 25 Hz frequencies characteristic of the wire resonance for 350 gram wire tension and tubes of 1 to 6 meters length, respectively, the reactance of the other circuit elements are small. The frequency is scanned until a maximum is obtained in the detected bridge voltage. Typically for driver currents of 23 milliamps (Hewlett-Packard 3310B Function Generator) an offset voltage of about 30 mV is developed when using an Edmund's Scientific "C" magnet (Raytheon RK 6249) placed at the middle of the wire span. This voltage corresponds to a inductive reactance of about 1.5 Ω. From the circuit above the current is roughly constant as function of frequency.

The resonance signal is easily detected by means of an oscilloscope with a good differential amplifier front-end with reasonable common mode rejection (Tektronics 7834 Storage Scope with 7A13 Differential Comparator). A Hewlett Packard frequency meter (5315B Universal Counter) is used to quite accurately measure the frequency. Figure 2 shows a typical resonance curve of the fundamental oscillation of a 76.5 cm wire at roughly 350 grams tension. The full width at half maximum is about 2 Hz or 1%. The peak can be determined to about 0.2 % - well within the accuracy needed to measure the wire tension to 1%.

This method was developed to measure the wire tension in limited streamer tubes of the muon system for the SLD experiment at SLAC. Further details of the circuit used in the SLAC experiment are given in the Appendix. The concept of the circuit is amiable to automation with LabView.

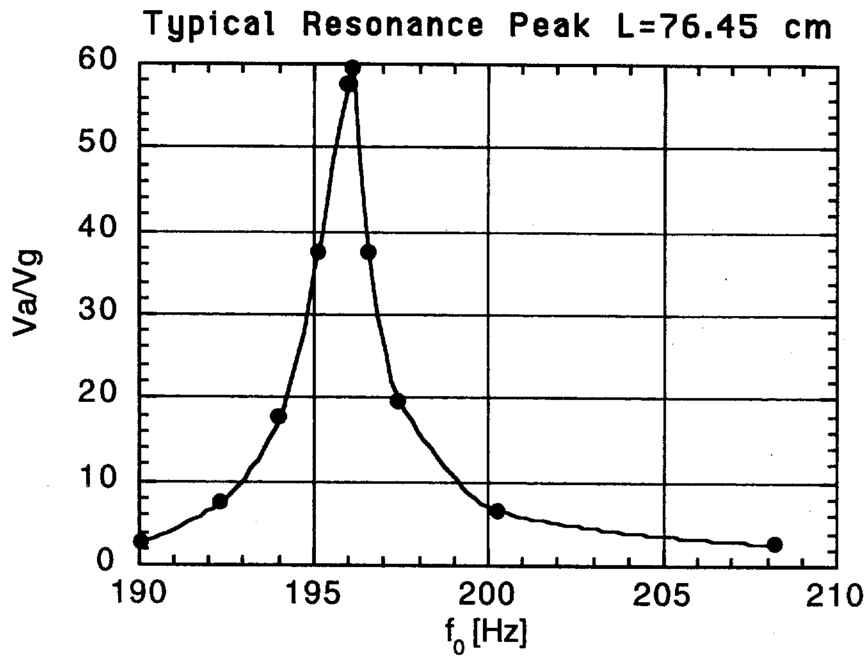

Figure 2: A typical resonance curve taken by sweeping the oscillator frequency through the fundamental frequency. The full width of the resonance is about 1 % while the peak can be easily determined to about 0.2 %.

As another demonstration of the AC bridge technique, the wire tension is swept through resonance at a fixed frequency in Fig. 3. Here we display the raw output of the strain gauge, which has a calibration of roughly 0.32 mV/g. We note that the peak can be determined to roughly 0.5 mV, or about 0.5 %. Such a technique could be used in tube production. Given a particular length tube, the fundamental frequency is known from the wire length and tension so that the wire tension could be adjusted (after prestressing) until the resonance is achieved, thereby guaranteeing the proper wire tension.

