ULTIMATE TENSILE STRENGTH OF THE STRING DETERMINATION USING SPECTRAL ANALYSIS

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Abstract
The paper is focused on ultimate strength of guitar string using spectral analysis of rupture process sound recording from which the frequency of vibration right before failure was determined. The tension thus the stress can be calculated from fundamental frequency of the string. Two materials – High Carbon Steel and Nylon – were tested. Also two diameters of the string for each material were used. The results were verified by classic tension test and also by modal analysis in ANSYS Workbench environment. It was shown that this method gives relevant results.

Key words: *spectral analysis; ultimate strength; guitar string; modal analysis.*

INTRODUCTION

Ultimate tensile strength of material is usually determined using classic tension test *(Davis, 2004; Campbell, 2013)*. There are also other methods such as small punch testing *(Holmström, 2019)* or for dynamic tensile strength using Charpy data *(Lucon, 2016)*.

It is not always possible to provide or use appropriate equipment due to time, operational or economic conditions. But there is possibility to record the sound on almost every mobile device and also applications for spectral analysis or frequency measurement to be done “in the field” are available. There are also numerous possibilities how to apply tension to the object when applied force is not needed to be known. This could be useful in less developed countries or remote location when strength properties of constructional part needs to be verified.

Aim of this article was to introduce contactless method for measurement of ultimate tensile strength of straight vibrating object with constant cross-section what was represented by guitar string. The method shows that it is possible to determine ultimate strength without direct force measurement using shredding machine or similar testing device.

MATERIALS AND METHOD

Selected strings were attached to the guitar and the process of tightening was recorded as audio wav file. For steel strings audio recording electric guitar Fender Stratocaster (made in China) equipped with custom R.M. Pickups was used. Bridge pickup type RS3000 was selected. The guitar was connected over USB soundcard UGM96 into MacBook Pro 13’ early 2015 running OSX 10.14.5. Audacity 2.3.0 free software was used for recording and editing. Electromagnetic pickups cannot obviously pick sound from nylon strings therefore acoustic guitar Nashville NW-020N with Thrust Emita USB Studio microphone was used for audio input. Sonic Visualiser version 3.3 what is free software developed at the Centre for Digital Music, Queen Mary, University of London was used for spectral analysis.

Not many string manufacturers offer more detailed information about their products, thus d’Addario strings were chosen because this manufacturer provides enough input parameters for this test to be executed. According to d´Addario tension chart *(d’Addario 2019)* high carbon steel strings PL009 and PL020 and nylon strings J4501 and J4503 were chosen. All strings are plain which means it has no wound therefore its physical and mechanical properties depend only on basic material and cylindrical shape. Required parameters are provided in Tab. 1. Some parameters had to be converted to international system or calculated from others, such as material density which is calculated from unit weight and string dimensions. The density was needed for correct material definition in FEA analysis. Length of all strings was 647.7 mm which is typical scale length of guitar thus 25.5 inches. It was also verified by measurement on the instruments.

Tab. 1 String properties

String	diameter inch	diameter mm	unit weight lb. · inch^{-1}	ρ kg · m^{-3}
PL009	0.090	0.229	$17.94 \cdot 10^{-6}$	7779
PL020	0.200	0.508	$88.61 \cdot 10^{-6}$	7807
J4501	0.280	0.711	$20.92 \cdot 10^{-6}$	941
J4503	0.403	1.024	$46.79 \cdot 10^{-6}$	1015

For each string 5 tests were carried out. The string was attached to the guitar and tuned on its nominal frequency what was verified by guitar tuner. Then the recording was started and the string was tightened using tuning knob of the guitar. The string was lightly hit with guitar pick each 1-2 seconds so that the sound can be recorded but the added force was as low as possible. When the string broke the recording was stopped. The audio wave was then shortened from dozens of seconds even minutes to only last seconds before rupture using editing software. After that the file was saved as wav and opened in spectral analysis software where fundamental frequency of the string in the moment before failure was obtained.

