Investigation of Play-Wear Damage on Steel Music Strings Using Atomic Force Microscope and Low Level Resistance Method

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Abstract— The strings of stringed musical instruments are subject to both reciprocating sliding wear due to contact with the player's fingers and repetitive impact with a plectrum, therefore, they gradually lose their brilliance and responsiveness. Nevertheless, there has been almost no scientific investigation about the effects of play-wear on music strings and its determination. In this study, the investigation of play-wear on the strings of C1085 steel wire was performed using the lute-like Bağlama stringed instrument. The wear loss of the strings was investigated using atomic force microscopy and the low level resistance measurement method. Increasing the number of wear cycles increased the surface roughness and material removal, identified by increased electrical resistance of the strings. The increase in the resistance and frequency were due to both a reduction and variations in the cross sectional area caused by wear.

I. INTRODUCTION

The *bağlama* is a synthesis of historical musical instruments in Central Asia and pre-Turkish Anatolia, and is a unique instrument representative in Turkish folk music. There is no region, no village in Anatolia which is not familiar with this stringed instrument. It is a successor of the kopuz (or komuz), which is an ancient fretless Turkish instrument, known as the forefather of plectrum instruments and frequently mentioned in the sagas of Dede Korkut dating back to 6000 BC. Stringed instruments can be played in many ways. Some are played with bows, some with picks, and some by plucking or strumming with your fingers. The *bağlama* is a plucked string instrument from the lute family (mandolin, guitar, sitar, pipa, balalaika and banjo etc.) and can be played with a plectrum (*mızrap* or *tezene*) or with a fingerpicking style known as *şelpe*.

Strings are very important and often overlooked parts of a stringed instrument. Therefore, to properly care for a stringed instrument, it is important to pay particular attention to its strings. Music strings are subjected to hand pressure and sliding wear of the musician during playing, and even to the corrosive effects as a result of air, moisture, and dirt coming into contact with the strings. As a result, although the strings may visibly appear to be in good shape, over several months of playing, the strings gradually lose their brilliance and responsiveness. Strings made from metal alloys are particularly more prone to rust and tarnish. Therefore, they are mandatorily changed for new ones periodically [1]. Many professional musicians change their strings after every gig. To get over this necessity, several companies have produced strings that have a coating layer on the outside of the string. These strings can last considerably longer due to this coating layer, which helps them to resist wearing and tarnishing. These longer lasting strings are available at a slightly higher price, and can last much longer than untreated strings. However, the trade-off is that the initial timbre of the string is dampened and many players prefer the bright tone of new untreated strings. Steel strings are particularly economical, and they produce larger and brighter volumes of sound with a minimal break-in period in comparison to others.

A vast number of theoretical and experimental studies are available on music strings. However, a great majority of these studies are concerned with either fundamental acoustic characteristics [2-20] based on the length, mass or tension of the string, or the acoustic properties based on the material [21-34] or gauge effects [35-37] of the strings. Correspondingly, there are very few studies [38-45] that discuss the issues of friction and wear. The wear problem on music strings has been mentioned in these studies. Accordingly, Lazarus has researched the characteristic of friction between the bow and string and the results demonstrated the influence of the normal force between the bow and string on the steady vibration. Results were confirmed by an electromechanical model of a bowed string [39].

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McIntyre and Woodhouse [40] have discussed some aspects of bowed string vibration with particular emphasis on a regime that is sensitive to details of the friction-velocity characteristics. Keisuke [41] has explained that the repeated vibration of the string increases the friction coefficient between the core wire and the winding wire. Pavlidou and Richardson [42] have described a one-dimensional model, which relies mainly on the frictional force between the fingernail and the string, and is solved numerically through the finite differences method. Serafin et al. [43] have proposed a digital waveguide model of a bowed string in which the interaction between the bow and the string was modelled using an elastoplastic friction model. Schumacher et al. have stated that friction force during slipping shows complex behaviour, which is not well correlated with variations in the sliding speed, which means that other state variables such as temperature near the interface must play a crucial role. They have suggested a new constitutive model for rosin (used as a friction material) friction, based on the repeated formation and healing of unstable shear bands [44]. Kucukyildirim et al. [45] have found that the abrasion and corrosion behaviours of electric guitar strings depend on playing periods. In this study, the effect of the axial load on wear is investigated, therefore it has been obtained that the wear rate showed a linear rising by increasing the distance of sliding in dry friction aspect for the starting period (0-15s). Olver et al. [46] have examined a number of service failures in guitar, electric bass and mandolin steel (music wire) strings by scanning with an electron microscope (SEM). They suggested that fatigue was the main cause of the failure and that the failures were associated with plastic bending at the bridge or nut of the instruments. Consequently, when all these studies are evaluated, it is discovered that the effect of play-wear on the lifetime of steel strings and its measurement has been insufficiently studied.