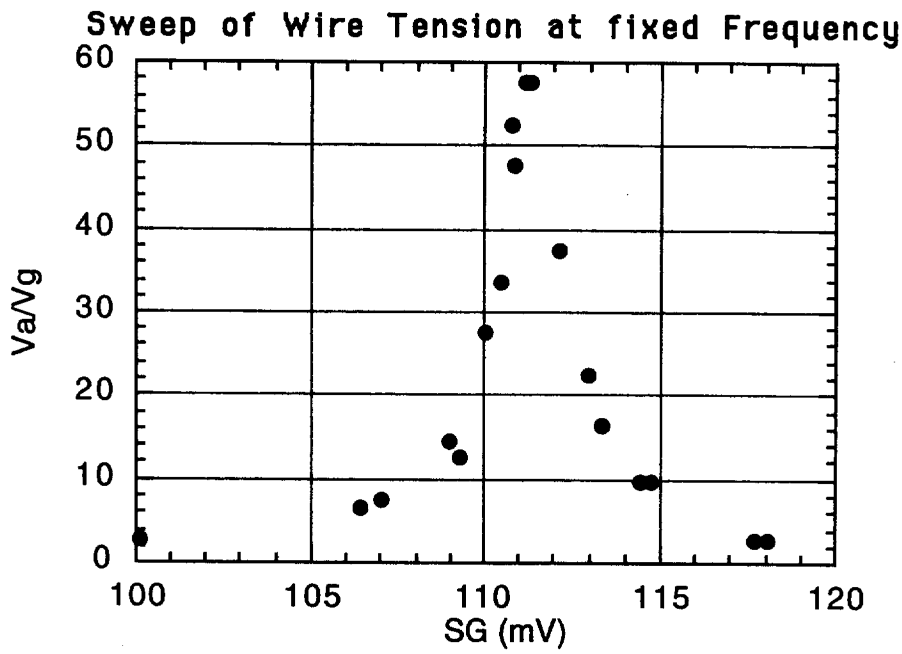

Figure 3. A typical resonance curve taken by sweeping the wire tension for a fixed frequency. The full width of the resonance is about 2 % while the peak can be easily determined to about 0.5 %.

Direct Calibration of Strain Gauge

As a simple check of the calibration of the strain gauge a series of carefully determined weights were hung from the strain gauge. The result is shown in Fig. 4. The weights were crossed checked against a set of standard weights and were determined to an accuracy to ± 0.02 g. It was found that under no tension, the strain gauge read -0.5 mV when hung vertically with the "plunger" side down so that only the weight of the connecting piece and not the strain gauge itself contributed to the pedestal strain. When placed horizontally, as in most of the wire tension tests, the strain gauge read -5.0 mV. In all cases the strain gauge was energized with +5.00 V as read by a precision digital voltmeter.

It is troublesome that the direct calibration of the strain gauge does not agree with the "NIST" traceable factory calibration. The calibration of the Data Precision voltmeter was checked against a Fluke hand-held voltmeter. The discrepancy is not completely understood at this time. For the rest of this note, the precision weights are taken as the standard and the strain gauge calibration is 0.3246 mV/gram.

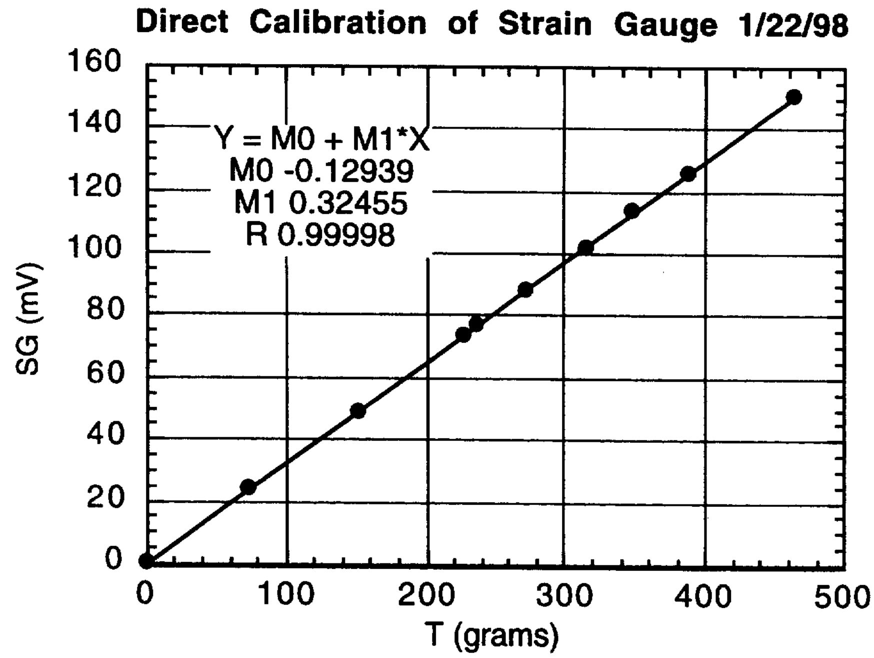

Figure 4. The direct calibration of the strain gauge by a set of calibration weights. The factory calibration is 0.3187 mV/gram which is within 1.85% of the measured value.

Wire Tension and Relaxation

In order to have stable MDTs, the wire tension must not change significantly after wire stringing. It is well known, and described in detail in the ATLAS TDR, that the wire tension slowly relaxes when the wire is stung from 0 to 350 grams operating tension. In order to reduce the relaxing of the wire, it was found that over-stressing the wire to ~ 450 grams for about 5 minutes will reduce the creep at 350 grams. Fig. 5 shows a typical relaxation of the wire tension versus time for an initial tension of 440 grams.

