On the Violin Bridge Hill – Comparison of Experimental Testing and FEM

Erik V. JANSSON
Department of Speech, Music and Hearing, KTH
SE-10044 Stockholm, Sweden, erik.jansson2@ownit.nu

Roman BARCZEWSKI
Poznan University of Technology – Institute of Applied Mechanics
Jana Pawła II 60-965 Poznań, Poland, roman.barczewski@put.poznan.pl

Andrzej KABAŁA
Poznan University of Technology – Institute of Applied Mechanics
Jana Pawła II 60-965 Poznań, Poland, kabalaandrzej@gmail.com

Abstract

Italian violins of the golden era and French violins are different. Measurements of bridge mobility show that the Italian violins have a local maximum (a hump) at approx. 2,5 kHz in the bridge mobility. The French violins do not show this maximum. The arching along the centre line is different. The Italian violins are flat between the f-holes while the French ones are arched. Does this difference in design explain the difference in bridge mobility and tone? Proposed FEM simulation and digital signal post-processing of the time series are promising methods of the virtual testing of various violin models. These techniques may give an answer for the question above and they should be helpful in achieving high tonal quality of violin.

Keywords: Bridge mobility, top plate arching, experiments and FEM

1. Introduction

A large number of wooden blanks was free for further experiments. It was planned to use the blanks to investigate the influence of material properties on the top plate of the violin. In introductory pilot experiments it turned out that the geometry influenced more than the material properties. Therefore it was decided to cut a large number of rectangular plates to the same measures and to investigate the effects of f-holes in each plate. The f-hole shapes were simplified to three rectangular sections making various perturbations possible in simple ways.

Thereby it was found that the longer parts along the wood fibres and the lower transversal parts of the f-holes gave small effects. The largest influence was given by the upper transversal parts. The influence of two f-holes was well given by f-holes in shape of two letters, uppercase L:s, one upside down and the other in mirror image (Fig. 1). The findings were in line with previous f-hole experiments on an assembled violin. Thus the influence of f-hole geometry had been mapped [1] as well as thickness previously. The violin top is not flat but arched. No way to explain the influence of differences in arching had been found. In this report we present experiments and FEM analysis of “arched” plates. The experiments indicate the effect of arching which can be tested by FEM. The traditional way of violinmaking does not offer investigation of arching, only of thickness.

The frequency range of the so called bridge hill is of special interest. The fundamental bridge resonance was presented by Reinicke [2 and 3]. The resonance was found at approximately 2,5 kHz. In this frequency range the ear can register small level changes of a played tone. The 2,5 kHz-range is most interesting. In experiments with violins it turned out that at least for this very violin the shape of the bridge was of minor influence. A plate bridge i.e. a bridge with only a plate and two feet gave the same hump at 2,5 kHz. The plate bridge resonance frequency was far above that of the normal bridge. Thereby it was asked whether does the 2,5 kHz hump would be described as a body-hill rather than bridge-hill (BH) [4]. This plate bridge thus makes it possible to measure body properties with no addition of complex violin bridge properties. In this paper we are mainly interested in body properties and we use the plate bridge in the experiments and the FEM. This makes experimental modelling and FEM of arching attractive.

The bridge-body properties and their influence on the 2,5 kHz hump found in good violins have been modelled as coupled circuits [5]. The bridge is modelled as a mass-spring resonator coupled to the violin body. The body properties are modelled by means of averages. So called skeleton technique is used and the influences of bridge and body properties are predicted. It is suggested to start measuring a violins input mobility using plate bridges [6]. This approach is the background of experimenting. Physical models can be more easily built for experiments as will be reported here.

Measurements of Italian violins from the “golden era” show clear BH humps in the 2.5 kHz range [7]. Similar measurements of later French violins do not show the BH. Possibly it is the difference in lengthwise arching between the “golden” Italian (flat not arched) and the French (more arched) violins. Good old Polish violins also have a BH [8].

The BH also shows up in spectra of played test music, i.e. the common test music the prelude of the Bruch violin concerto. Such attest was made with the concert master Bernt Lysell of the Swedish radio and his Italian Guadagnini showing a BH but not a French violin by Leon Bernardel, see Figure 1 [9]. The test playings were preformed in the main concert studio of the orchestra. The two Stradivari violins and the J. Guarnerius del Gesu violin in the Strad3D playing tests also show a BH [10]. This background makes the influence of arching the main question of the present project. What influence has the lengthwise arching on the BH?