Guitar picking is a collection of many techniques (flatpicking, alternate picking, sweep picking, economy picking, gypsy picking, anchoring, hybrid picking, hammer-on and pull-off, tapping etc.) for plucking or strumming with a plectrum or fingers the strings on a guitar. On the guitar, picking with a plectrum or fingers is more dominant compared to the *bağlama*. On the other hand, on the *bağlama*, solely reciprocating-sliding wear with the finger is applied most intensively to the strings on the fretboard, due to various factors such as a longer sliding length and the course and tuning arrangement of this instrument. The sliding length of other plucked string instruments is shorter; thereby sliding wear region is less. Sliding motion and stroking is easier on this instrument than some others because the neck of the *bağlama* is small in diameter and the tied gut frets are thinner than wire frets. Because of all these reasons, it seems that a long-necked *bağlama* is the most practical instrument of the plucked string instruments to characterize the sliding wear of the finger on the strings. The present research is an initial study and focuses on the sliding-wear phenomena on the steel strings by the finger. For this, a play-wear procedure of 6000 cycles at andante moderato speed of 100 beats per minute was performed in the region of the ascending and descending Do (C) major scale. The string is made from 0.20mm diameter C1085 steel wire (ASTM A228 music wire) [47]. The low level resistance measurement was used to determine the losses caused by wear. A digital storage oscilloscope with signal processing software was used to determine whether any change in frequency of the played note occurred after play-wear. Surface structural changes of the string were tracked using an atomic force microscope (AFM) before and after wear.

II. DESCRIPTION OF THE EXPERIMENT

A stable test environment is essential when making accurate low level measurements. Important factors which may affect the accuracy of low level resistance measurements and solutions are as follows:

a) Relaxation factor of tuning pegs owing to playing: In this study, to solve the relaxation of pegs, mechanical tuning pegs made from geared systems were used to tighten strings, so that they did not allow any relaxation after long periods of playing. The geared pegs present a “non-slip” solution for *bağlama*, guitar, violin or cello players.

b) External environmental factors such as temperature, humidity and light: In order to minimise the effects of the environmental corrosion and to only evaluate the wear influence of the hands on the strings, before each study the hands were cleaned of grease and dirt because the skin surface is protected by an acidic hydro-lipid film (pH 4–6) [48]. Furthermore, string stability may be affected by temperature and humidity. In order to minimize adverse environmental effects, the playing wear and all measurements were realized in a special room (**figure 1**) where a temperature of 25°C, a relative humidity of 46%RH, a light level of 0.18lux and a noise level of approximately 30dB (it is accepted as a “quite room environment”) were kept constant. These measurement values were obtained by using a C.E.M-DT8820 4 IN1 Multifunction Environment Meter. Consequently, all experimental conditions affecting the strings had been fixed apart from the mechanical wear process.

c) Other factors that affect the resistance measurement system such as ionization interference from sources like alpha particles, radio frequency sources such as nearby transmitters, contactors, solenoid valves, and even cellular telephones and portable two-way radios. In order to minimize noise in the test system owing to ionization interference, the volume of air inside the shield around sensitive input nodes was minimized and also sensitive nodes were kept away from high intensity electric fields. Radio frequency energy was reduced or eliminated by shielding and adding snubber filters at appropriate points.