The wire permanently stretches at 450 grams. For example, a 3 meter wire elongates by almost 6 mm (~ 0.2 %) in the first hour of tensioning at 450 grams. Following the pre-tensioning, the wire seems to hold a stable tension at 350 grams - for example falling by only ~ 0.32 % over the first 2 hours and another 0.4% in the next 3 days. As described in the TDR this pre-tensioning is quite necessary in order to achieve stable tension at 350 grams. Our measurements verify this conclusion.

Figure 6 shows the wire tension as a function of length. From the slope $dT/dL = 960.7$ g/cm we determine $Y_m = 36.6 \times 10^6$ Nt/cm^2 to be compared with the value given above (Y_m = 35.5 x 10^6 Nt/cm^2 and see eq. 2). The data shown here are from a wire that had been stretched to 450 grams several previous times.

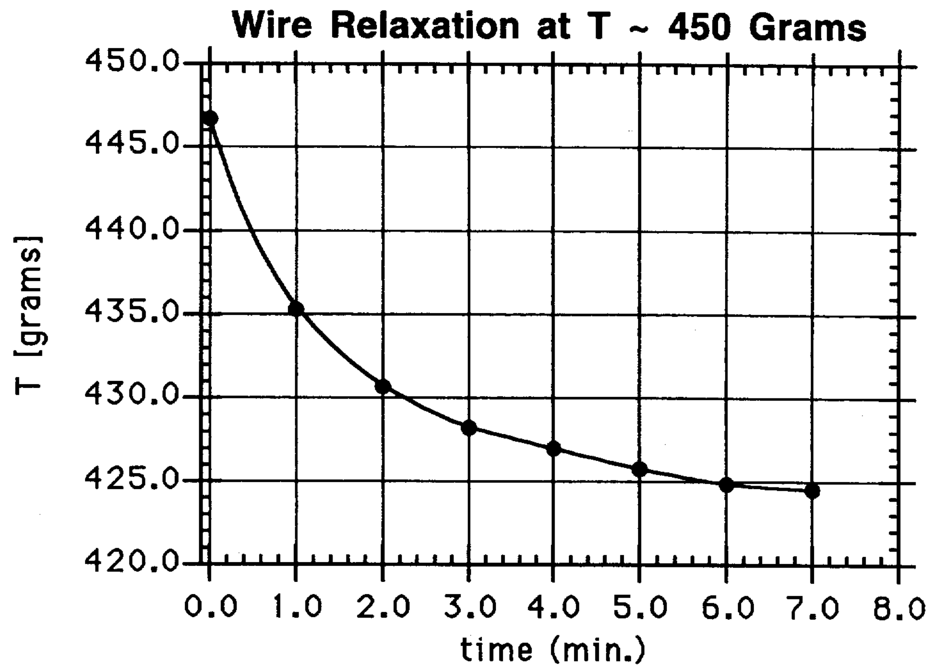

Figure 5. The tension versus time of a virgin 3.09 meter wire. Quite rapid relaxation is noticed immediately following the tensioning.

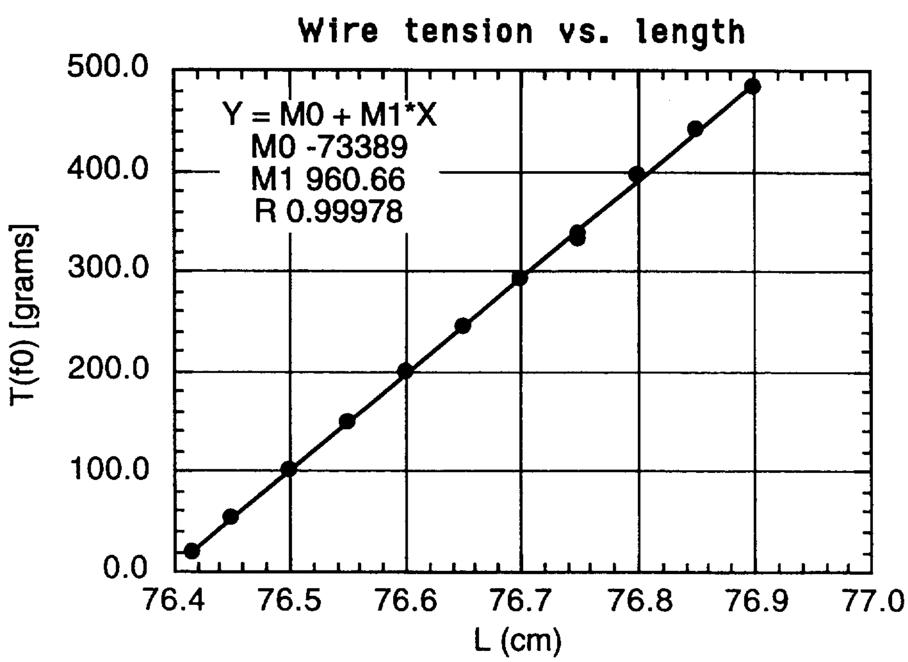

Figure 6. Wire tension versus length for a 'conditioned' 76 cm wire. The slope dT/dL indicated by the "M1 " parameter of the linear fit is 960.7 grams/cm.