2. Experiments

A half of wooden blank for a guitar top was selected and cut into two pieces. One piece was made with measures close to earlier experiments and a second smaller piece for pilot experiments. The smaller piece was soaked in water and its mass (weight) was noted as function of time. After twelve hours the amount of water absorbed was close to maximum. Drying the plate in hot air oven at 80ºC for 2 hours dried the plate. Therefore it was decided to soak the test the plate in water for twelve hours, clamp it in a bent form and dry it for two hours to make the larger plate arched.

The test plate was first arched by soaking, placing a 5 mm diameter rod under the bridge line and clamped to a grid, 0 mm, at the shorter sides, and dried in the oven. After removing the clamps a 3 mm arch remained. The “rectangular” simplified f-holes were cut and a plate bridge glued to the centre of the plate see Figure 1.

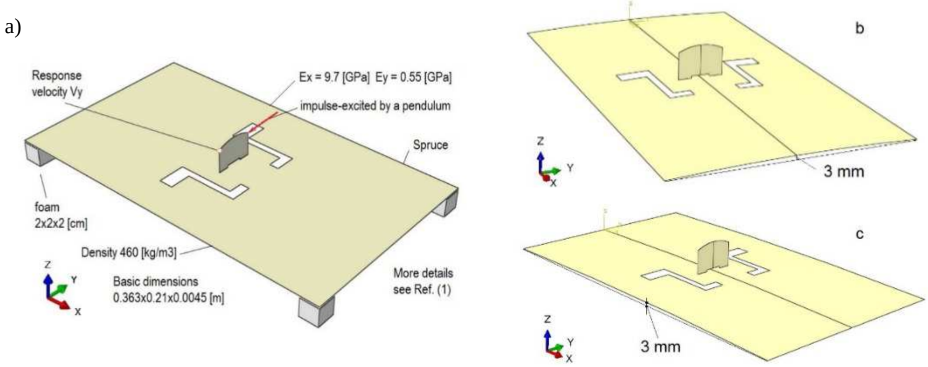


Figure 1. Plate with “f-holes”; a) sketch of bridge and supports
b) center line bending; c) bridge line bending

Secondly the plate was flattened by doing the same procedure but slightly bent in the opposite direction. The plate was now flat after drying. Finally the rod was placed under the centre line, see figure 1b and a 3 mm arching along the centreline was obtained.

In each case the plate was placed on soft supports at its corners. This was found close to free edges in measurements. In the acoustical measurements the bridge was impulse-excited by a pendulum hitting the bridge in the y-direction. A small magnet, mass approximately 30 mg was waxed to the other, opposite bridge corner. The resulting velocity, time history, in the y-direction was recorded by an electrical coil over a small airgap; see recorded time histories in Figure 2. By means of FFT the frequency spectra of the time histories were obtained, see Figure 3. The Figure 3a thus represents the frequency response of the plate bent with maximum arch along the bridge line, Figure 3b the plate “flat” and Figure 3c the plate bent along its centre line. In Figure 3a compared to Figure 3b flat plate it can be seen that the response level in the 2,5 kHz range is the lowest, i.e. the lowest for the “French” arching.

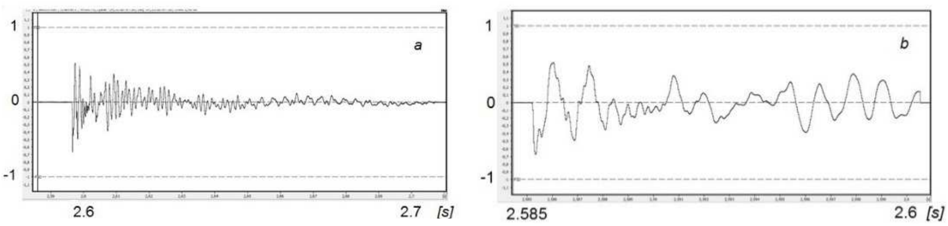


Figure 2. Time history (velocity) of plate flat a) initial 0,1 s and b) initial 0,015 s

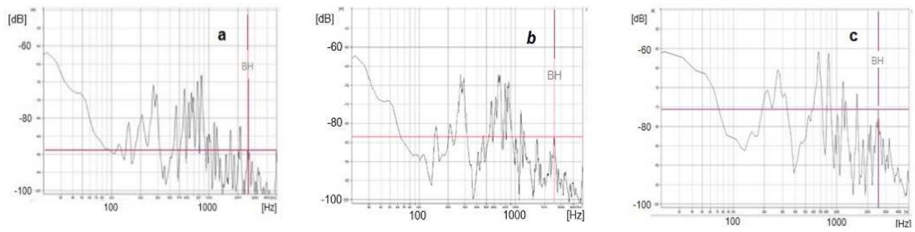


Figure 3. Frequency response of bridge time histories (velocity) for: a) plate bent as in Figure 1c; b) plate flattened; c) plate bent as in Figure 1b

3. FEM simulation

The geometry and properties of the plate applied for the experiment described above are used to create a discrete model in the FEM study. The basic difference between FEM model and experiment is application of the springs and dashpots instead of the foam to model boundary condition of the plate. It is shown in Figure 1a and Figure 4b.