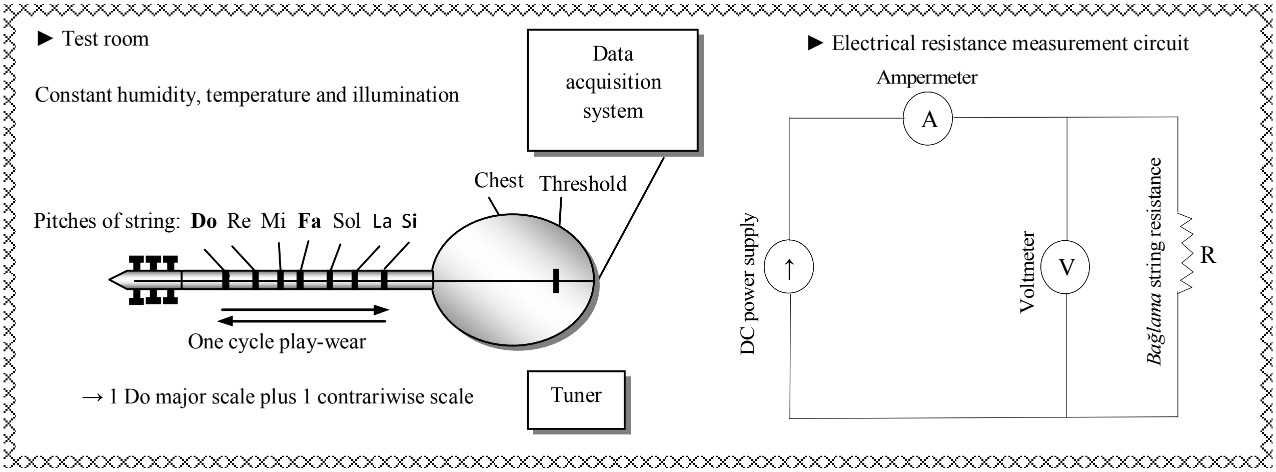


Figure 1 - Schematic presentation of the test medium and circuit connection assembled for low level resistance measurement

A stringed *bağlama*, with neck made of juniper wood, was used as a play instrument (**figure 2**) and was picked with a thermoplastic plectrum. The body length, string length (between nut and bridge) and neck length of the *bağlama* were approximately 43, 91 and 57 cm, respectively. The tuning was done on the basis of the bottom-string note of the *bağlama* accord order (disordered/in Turkish this is called *Bozuk* or *Kara* order) which is a well-known and widely used tuning for the *bağlama.* At the start of each playing session, the strings were tuned to A3 220Hz (third octave La) using both a Seiko SQ 100-88 digital tuner and NI LabVIEW Signal Express Tektronix Edition software connected to the oscilloscope. The strings were worn by reciprocating with the finger on a total of 14 pitches per wear cycle. Each cycle consisted of an ascending slide through the notes of the Do (C) major scale and then a descending slide back to Do (C) as shown in **figure 1**. The properties of the string used and the playing parameters are also presented in summary in **table 1**.

After each wear procedure, the low level electrical resistance values of the strings were measured before the strings were dismantled from the instrument. A low-level resistance measurement system, which consists of a GW-INSTEK GPS-3303-DC power supply and BRYMEN-two digital multimeters were used for the measurement of electrical resistance. Next, the samples from the worn locations were cut out, these locations were imaged and their surface roughness property was investigated using Nanomagnetics Instrument (AFM) and NMI SPM Image Analyser v.1.12. The AFM tip had a length of 225μm and sensitivity in the range of 10 to 20nm. The images were acquired at a resonant frequency of 330 kHz and a typical force constant of 42 Nm−1 in the tapping mode of operation using Si cantilevers.

Figure 2 – Long-necked *bağlama* used for play-wear tests

Different roughness parameters can be calculated based on the acquired AFM data. The R_a roughness value represents the standard deviation of pixel value from the mean plane:

$$R_a = \sqrt{\frac{\sum_{\substack{x=1,N \\ y=1,M}} (Z_{x,y} - \bar{Z}_{x,y})^2}{(N-1)(M-1)}} \qquad (1)$$

where N and M are the number of pixels in the x and y directions, and $Z_{x,y}$ is the image pixel height with respect to the centre plane height $Z_{x,y}$ for the pixel (x, y) [49]. These and other roughness parameters are discussed in Ref. [50].

