

A New Approach for Non Contact Measuring of Tension in Fixed and Moving Wires

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Abstract: In this paper, a non contact method for measuring instantaneous tension in a wire, based on equations of lateral vibrations of wires, is introduced. The lateral vibration of the string is measured using an eddy current transducer and is sent to a computer. This signal is then imported to a suitable software for fast Fourier transform (FFT) processing. The first natural frequency of the string is calculated online using FFT plot of the imported signal. This proposed method can be used for measuring tension for both fixed and moving wires with constant velocity, which is a usual case in wire processing. Results show good agreement with theoretical estimations and errors measured are less than 8% at the worst case. This experimental study introduces a simple and low cost method which can be implemented in existing non-contact wire measuring tension apparatus.

Keywords: Non Contact Measuring, Tension, Vibration, Fixed & Moving Wires

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1 INTRODUCTION

Wire tension is a vital parameter which affects the quality and efficiency in wire manufacturing processes. It determines structure of the process and has a significant influence on productivity of various processes such as winding, twisting and cabling and subsequent processes. Precise measuring and control of wire tension can lead to an increase in loom speed. The method of performing precise and quick wire tension measurement in various processes has been the subject of research and development for several years. This area of research is important for researchers in several branches of science, for example, in biomechanics [1], nuclear engineering [2-4], medicine [5] and textile engineering [6-8].

In textile industries, measurement of string tension is mainly carried out using contact tension-meters. Using this kind of yarn tension-meters causes increased hairiness of the yarns. In the meantime, the friction between the yarn and the tension-meter affects the amount of yarn tension, so that an error of 5-15% occurs [6], [7]. Measuring instruments of yarn tension can be categorized into two groups of contact and non-contact instruments. A complete review of these methods is presented in [9], [10]. A survey reveals that very few papers have dealt with theoretical analysis and experimental results of non-contact methods for yarn tension measurements.

Some researchers have used a wireless sensor for yarn measuring [11]. Most yarn tension measurement systems included strain gauge, capacitive and Hall Effect sensor for sensing parameters affected by yard tension. These transducers are also used in automatic yarn tension control systems, but contact with the yarn is inevitable for some sensors. Also, some non contact methods involve technical problems [12]. Therefore, novel techniques with more simplicity and lower costs need to be further investigated. There are some commercial non contact tension measurement instruments. Some of them operate on the principle that when a tensioned member is anchored between two points, it vibrates at a frequency related to its tensile stress. To measure this frequency it only needs to be close to the strand or wire, without reading any contacts. Also, most existing instruments only measure the tension of the wire in the static case.

Therefore, they cannot measure the tension force of the moving wires. More over, since such instruments measure the free vibration frequency of a specified point of the wire and use it as the first natural frequency, some errors occur in the computation of the tension force because every point of the wire vibrates

with a combination of several natural frequencies. This subject will be discussed in the next section. The importance of this limitation will increase when the wires move with a fixed linear velocity. In [13] this method was investigated for both fixed and moving yarns and it was concluded that the range of error for the fixed yarns is about 10-15% and between 15-30% for moving yarns.

In the present study, a new method will be presented for measuring the string tension using an eddy current sensor. The basic logic supporting the present method is different from currently prevalent methods used for measuring frequency of vibrations. The measured frequency in current methods is not precise because any point of the wire vibrates with a combination of natural frequencies of the wire. Whereas, in the present method, time history of lateral vibration of the wire is measured by the sensor and by using Labview software, and from the FFT spectrum of the signal plotted. Since the tension in the string and the first natural frequency of string are theoretically related, the tension is calculated from the first natural frequency readouts using FFT plots.

An experimental setup for implementing this method is prepared. It is assumed that the strings are metallic because the eddy current sensors are sensitive to only metallic objects. For non metallic string in fixed case, a metallic clip can be attached to the string and for moving case, a type of transducer sensitive to such string should be implemented. The tensions in the strings, for both fixed ends and moving strings, are calculated with this method and the results are compared with the actual values.