Plate (spruce) Young's modulus $E_L = E_x = 9{,}7$ GPa; $E_R = E_y = 0{,}55$ GPa
Density $\rho = 460$ kg/m^3, Poisson's r. $\nu_{xy} = 0{,}44$; $\nu_{xz} = 0{,}33$, $\nu_{yz} = 0{,}42$
Bridge (maple) Young's modulus $E = 10$ GPa
Density $\rho = 600$ kg/m^3, Poisson's ratio $\nu = 0{,}43$
Additional properties were given from [11]

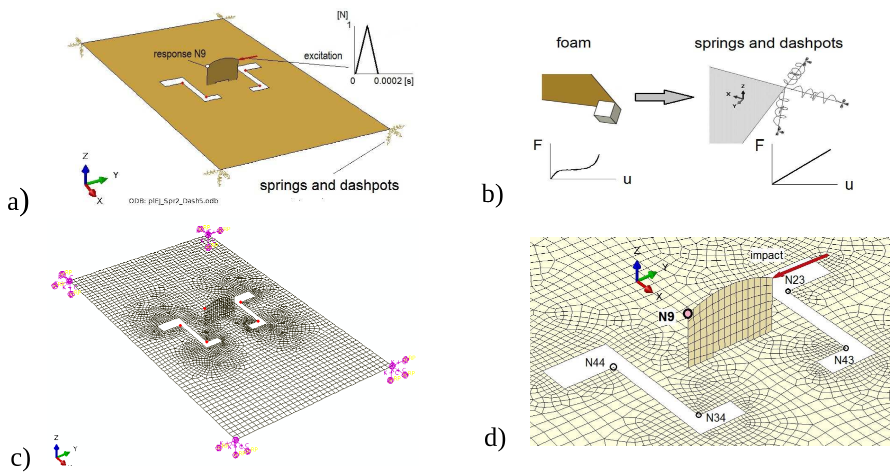


Figure 4. FEM model of the plate; a) shell model of the plate, b) support of the corners – foam (experiment) and springs (FEM), c) discrete model of the plate – 4016 shell elements type 4SR, d) "f-holes" and bridge with numbers of the output nodes

FEM model of the plate and boundary conditions are shown in Figure 4. Loads – excitation: see Fig. 4a and Table 1. The procedure *Dynamic*, *Explicit* of ABAQUS/Explicit System was used to lead simulation of the plate vibration. Selected results of FEM simulations are shown in Figure 5.