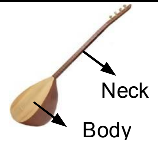
String	-Specification: C1085 high-carbon steel (ASTM A228 music wire) -Diameter: 0.20mm -Chemical composition: 0.85%C, 0.40%Mn, 98.75%Fe -Unit mass: 0.245g/m -Density: $7.8x10^3$kg/m -Hardness: 45 Rockwell-C 
Stringed instrument	Long necked *bağlama* made from juniper Its fingerboard made from beech (Hardness, Wood indentation: 4600N)
Abrasive counterparts	-Left forefinger (for reciprocating on stem region) -Plectrum (for stroke on body region): Made from a thermoplastic nylon material (65 Rockwell-R)
Medium	-Relative humidity: %46RH -Illumination: 0.18lux -Temperature: 25°C -Sound level: 20dB
Playing parameters	-Initial frequency: A3 (3rd octave La) note providing a sound with 220Hz frequency -Tension of string: ~4kg -Wear region on the string: Do major and contrariwise scales (including total 14 notes) by left forefinger -Number of wear cycles: 6000 -Wear speed: 100bpm andante moderato -Stroke on the body: once down (↓) and once top (↑) with the plectrum

Table 1 - Properties of the string used and playing parameters

In order to detect the mass losses caused by wear of the strings, a low level resistance circuit (see [50] for detailed information) as seen in **figure 1** was constructed, taking into account the resistance-cross sectional area relationship in the equation $R=\rho\ell/A$ (where ℓ is the length of the conductor, measured in meters; A is the cross-sectional area, measured in square meters; ρ is the electrical resistivity of the material, measured using an Ohm-meter). Two multimeters were used for the resistance measurement. One of them functioned as an ammeter and was connected in series with the string, and the other functioned as a voltmeter and was connected in parallel to the string. Measurement probes were tightly connected to the string samples by using probe fasteners. The measurement equipment was fed by a switched-mode dc-power supply of 100mA in constant-current mode. Both voltmeter and ammeter readings were taken and recorded. The resistance was calculated from the R=V/I equation by using these values. At least ten resistance measurements were averaged for the play-wear of each string.

In this study, low-resistance measurement is performed in constant current mode. If a higher current value is applied, then the string will be heated and loosen, thus resulting in a substantial change in the resistance value, and even in corrosion of the string. Low constant current provides a more controllable measurement. A number of measurement values are obtained taking into account the possible errors caused by ammeter and voltmeter. Suppose that V_M is the voltage measured by multimeter; I_M is the current value measured by multimeter; R_M is equal to V_M/I_M ratio. AVOmeters (multimeters) have 0.1mV and 0.01mA resolution for voltage and current measurements, respectively. $R_{average}$ is equal to the average of the resistance values calculated.

Both before and after play-wear, to characterise the change in frequency, recognised as one of the most important properties of musical sounds that distinguish a music sound from other sounds, the frequency spectra were captured by using NI LabView Signal Express Textronix Edition software connected to an oscilloscope before dismantling the string.

III. RESULTS AND ANALYSIS

Figures 3 (a), (b) and **(c)** illustrate the surface topography and provide three dimensional images of both the unworn and the worn strings, respectively. When the AFM photo of the worn string in **figure 3 (b)** is examined, it is understood that the straight tracks on the string surface were generated as a result of the reciprocation of the string by finger skin (horny cell layer) and the abrasion by nano-particles possibly separated from the finger skin and/or steel string surface with respect to the reciprocating movement.