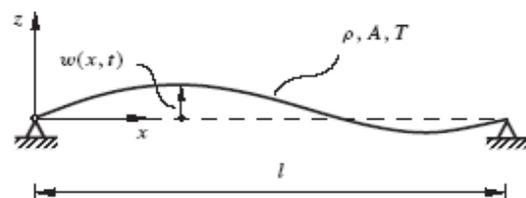


Fig. 1 Schematic representation of a taut string [14]

2 GOVERNING EQUATION

2.1. STRING WITH FIXED ENDS

Consider a string, stretched along the x-axis to a length l by a tension T , as shown in Fig. 1, where ρ and A are mass density per unit length and area cross section of the string, respectively. The transverse motion of any point on the string, at coordinate

position x , is represented by the field variable $w(x, t)$, where t is the time.

The equation of motion of this string in the transverse direction in the case of free vibration, can be written as:

$$\frac{\partial^2 w}{\partial t^2} = c^2 \frac{\partial^2 w}{\partial x^2} \tag{1}$$

where, $c = \sqrt{T/\rho A}$ is a constant having the speed dimension. This differential equation is known as the linear one-dimensional wave equation, where c is the wave speed [14]. The complete solution of Eq. (1) is computed as:

$$w(x, t) = \sum_{k=1}^{\infty} (A_k \cos \omega_k t + B_k \sin \omega_k t) \sin \frac{k\pi x}{l} \tag{2}$$

Or, in another form, as:

$$w(x, t) = \sum_{k=1}^{\infty} C_k \cos(\omega_k t + \phi_k) \sin \frac{k\pi x}{l} \tag{3}$$

where,

$$\omega_k = \frac{k\pi c}{l} \quad k = 1, 2, 3, \dots \tag{4}$$

ω_k is the k_{th} natural frequency of the string. If a sensor is placed at a specific $x = x_0$, Eq. (3) can be rewritten as

$$\begin{aligned} w(x_0, t) &= \sum_{k=1}^{\infty} C_k \cos(\omega_k t + \phi_k) \sin \frac{k\pi x_0}{l} = \\ &= \sum_{k=1}^{\infty} D_k \cos(\omega_k t + \phi_k) \end{aligned} \tag{5}$$

where, $D_k = C_k \sin(k\pi x_0/l)$ for $k = 1, 2, 3, \dots$ are new coefficients. Therefore, the transverse vibration of the string in this location is only a harmonic function of time. In fact, FFT of Eq. (5) is a plot of D_k versus ω_k (for all $k = 1, 2, 3, \dots$).

Hence, FFT of $w(x_0, t)$ can always show the value of ω_1 with respect to the location of $x = x_0$.

2.2. STRING WITH CONSTANT SPEED

Consider a string under a tension T between two fixed supports, translating along its length at a constant speed

' v ', as shown in Fig. 2. Let $w(x, t)$ denote the string displacement field variable which will be assumed to be small.

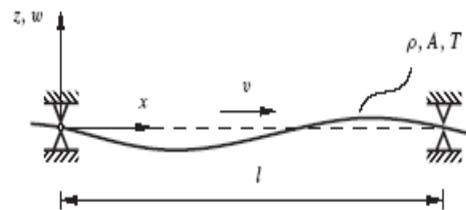


Fig. 2 A translating string [14].

Differential equation of this string using Hamilton's principle is derived as follows [14]

$$\frac{\partial^2 w}{\partial t^2} + 2v \frac{\partial^2 w}{\partial x \partial t} - (c^2 - v^2) \frac{\partial^2 w}{\partial x^2} = 0 \tag{6}$$

where $c^2 = T/\rho A$ is the same as the previous case. The general solution of Eq. (6) can be obtained as

$$\begin{aligned} w(x, t) &= \sum_{n=1}^{\infty} (B_n \cos[\frac{n\pi}{cl}(vx + (c^2 - v^2)t)] + \\ &+ C_n \sin[\frac{n\pi}{cl}(vx + (c^2 - v^2)t)] \sin \frac{n\pi x}{l} \end{aligned} \tag{7}$$

or in another form as

$$w(x, t) = \sum_{n=1}^{\infty} D_n \cos[\frac{n\pi}{cl}(vx + (c^2 - v^2)t + \theta_n)] \sin \frac{n\pi x}{l} \tag{8}$$