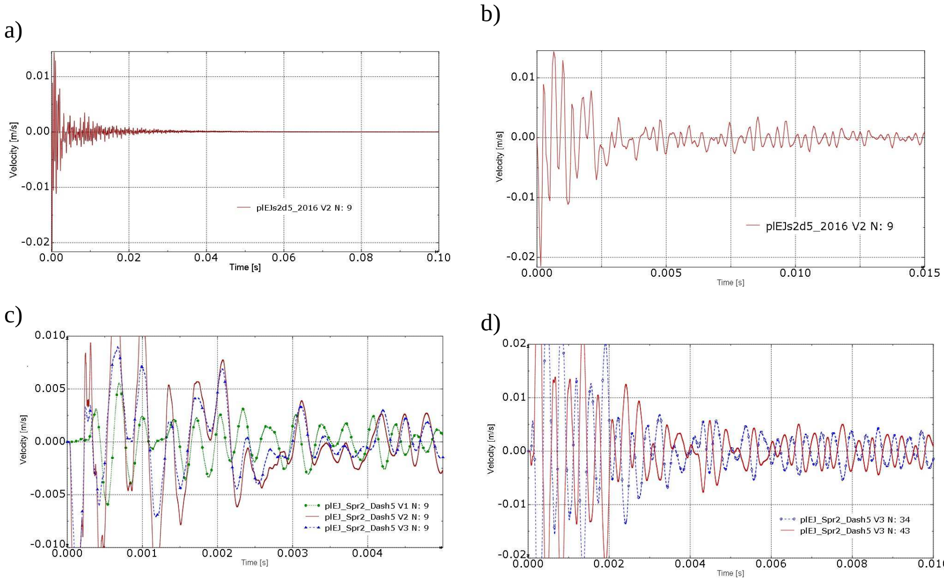


Figure 5. Time history (velocity) of the plate a) response of V_y in node N9 (see Fig. 4d) - initial 0,1s; b) response of V_y in node N9 initial 0,015 s; c) comparison of response V_x, V_y, V_z in node N9, d) comparison of response V_z in nodes N34, N43 (see Fig. 4d)

4. Signal post-processing

The FEM simulation gives results in the form of the time series (see Fig. 5). The mobility (admittance) can be obtained by digital signals processing (DSP) of excitation signal (force – see Fig. 4a) and the response signal of the tested model (velocity – e.g. Fig. 5a). A simplified algorithm of DSP procedures has been outlined in Figure 6. In the first step the output data from FEM simulation is windowed. Then, by FFT procedure the time signals are transformed into frequency domain. The transmittance (in this case module of the mobility in [ms^{-1}/N]) is obtained by dividing the response spectrum by the excitation spectrum. In the last step, magnitude of mobility is converted from linear to logarithmic scale which is more useful for comparisons of results of experiments and numerical simulations. The reference value equal to 1 ms^{-1}/N has been used. The sampling frequency used in the DSP system was equal to 20 kHz. It results from the time step of FEM analysis (Δt = 0,0005 s). The rectangle time window of the size of 2048 samples has been applied. Taking into account these parameters we can state that only a short signal sequences (of excitation and response about 0,1 s) has been used to determine the admittance (see Fig. 5a).

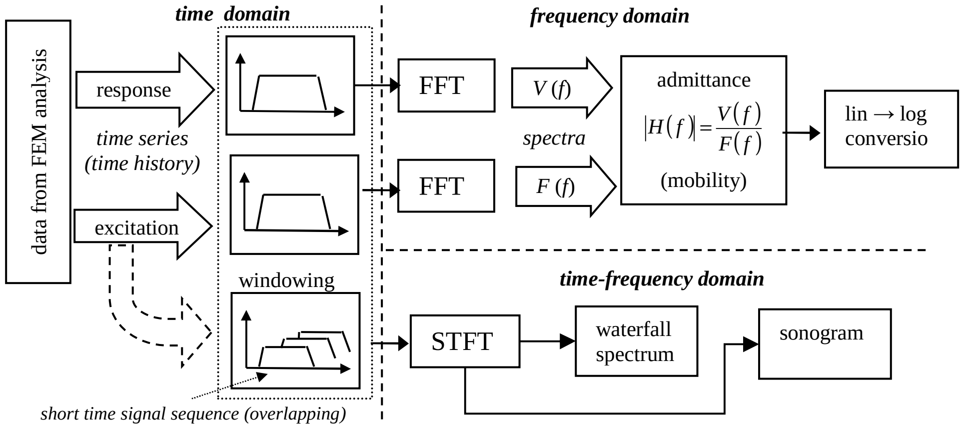


Figure 6. Simplifies scheme of digital signal post-processing used to the mobility determination of the violin bridge (based on FEM results)

The first 10 milliseconds of analyzed signals (excitation and response) are shown in Figures 7a and 7c. The short triangle force impact equal to 1 N and duration of 0,2 ms is visible in Figure 7a. Spectra of the excitation and the response are presented in Figures 7b and 7d respectively.