Comparison of Strain Gauge with T(fo)

The AC bridge measurement of the wire tension can be compared with the strain gauge as the wire is tensioned to give an independent calibration of the strain gauge. This correlation was studied through several iterations involving different mounting schemes of the strain gauge and a range of excitation currents with the 76 cm wire. The best scheme had the strain gauge mounted horizontally with the plunger side attached to the wire to minimize the pedestal wire strain. In this configuration the strain gauge pedestal is -5.0 mV. The parameters of the measurement were varied to investigate systematics of the measurement. Figure 6 shows the strain gauge value as a function of the measured wire tension from the AC bridge for a typical tension scan. These data were taken with the driver voltage set to 5 V (peak-to-peak) corresponding to a wire current Imax = 10 mA.

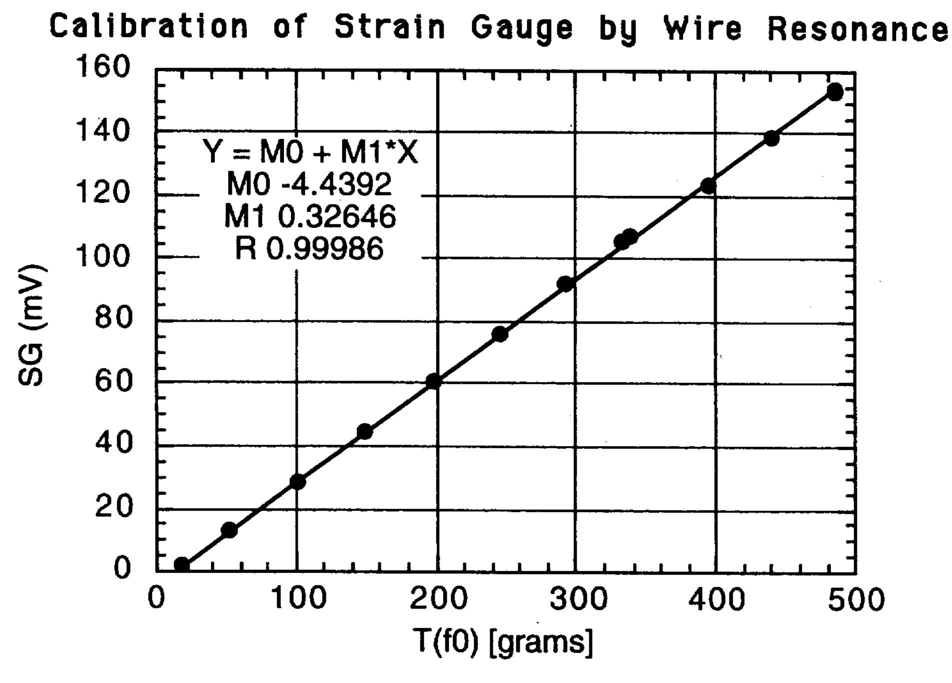

Figure 6. Plotted is the correlation of the wire tension as measured by the strain gauge with the tension as determined by the first mechanical resonance. The data were taken with $V_g = 5$ V. Indicated is the linear fit of this correlation which shows a pedestal of -4.4 mV and a slope of 0.3265 mV/gram.

Comparing Fig. 4, the direct calibration of the strain gauge, with Fig. 6 we note that the calibrations by the two methods agree to within 0.6% and that the measured pedestal of the wire vibration data agrees to within 0.6 mV of the expected pedestal.

When taking wire vibration data it was noticed that for small wire tensions the wire tension itself was dependent on the proximity to resonance. When on-resonance the wire tension as measured by the strain gauge increased slightly indicating that the amplitude of the mechanical oscillation was sufficient to change the wire tension. By very rough considerations we expect that the mechanical restoring force is given by:

$$F_r \approx \frac{2Td}{L}, \tag{4}$$

where T is the wire tension, d is displacement of the middle of the wire and L is wire length. The driving force is given by:

$$F_d \approx I\, y\, B, \tag{5}$$

where I is driver current, B is magnetic field and y is length along the wire of the magnetic field. Therefore, we expect the amplitude of the vibration to scale as:

$$d \approx \frac{L}{2\,T} I\, y\, B. \tag{6}$$

The wire tension increases by the second order term given by:

$$\Delta T \approx \frac{L' - L}{k\,L} \approx \frac{2\,d^2}{k\,L^2}. \tag{7}$$

Thus, the wire tension is dependent on the drive current (voltage) by:

$$\Delta T \approx \frac{I^2\, y^2\, B^2}{2\,k\,T^2} \sim V_g^2. \tag{8}$$

The response of the wire was studied as function of the driving voltage (current) to investigate this nonlinear effect. Figures 7a and 7b show the value of the strain gauge on-resonance as a function of the drive voltage. The corresponding tension measured by the vibration tracks the strain gauge. The curve in the fig. 7a is a quadratic fit to the data which we observe is a reasonable fit. Further, the effect observed and predicted by this simple model is independent of the wire length and is most potent at small tension and large drive currents. The most careful calibration of the strain gauge using wire vibrations was therefore taken at the lowest excitation voltages. Fortunately, the effect is quite small at the 350 grams operative tension ($\Delta T/T \approx 0.15$ %) and is independent of the wire length.