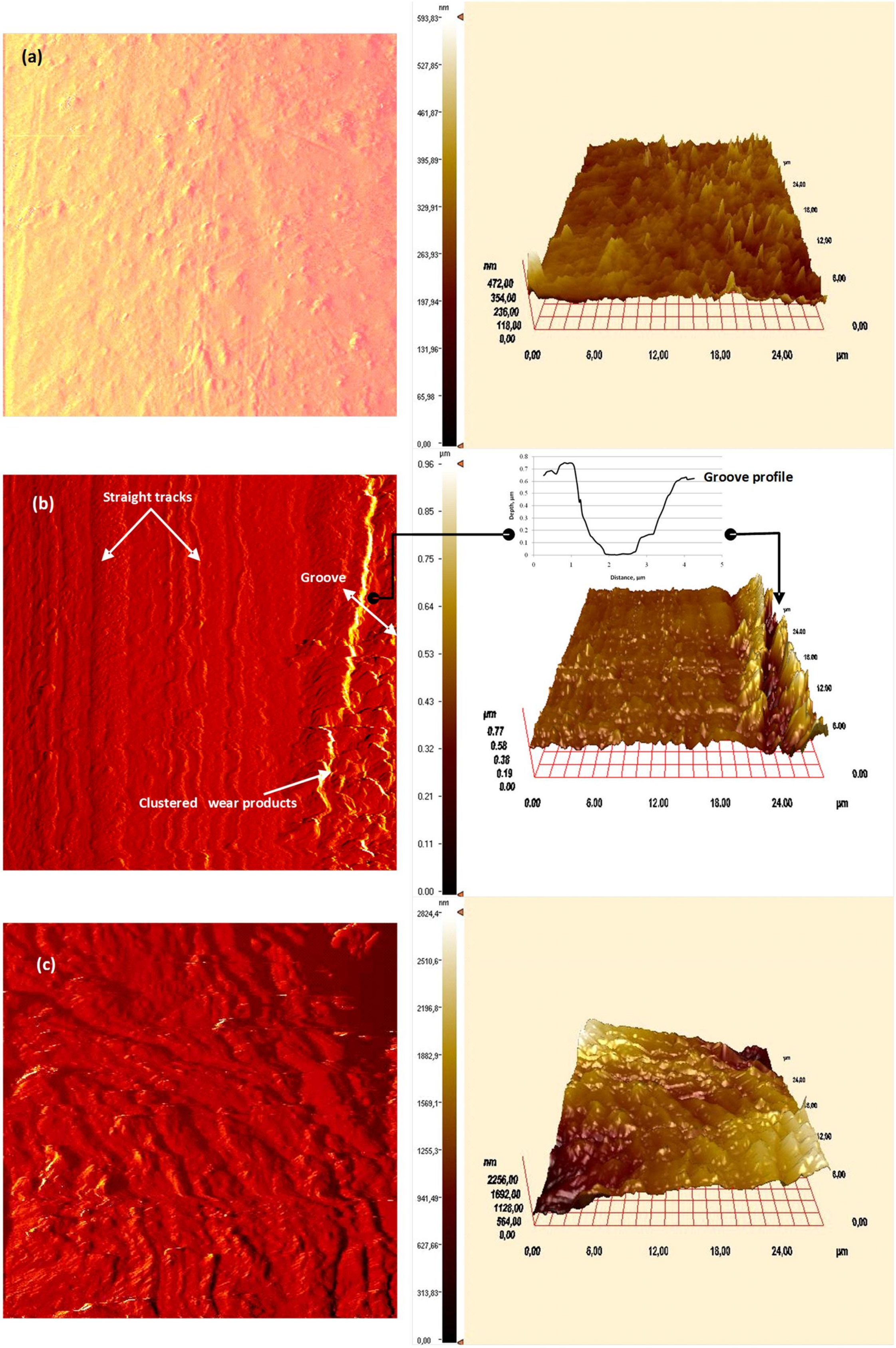


Figure 3 - Typical AFM surface morphology and 3D images of (a) the unworn string, (b) the string pertaining to the neck region worn by finger-reciprocation and (c) the string pertaining to the body region worn with a plectrum

Sugishita et al. [52] have mentioned tactile abrasion and its abrasive effect on metals. The linear traces on strings are reminiscent of abrasion mechanisms such as ploughing [53] or plowing abrasion. As seen in **figure 3 (b)**, it is noted that the finger skin and/or wear both form a groove with approximately a depth of 0.7µm on the string and debris also diffuses to the track edge by a ploughing mechanism, then accumulate around the contact area. **Figure 3 (c)** shows AFM surface morphology and 3D images of a part of the string over the instrument body worn by the polymer plectrum. Random ridges and grooves and a texture that presents a wavy and wrinkled appearance, even swelling, due to the repetitive impacts of the plectrum on the string surface are observed.