The ultimate strength of the string was calculated as stress for measured frequency using equation (2) which can be simply derived from equation (1) *(Rayleigh; 1945; Raichel, 2006; Inman, 2017).*

$$f = \frac{1}{2 \cdot L} \cdot \sqrt{\frac{T}{m_1}} \tag{1}$$

where *f* is frequency of the string (Hz), *L* is length of the string (m), *T* is string tension (N) and m_1 is unit weight (kg · m^{-1}).

$$\sigma = \frac{16 \cdot f^2 \cdot L^2 \cdot m_1}{\pi \cdot d^2} \tag{2}$$

where σ is tensile stress in the string (Pa), *f* is frequency of the string (Hz), *L* is length of the string (m), *d* is string diameter (m) and m_1 is unit weight (kg · m^{-1}).

Subsequently all types of strings were tested using testing machine MPTest 5.050 for verification of ultimate tensile strength values. Custom made fixations were used for considerate string attachment. For steel strings testing speed 5mm · min^{-1} was used. Speed 20mm · min^{-1} was used for nylon strings to reduce test time according to much lower Young’s modulus.

Also ANSYS Workbench 2019 R1 modal analysis using obtained material properties and ultimate stress values converted to tension used as bolt pretension load was used to verify values of frequency.

RESULTS AND DISCUSSION

The sound wave example with obvious failure moment is presented in Fig.1. Peak frequency spectrogram is shown in Fig.2. Horizontal-like lines show frequencies of clean tone. The lowest one is fundamental frequency of the string which was used for measurement in moment before string failure. Higher frequencies are harmonics which influence the sound of the instrument. The software is showing frequency of selected point in spectrogram on mouse over.

Tab.2. shows results of spectral analysis including standard deviation compared with tensile test ultimate strength results and FEA modal analysis for mean value of ultimate stress obtained from spectral analysis.