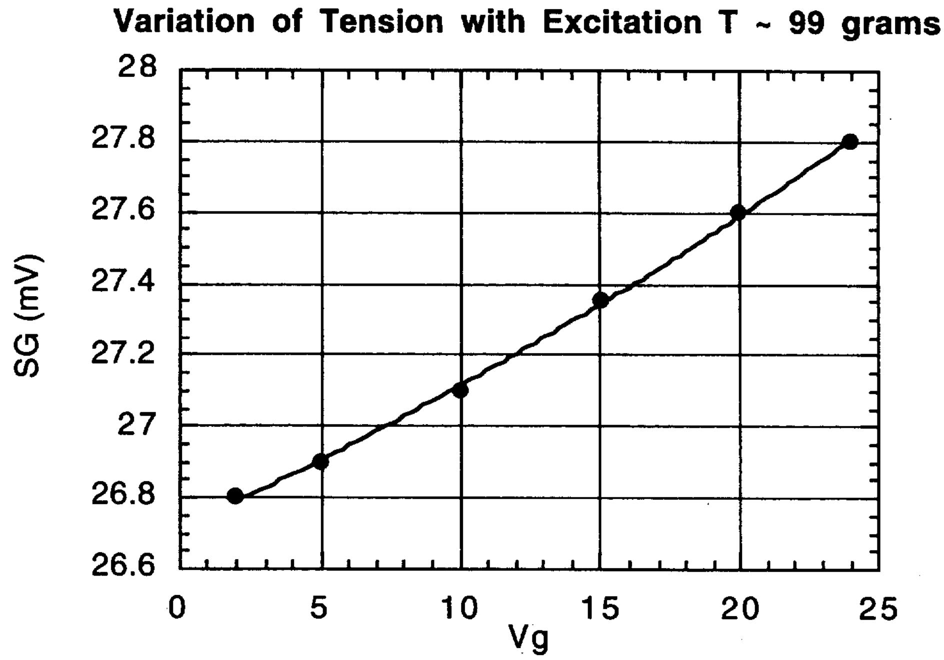

Figure 7a. The wire tension, as measured by the strain gauge, is plotted against the excitation voltage. The expected quadratic dependence is observe. At this wire tension the tension changes by 4% over the excitation voltage range indicated. At 65 grams the slope changes by 8%.

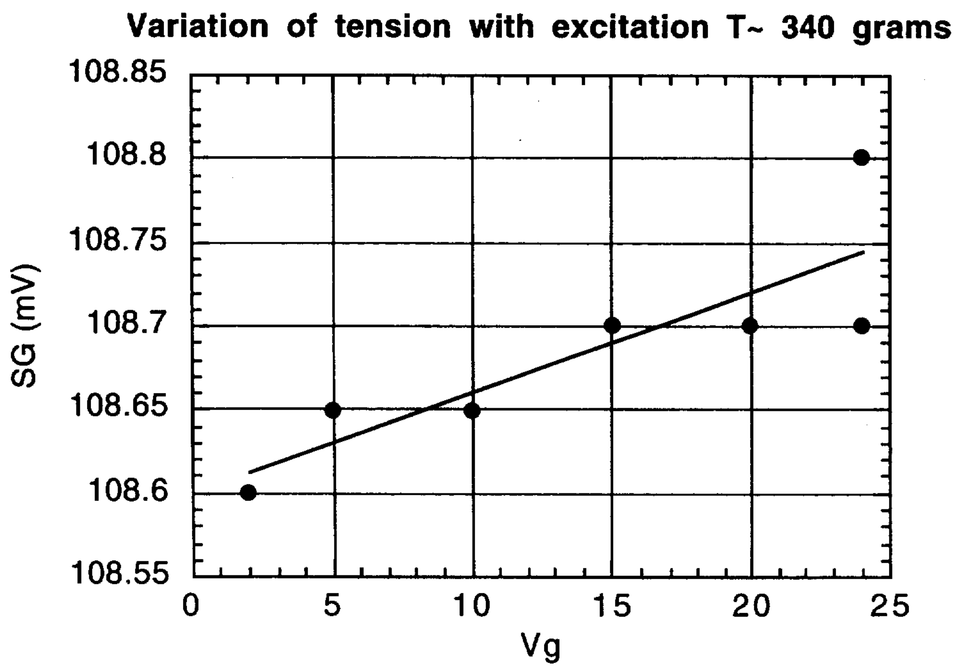

Figure 7b. The wire tension, as measured by the strain gauge, is plotted against the excitation voltage for the operative wire tension. The nonlinear effect is quite small at this tension.