Again, transverse vibration of the string at $x = x_0$ will be defined as,

$$w(x_0, t) = \sum_{n=1}^{\infty} D_n \cos[\frac{n\pi}{cl}(vx_0 + (c^2 - v^2)t + \theta_n)] \sin \frac{n\pi x_0}{l} \tag{9}$$

or

$$w(x_0, t) = \sum_{n=1}^{\infty} E_n \cos[\frac{n\pi}{cl}(vx_0 + (c^2 - v^2)t + \theta_n)] \tag{10}$$

where $E_n = D_n \sin(n\pi x_0/l)$ is a new coefficient replaced by D_n . Eq. (11) also shows a harmonic motion with its first frequency obtained as,

$$\omega_1 = \frac{\pi}{cl}(c^2 - v^2) \tag{11}$$

3 EXPERIMENTAL INVESTIGATION

3.1. EXPERIMENTAL COMPONENTS

In this research, a set of components, as shown in Fig. 3, are used for constructing the device. These components are an eddy current sensor and its amplifier, some metallic string (copper and nickel), mechanical parts, namely two pulleys and one base for holding an eddy current sensor, type IPS-308-AV-18-P, linear input ranged 3-8 mm, output range 10 V, sensitivity 1.428 V/mm, fabricated from Tabriz Peghuh, Iran, also a simple DC motor (6 volt power supply) for rotating the string at a constant speed, some known weights, cable and a laptop for receiving and processing the signals. These components are installed as shown in Fig. 4.

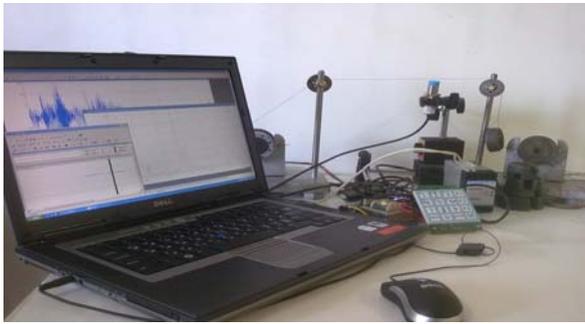


Fig. 3 The set up used to measure the frequency of vibrating string.

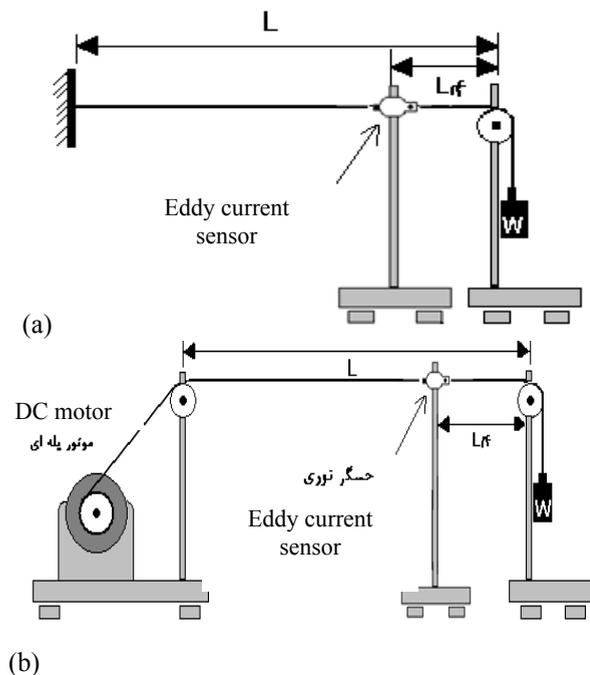


Fig. 4 Schematic representation of the experiments
(a) Fixed string and (b) Constant speed string

3.2. EXPERIMENTAL PROCEDURE

The Labview software must be ready to receive the output signal of eddy current sensor which is in volts. The head of the sensor and the string must be laid out at an allowable distance (3 to 8 mm). The string, in static case, is excited by a lateral impulse (e.g., by a pen). This excitation must be quick but not so large that the string gets transverse displacement more than 8 mm in this case.

The software must start immediately after exciting the string and stopped a few seconds later. This signal is saved as a WAV file and then imported to Sigview software for FFT signal processing. In dynamic case, excitation is not required because the string has a self excitation which is enough to affect the sensor.