The average surface roughness of an unworn string was approximately 120nm. After wear of 6000 cycles, the surface roughness of the string on the finger-wear (neck) region was 200nm, while it increased to approximately 564nm on the plectrum-wear (body) region. Deviation in roughness is less than 0.5%R_a.

While the electrical resistance of the string is 7.18533 Ohm before wear, it is 7.20647 Ohm after wear. The difference between R_M and $R_{average}$ is 5 digits, which means that 5 zeros from the right of the decimal point are significant. Although the power supply is adjusted to 10mA value, the real current values are measured in the 9.82 to 10.28 mA range by the power supply display, which has accuracy (sensitivity) of ±0.5mA. However, in the study, the more accurate current values of the multimeter ammeter are used. As a result, the resistance measurement has five significant digits after measurement errors of the multimeters, which have a 0.1mV and 0.01mA resolution for voltage and current measurements respectively, are taken into account. The increase in electrical resistance after play wear corresponds to an enhancement of approximately 3/1000. This is attributed to the electrical resistance that is inversely proportional to the cross-sectional area reduction following play-wear of 6000 cycles. However, this reduction in the cross-section is not homogeneous throughout the string with regards to the nature of the abrasion mechanism. Therefore, variable section areas contribute to non-uniformity of the section. If these section areas are represented as having different resistance values, then they will sum and increase the total resistance of the series circuit. Stick-slip abrasion on different parts of the string is caused by the reciprocating movement of hand on the strings. Material removal from the string surface is at the micro/nano-level, even the subnano-level. In **figure 4**, the relationship between section area and electrical resistance is schematized with an exaggerated drawing.

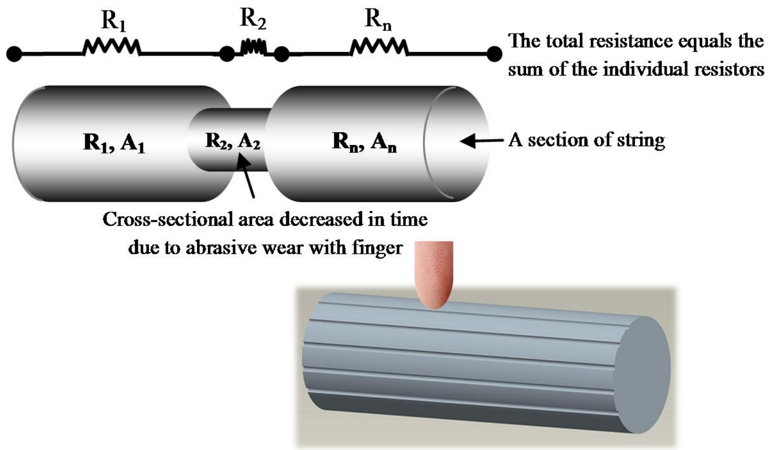
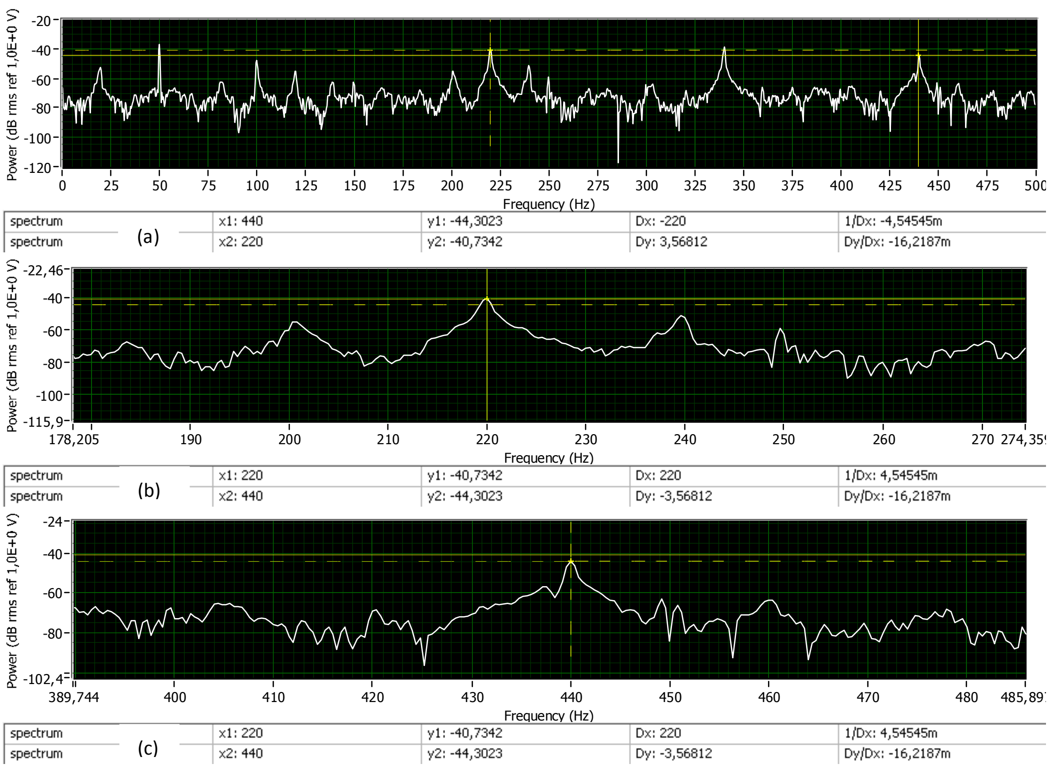