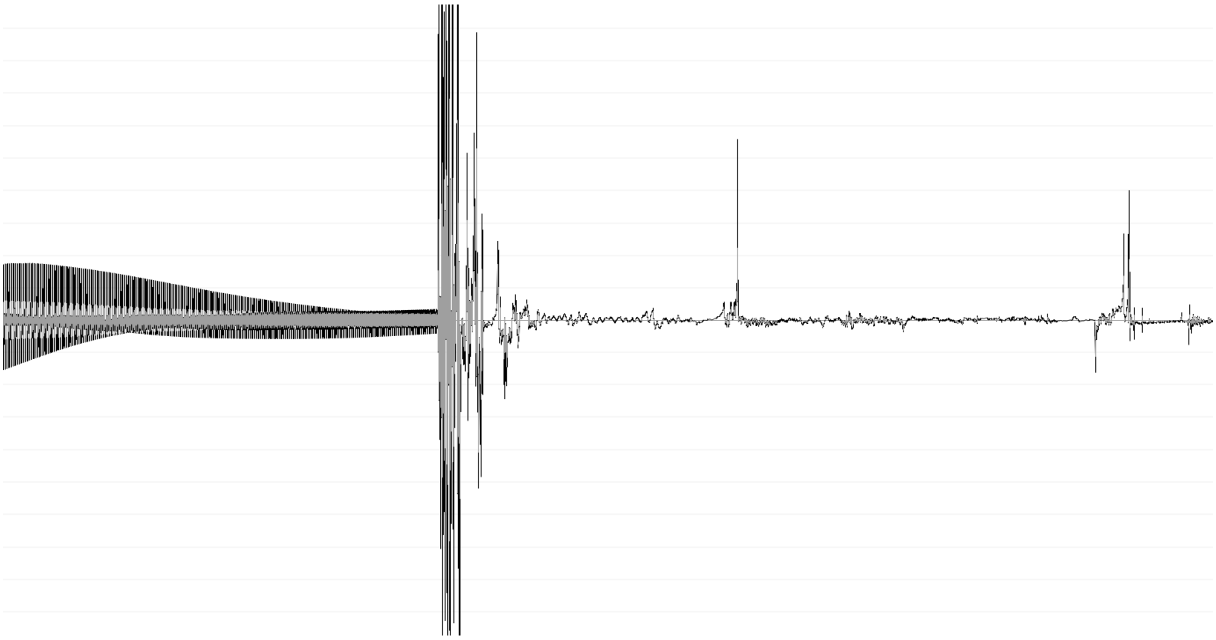

Fig. 1 Sound wave for string P009

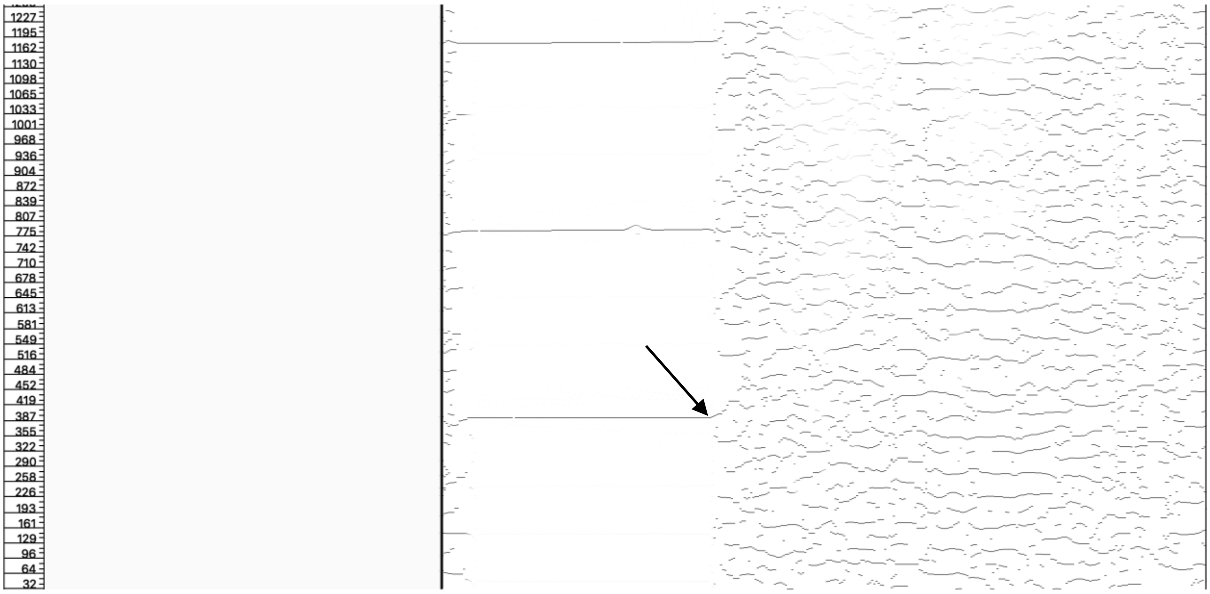

Fig. 2 Peak frequency spectrogram (the arrow is showing place of frequency measuring)

Tab. 2 Results

String	frequency Hz	ultimate strength MPa	tensile test MPa	FEA frequency Hz
PL009	405 ± 10	2143 ± 112	2306	403.2
PL020	350 ± 7	1606 ± 67	1623	350.1
J4501	431 ± 9	293 ± 13	292	408.5
J4503	432 ± 6	318 ± 9	308	424.2

From Tab.2. it is obvious that spectral analysis method gives relevant results. Lower values for steel strings can be explained by added stress of vibrating string in contrast to static tensile test. Result for nylon strings were also influenced by vibration but tensile test was influenced with pressing fixation of softer material what could also reduce the maximal value. The modal analysis for steel strings showed that equation (2) gives correct correlation between frequency and stress. On the other hand, Young's modulus of nylon strings is strongly dependent on stress *(Lynch-Aird & Woodhouse, 2017)* thus its correct definition in ANSYS analysis would require deeper research in mechanical properties of current strings which is out of aim of this study. Therefore, the results of modal analysis for nylon strings are not as relevant as for steel because nylon material provided in ANSYS has constant Young's modulus defined – in this case 3GPa what was estimated from tensile test.

According to *(Olmer, 2007)* music wire with diameter under approx. 0.3mm can have ultimate tensile strength up to 2600MPa what corresponds with obtained results. Decreasing ultimate strength with increasing diameter of the steel strings also corresponds to *(Ono, 2019)*. This effect was not observed at nylon strings what can be caused by different technology in steel and nylon string production. Also different material density thus slightly different basic material or process for each nylon string can explain the results.

CONCLUSIONS

Method for determination of ultimate tensile strength of straight vibrating object with constant cross-section represented by guitar string was introduced. It was shown that it gives relevant results. This method could be used at much enhanced condition with optimized fixations, automated tightening and recording or direct frequency measurement. Or, on the other hand in field conditions with mobile sound recording and analyzing or whenever advanced equipment is not available.

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