4 RESULTS AND DISCUSSIONS

4.1. FIXED WIRE CASE

Two types of strings (made of copper and nickel) with various diameters and lengths are used in this research. The densities of these strings are $\rho_{cu}=7.93$ and $\rho_{ni}=7.5$ gram/cm³ respectively. These wires are stretched by tension forces with known weights as shown in Fig. 4. Because the quality of the frequency domain plots improves, provided power spectrum density (PSD) format is used, FFT of the PSD of all time domain signals have been plotted.

This format helps better reading of the first natural frequencies of the wires. Several plots according to the cases listed in Table 1, were extracted from the experiments, but only two cases have been shown in Figs. 7 and 9 to shorten the paper. Also, hanning function is used to increase the quality of FFT plots as a window function.

The sampling frequency in all tests is 32 kHz. Since technical data of some used devices (especially the sensor) was not available, the vertical units of all graphs are unknown. This is not an important limitation because we only need to know the values of frequencies.

Figures 7 and 9 show that the frequency of vibration of the wire is not one unique value and based on Eq. (4), each of these frequencies have a different dependency on the tension force in the wire.

Therefore the first frequency must be obtained to measure tension in the wire. The combination of these frequencies depends on the initial excitation of the wire in the measuring step. Results also show that the maximum error in the worst case doesn't exceed 5.7%.

Table 1 Summary of results for fixed wires with the same lengths L=50 cm

| Material | Dia. (mm) | Theoretical ω_1 (Hz) | Test No. 1 $x=L/4$ | | | Actual Tension divide by gravity (gram) |
|----------|-----------|-----------------------------|---------------------|---------------------------------------|----------------------|---|
| | | | Exp. ω_1 (H) | Exp. Tension divide by gravity (gram) | Error in Tension (%) | |
| Copper | 0.32 | 55.66 | 55.7 | 201.7 | 0.85 | 200 |
| | | 68.17 | 67.8 | 298.85 | 0.38 | 300 |
| | | 78.71 | 79.6 | 411.93 | 2.98 | 400 |
| | | 88.00 | 89.4 | 519.60 | 3.92 | 500 |
| Nickel | 0.28 | 65.18 | 64.20 | 205.15 | 2.57 | 200 |
| | | 79.83 | 77.95 | 302.44 | 0.81 | 300 |
| | | 92.18 | 91.30 | 414.91 | 3.72 | 400 |
| | | 103.1 | 98.14 | 479.4 | 4.12 | 500 |

Table 2 Summary of results for fixed wires with the same lengths L=50 cm

| Material | Dia. (mm) | Theoretical ω_1 (Hz) | Test No. 2 $x=L/2$ | | | Actual Tension divide by gravity (gram) |
|----------|-----------|-----------------------------|---------------------|---------------------------------------|----------------------|---|
| | | | Exp. ω_1 (H) | Exp. Tension divide by gravity (gram) | Error in Tension (%) | |
| Copper | 0.32 | 55.66 | 55.57 | 200.76 | 0.38 | 200 |
| | | 68.17 | 67.14 | 293.06 | 2.31 | 300 |
| | | 78.71 | 77.82 | 393.71 | 1.57 | 400 |
| | | 88.00 | 86.37 | 484.97 | 3.00 | 500 |
| Nickel | 0.28 | 65.18 | 65.43 | 213.09 | 6.54 | 200 |
| | | 79.83 | 77.34 | 297.73 | 0.76 | 300 |
| | | 92.18 | 89.2 | 396.04 | 0.99 | 400 |
| | | 103.1 | 100.0 | 497.75 | 0.45 | 500 |

4.2. MOVING WIRE CASE

The same materials have also been used in this case, where the strings are pulled with constant velocity. The velocity of wires is set at 5.23 cm/s which is produced by a DC motor. Figs. 10 and 12 show that the string at any specific time vibrates with several frequencies. Thus determining the exact frequency to be used for evaluating string tension is important. This measurement is also applicable for belts because most existing non-contact belt tension meters operate only in the static case. Results in Tables 3 and 4 also show that maximum error reaches 6.54% at the worst case. One reason for occurrence of this error is the friction between the pulley and the wire.