In the following we tabulate the various calibrations of the strain gauge.

Table of Strain Gauge Calibrations

Date	Pedestal (mV)	Slope (mV/gram)	Method
	-5.0 hor, -0.5 vert	0.3187	Factory NIST
1/19/98 + 1/20/98	-3.65	0.3264	Vg = 24 V all data
1/21/98	-4.44	0.3265	Vg = 5 V
1/21/98	-1.83	0.3199	Vg = 5 V T>245 g
1/22/98	-0.93	0.3246	Direct/ weights

The values are consistent at the 2% level and the internal calibrations, especially the vibrating wire at low excitation and the direct calibration by weights, agree to within 0.6%. The calibration with the tension cut T>245 g agrees fairly well (0.4%) with the factory calibration. In none of the vibrating wire calibrations was the amplitude correction shown in Fig. 7 made. For the V_g=5 V data plotted above the correction is small.

Data were taken with 3 meter wires. Figure 8 shows the frequency scan for constant wire tension (109.5 mV) through the fundamental, 3rd and 5th harmonics. Converting to wire tension, the frequency data yields T0 = 348 grams, T3 = 344 grams and T5 = 345 grams, whereas the strain gauge with the direct calibration constant would predict 353 grams - discrepant from the resonance-average by ≤ 7 grams, or about 2 %. The higher harmonics are sharper and perhaps yield better measurements of the wire tension.

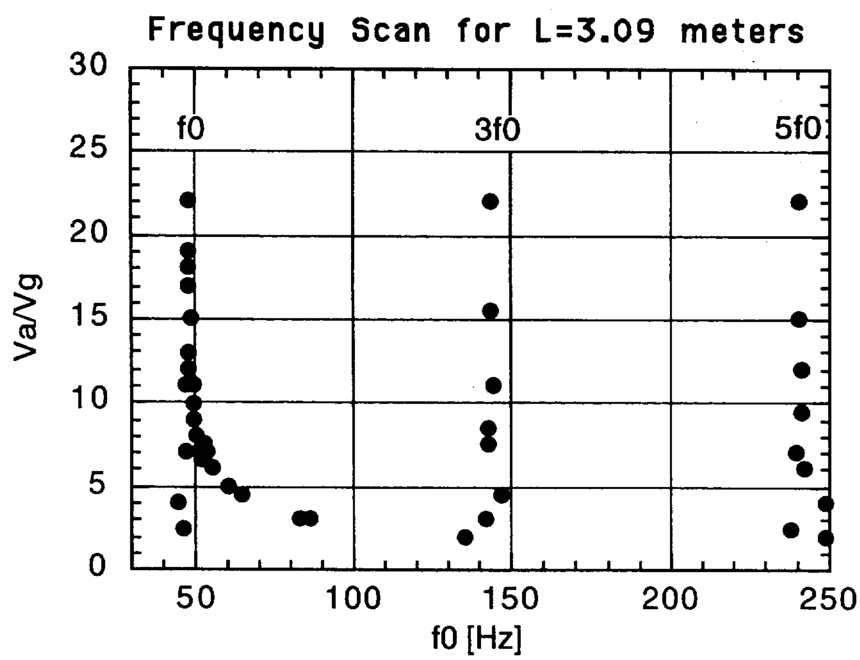

Figure 8. Frequency scan of L=3.09 m wire showing the 1st, 3rd and 5th peaks.

As a proof of principle, an ATLAS tube was measured with the AC bridge. Assuming the standard 50 μm wire and estimating the wire length to be 86.4 cm, the resulting wire tension was 339 grams, or about 3% too low. This tube would not be accepted by ATLAS.

Wire Resistance vs. Tension - A Curiosity

As tension scans were being made the values of the 1 k Ω pot. of the resistive bridge were recorded. By the construction of the bridge, the resistance of the wire could be precisely determined by:

$$R_w = \frac{500\, R_2}{R_p}, \tag{9}$$

where R_2 is the resistance "opposite" R_w and R_p is the pot. resistance. Changes of order 0.05 Ω could easily be measured. As the wire is stretched we expect that the resistance will change. Calling ε the fractional length change, the resistance as a function of ε is given by:

$$R_w = \rho_0 \frac{L_0}{\pi\, a_0^2}(1+\varepsilon)^2, \tag{10}$$

where ρ_0 is the resistivity of the wire, L_0 is length and a_0 is the radius at the pedestal tension. The measured resistance as a function of wire length is shown in Figure 9, where the data are indicated by the points and the simple model of equation 10 is shown by the dotted line. We note that the simple model under estimates the increase of the wire resistance with length. In fact, the slopes dR/dL between the data and the model are at least a factor of two discrepant. Many cross checks of the measurements were made, such as a direct measurement of the resistance with a precision ohm meter, calibration of the resistive bridge and demonstration of the discrepancy for different wire lengths. All data showed typically a factor of ~ 2 difference in dR/dL between the measured resistance and the prediction eq. 10.