Figure 4 - Section area-electrical resistance relation schematized with an exaggerated drawing

To characterise sound properties, before the wear process the unworn string was tuned to the A3 note and after play-wear, frequency change of the strings was obtained using NI LabView Signal Express Textronix Edition software connected to an oscilloscope. As seen in **figures 5** and **6,** the frequency of the string increased from 220Hz (A3 note, third octave La sound) to 220.4Hz due to a reduction in the cross sectional area, caused by play-reciprocating wear. Mersenne [5] (referred to as the father of acoustics) explained that the fundamental frequency of a vibrating string is proportional to the square root of the tension and inversely proportional both to the length and the square root of the mass per unit length. In the equation of $f=1/2\ell\,(F/m)^{1/2}$, f is frequency (Hz), ℓ is vibrating length (m), F is tension force (N) and m is the specific mass of the string (kg/m). According to this, it is seen that the frequency will also increase as the vibration number per unit section increases. Consequently, more acoustic energy will be emitted to environment, resulting in tonal loss. That is to say, the obtained result confirmed Mersenne's equation.



spectrum	x1: 440	y1: -44,3023	Dx: -220	1/Dx: -4,54545m
spectrum	x2: 220	y2: -40,7342	Dy: 3,56812	Dy/Dx: -16,2187m