The eddy current sensors are more sensitive to target planes made of copper than the ones made of nickel [15], but this fact has not significantly reduced resultant error. The values of the first frequencies of the wires in static and dynamic cases are very close because the velocity of wires (5.23 cm/s) is much less than $c = \sqrt{T / \rho A}$. There was a limitation on the length of the wire in this experimental study; increasing the

velocity of wires requires more length and this requires keeping more distance between the weights and the pulleys or the motor. As the weight was striking at the pulley, there was not enough time for data acquisition.

Table 3 Summary of results for moving wires with the same lengths L=50 cm

| Material | Dia. (mm) | Theoretical ω_1 (Hz) | Test No. 3 $x=L/4$ | | | Actual Tension divided by gravity (gram) |
|----------|-----------|-----------------------------|---------------------|--|----------------------|--|
| | | | Exp. ω_1 (H) | Exp. Tension divided by gravity (gram) | Error in Tension (%) | |
| Copper | 0.32 | 39.22 | 40.70 | 107.62 | 7.62 | 100 |
| | | 55.46 | 55.73 | 201.92 | 0.96 | 200 |
| Nickel | 0.28 | 46.09 | 46.4 | 101.35 | 1.35 | 100 |
| | | 65.18 | 64.24 | 194.27 | 2.86 | 200 |

Table 4 Summary of results for moving wires with the same lengths L=50 cm and velocity v=5.23 cm/sec

| Material | Dia. (mm) | Theoretical ω_1 (Hz) | Test No. 4 $x=L/2$ | | | Actual Tension divided by gravity (gram) |
|----------|-----------|-----------------------------|---------------------|--|----------------------|--|
| | | | Exp. ω_1 (H) | Exp. Tension divided by gravity (gram) | Error in Tension (%) | |
| Copper | 0.32 | 39.22 | 40.20 | 105.06 | 5.06 | 100 |
| | | 55.46 | 53.18 | 183.86 | 8.07 | 200 |
| Nickel | 0.28 | 46.09 | 45.59 | 97.84 | 2.16 | 100 |
| | | 65.18 | 62.99 | 186.78 | 6.61 | 200 |

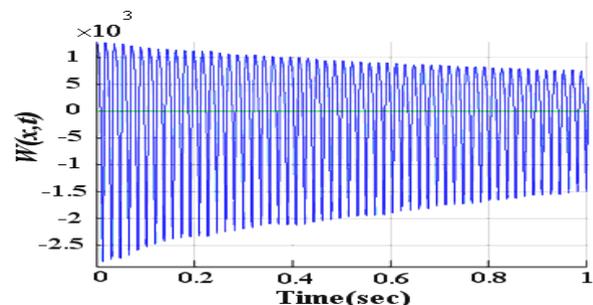


Fig. 5 Time history of transverse vibration of copper string (d=0.32 mm) for mass weight T=200 gram

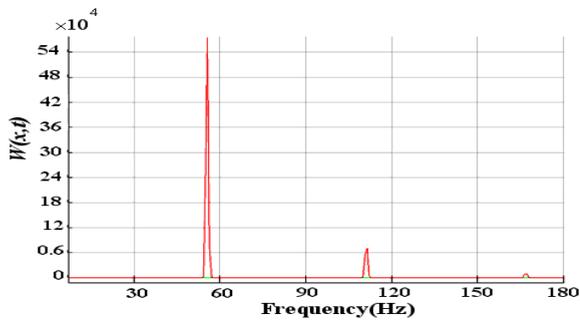


Fig. 6 FFT spectrum of transverse vibration of copper string (d=0.32 mm) for mass weight T=200 gram

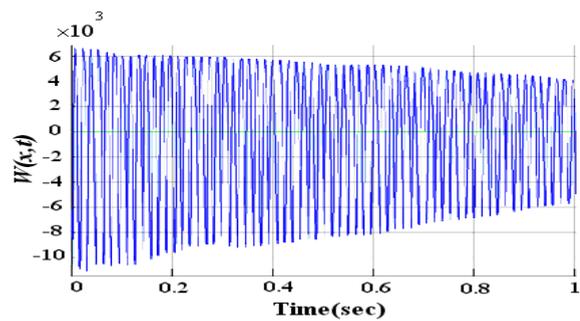


Fig. 7 Time history of transverse vibration of nickel string (d=0.28 mm) for mass weight T=200 gram