The resolution of the discrepancy follows from a well-known effect (after doing a little reading) that the resistance of a metal depends on the pressure (tension). Following Mott and Jones (The Theory of the Properties of Metals and Alloys, Dover Press, 1958), the resistivity of most metals increases (decreases) with tension (pressure) since the resistance is proportional to the mean square amplitude x^2 of the atomic vibrations. To paraphrase Mott and Jones, when a metal is under compression the atomic spacing decreases and mean square amplitude of the vibrations decreases making the scattering of the conduction electrons smaller.

In this model we have:

$$\frac{d\,(\log \overline{X^2})}{d(\log V)} = -2\frac{d\,(\log\Theta)}{d(\log V)} = \frac{d\,(\log\rho)}{d(\log V)} = 4.3 \qquad (11)$$

where Θ is the Debye temperature, V is the metal volume. The value of the resistivity slope from measurements is 4.3. With this additional dependence on ε we estimate:

$$R_w \approx \rho_0 \frac{L_0}{\pi a_0^2}(1 + 2\varepsilon)(1 + 4.3\varepsilon) \qquad (12)$$

where we have assumed that ε is small. We note that the agreement of theory with data in Fig. 9 is much better and the slope of the toy theory agrees with the data to within 20%.

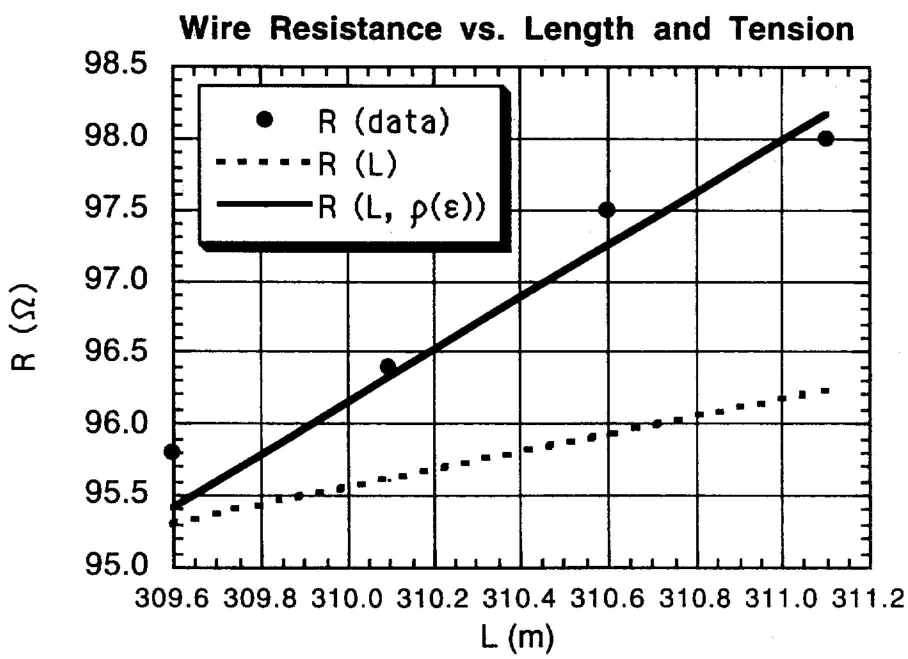

Figure 9. The measured wire resistance is plotted versus the wire length. The simple model, given by equation 10 is shown as the dotted line. Adding the change of the resistivity with wire tension gives the solid line, which is in much better agreement with the data. The data have a slope dR/dL ≈ 1.5 Ω/cm, whereas the simple model gives 0.62 Ω/cm and the better model slope=1.8 Ω/cm.

Summary

Some degree of care is needed to control wire tension to high precision. Techniques have been developed which allow the tension to be controlled and verified to ≤ 2%. This level of error is within the ATLAS specifications, but, ideally, we would like to control the process to better than this. Most troublesome has been the factory calibration of the precision strain gauge has not been verified by direct calibration or by wire oscillations. The best wire oscillation data and the direct calibration of the strain gauge agree to within 0.6%. In the production stringing, the precision mover will be replaced with a stepper motor and all the readout and control of the strain gauge, frequency sweeping and resonance detection will be replaced with a LabView automated system. A better suspension of the strain gauge will be implemented and two strain gauges will be compared with each other. Another concern is that the wire continues to relax for several days after it is strung, even following pre-tensioning. Experiments must be performed on the ATLAS tungsten-rhenium wire.

Note that many of the length corrections described here have to be reworked in the final stringing apparatus since there the wire length will be constant.

Acknowledgments

The author would like to thank Dale Ross for finding various instruments needed for the tests, Marg Neal for loan of the magnet, Leslie Rosenberg for loan of the Tektronics differential scope, Hermann Wellenstein for consultation on strain gauges and stepper motors and Justin Escalera for making the rough idea of the AC bridge into a working device.