spectrum	x1: 220	y1: -40,7342	Dx: 220	1/Dx: 4,54545m
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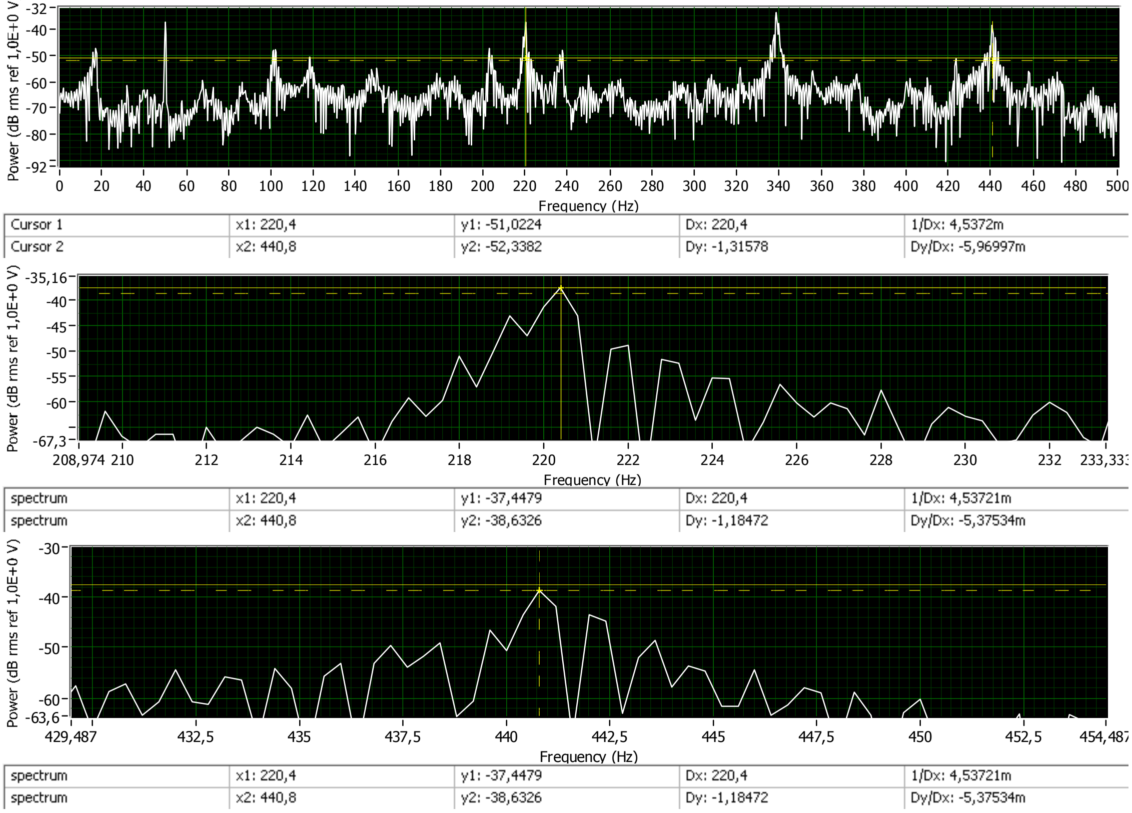
Figure 5 (a – c, top to bottom) - The characteristic frequency spectrum of (a) the string tuned to A3 between 0-500Hz, (b) the zoomed spectrums of the same string at A3 note (third octave La sound with 220Hz) and (c) the same string at A4 note (fourth octave La sound with 440Hz) for an unworn string



Cursor 1	x1: 220,4	y1: -51,0224	Dx: 220,4	1/Dx: 4,5372m
Cursor 2	x2: 440,8	y2: -52,3382	Dy: -1,31578	Dy/Dx: -5,96997m

spectrum	x1: 220,4	y1: -37,4479	Dx: 220,4	1/Dx: 4,53721m
spectrum	x2: 440,8	y2: -38,6326	Dy: -1,18472	Dy/Dx: -5,37534m

spectrum	x1: 220,4	y1: -37,4479	Dx: 220,4	1/Dx: 4,53721m
spectrum	x2: 440,8	y2: -38,6326	Dy: -1,18472	Dy/Dx: -5,37534m

Figure 6 (a – c, top to bottom) - The characteristic frequency spectrum of (a) the play-worn string, (b) the zoomed spectrum of the same string at A3 note region and (c) the same string at A4 note region after play-wear

When **figures 5** and **6** are examined, it can be seen that the unworn string has a frequency of 220Hz, and the frequency value tends to move together with wear.

IV. CONCLUSION

The play damage on the string was note-worthy even if wear is low or the number of wear cycles is not very high. Both decreases and changes (different roughness values) in different levels throughout the cross section of the string bring about wear depending on the number of wear cycles with respect to the duration, collaboratively causing increases in vibrating frequency and in electrical resistance of the string. Consequently, in terms of roughness, the contact roughness (e.g. finger and string) will have an effect on the electric field enhancement due to the accumulation of charges on the peak areas. This would lead to increased resistance. The low level resistance measurement can be used for accurate accounting of the wear losses as a result of play-abrasion on steel music strings and therefore for the lifetime determination of music strings. An atomic force microscope is also a useful instrument for determining the surface roughness of worn music strings, as it discloses the surface morphology and variations in the cross sectional area.

A string that is subjected to play-wear damage changes both its original structure and its acoustic properties. To minimise these losses, the origin of the mechanical and tribological effects during play on acoustics properties need to be examined in detail. This duty belongs to tribologists and acoustists. The information obtained on wear-acoustic relationships of strings will be useful for all stringed instruments. Scientific prescriptions showing wear lifetime can provide meaningful practical data.

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