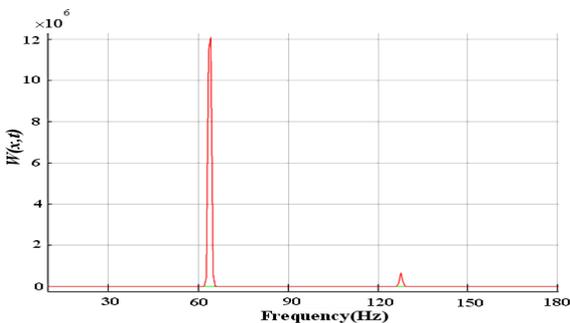


Fig. 8 FFT spectrum of transverse vibration of nickel string (d=0.28 mm) for mass weight T=200 gram

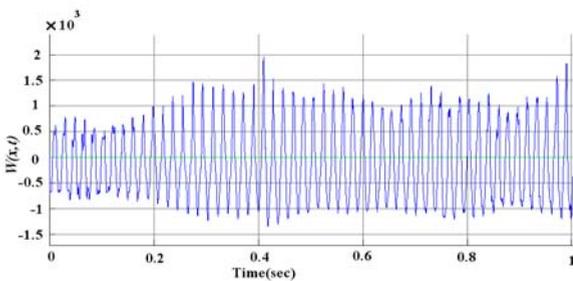


Fig. 9 Time history of transverse vibration of copper string (d=0.32 mm) for T=200 gram

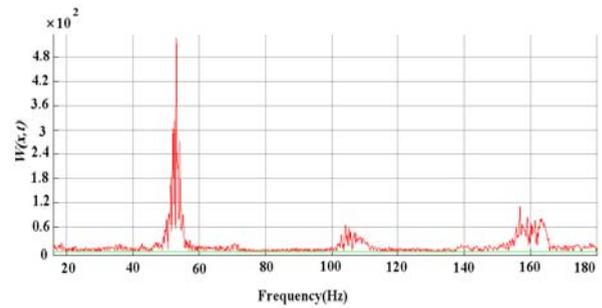


Fig. 10 FFT spectrum of transverse vibration of copper string (d=0.32 mm) for T=200 gram

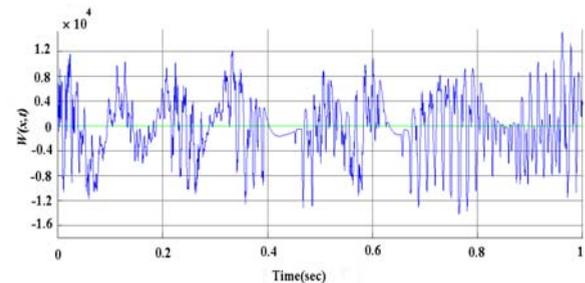


Fig. 11 Time history of transverse vibration of nickel string (d=0.28 mm) for T=200 gram

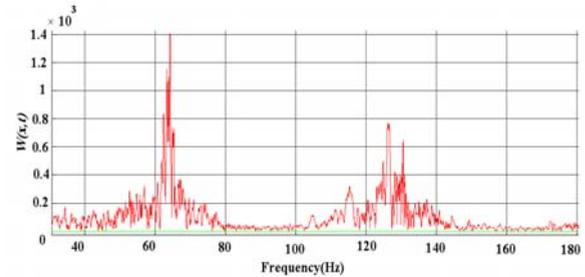


Fig. 12 FFT spectrum of transverse vibration of nickel string (d=0.28 mm) for T=200 gram

5 CONCLUSION

In this research, a new non-contact method for measuring the wire tension has been introduced. This method can be implemented in existing instruments in order to reduce resultant error. Also, it can be used for measuring moving strings and wires. The main contribution of this research is to use the spectrum analysis of the transverse vibration of the string signal to determine tension in fixed and moving wires. Results showed conformity between readings of the recommended method and actual values. Accuracy of results may be increased by selecting more accurate and sensitive displacement transducers. Also, this non-

contact method can be extended to non-metallic strings if sensors sensitive to non-metallic strings are used.

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