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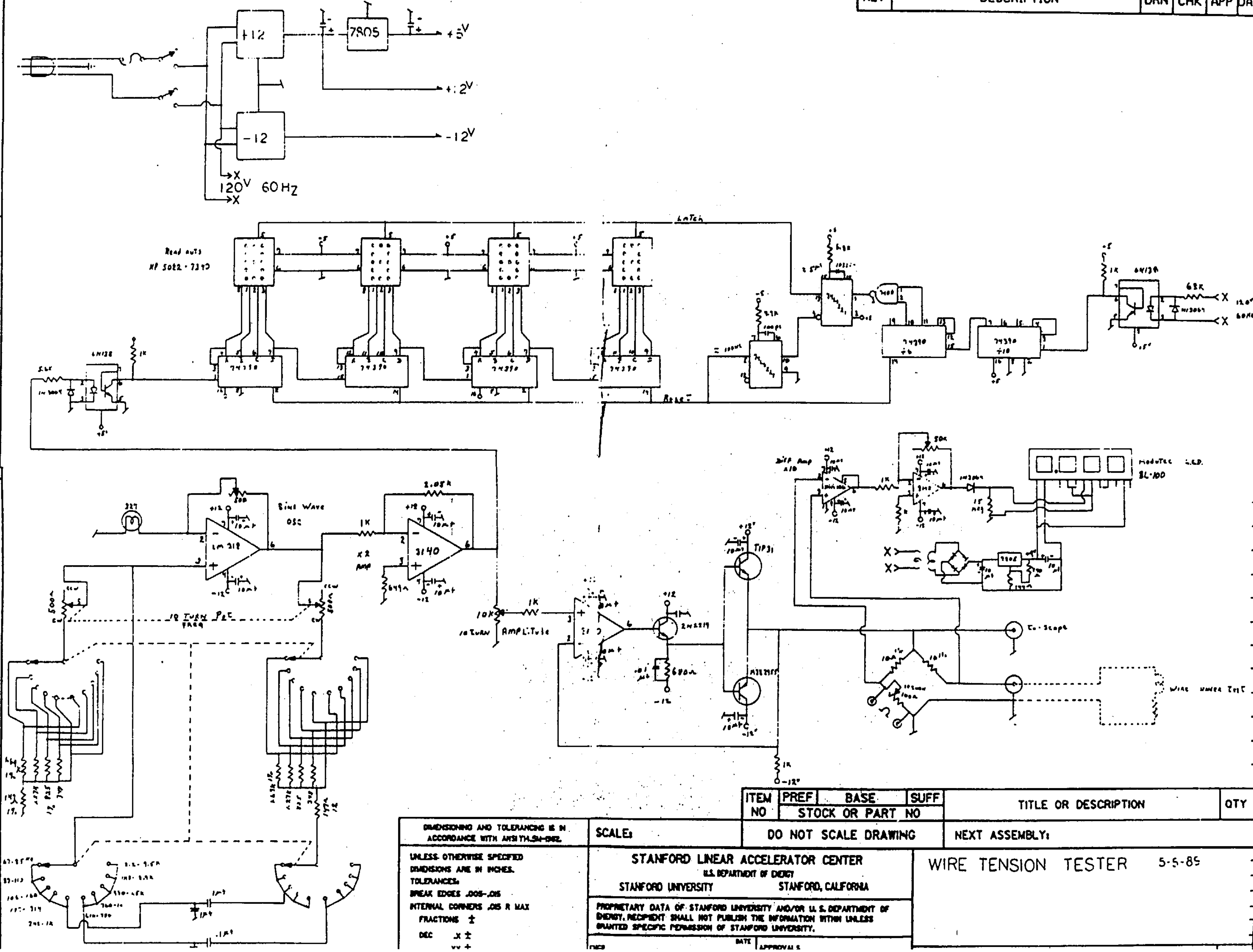
Appendix

Circuit diagram of SLAC-SLD wire tension tester from "Measurement of the Wire Tension", J. Escalera, F. E. Taylor, WIC-SLD Note May 5, 1989.

Resistors are 1% wire-wound.

Pot: 10 turn

Differential Amp: Burr-Brown INA106
CMR 100 dB



REV	DESCRIPTION	DRN	CHK	APP	DATE

ITEM NO	PREF	BASE	SUFF	TITLE OR DESCRIPTION	QTY
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DIMENSIONING AND TOLERANCING IS IN ACCORDANCE WITH ANSI Y14.5M-1982.

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES.
TOLERANCES:
BREAK EDGES .005-.015
INTERNAL CORNERS .015 R MAX
FRACTIONS ±
DEC .X ± .XX ±

SCALE:

DO NOT SCALE DRAWING

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APPROVALS

WIRE TENSION TESTER

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OF