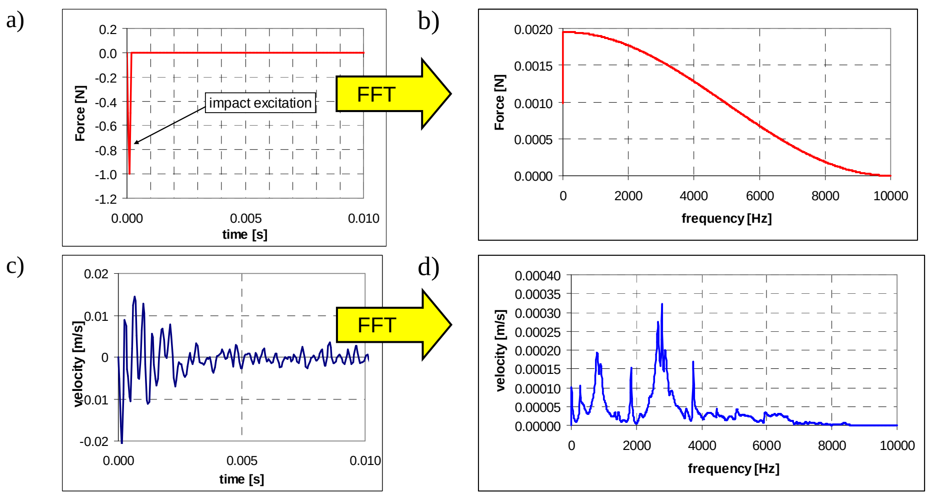


Figure 7. Example results of signals post-processing (flat plate; see Fig. 4) signals from FEM simulation : a) excitation signal c) response (V_y in node N9); spectra obtained by FFT: b) spectrum of excitation signal d) spectrum of response

The frequency range of spectral analysis and spectral resolution results directly from settings of DSP parameters. A sampling frequency f_s determines the frequency range. In this case it is limited to 10 kHz (½ f_s – Nyquist frequency). However a usable frequency range of the admittance may be lower. The frequency range depends on the shape and the duration of the virtual impact excitation which will be used for dynamic testing of FEM model. In practice the duration can not be shorter than Δt. The frequency resolution Δf (of spectra as well as the admittance) is determined by the sampling frequency and the number of signal samples (N) in the time window ($\Delta f = f_s/N$). Taking into account values of both these parameters the resolution Δf is approximately equal to about 10 Hz. It is worth mentioning that DSP software has been elaborated in the DASYLab® environment (*Data Acquisition System Laboratory*).

The mobility (admittance) in linear and logarithmic scale of the magnitude has been shown in Figure 8. In Figures 8a and 8b the BH ("Bridge Hill") frequency range has been marked.

a)

b)

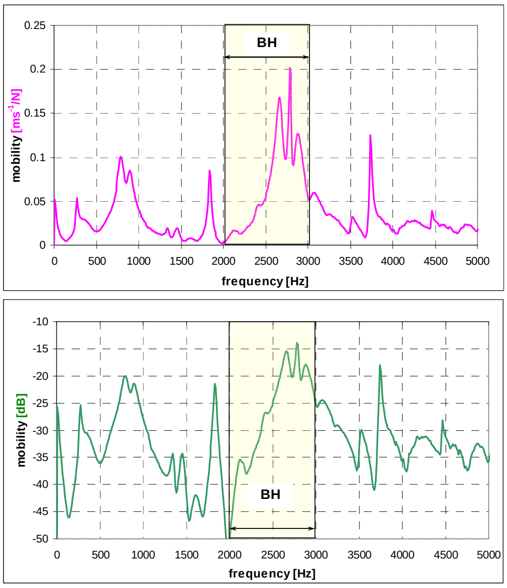


Figure 8. The final result of DSP – mobility (admittance) of violin FEM model; a) linear scale b) logarithmic scale (flat plate see Fig. 4 – corresponding to response of V_y in node N9)

The Short Time Fourier Transform (STFT) was applied as auxiliary analysis which shows well the nature of the response signal in the frequency and time domain. This type of analysis has been described in [12]. Some optimization techniques of STFT can be found in [13]. An interesting approach to the time-frequency analysis and obtaining of a time-variant frequency response function is proposed in [14]. The methods mentioned above can be useful in development of new testing methods as well as parameterization of the vibroacoustical properties of violins.

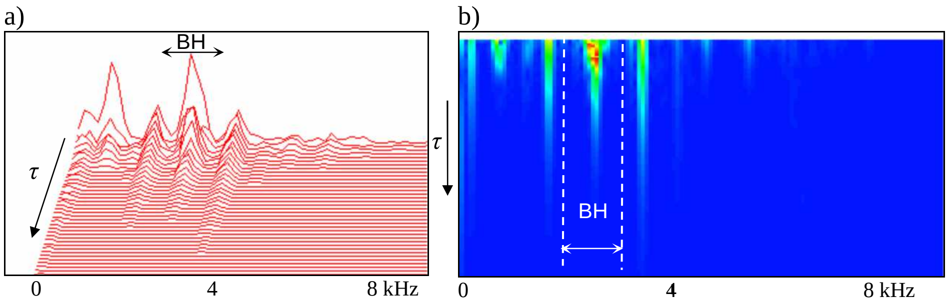
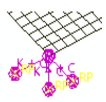
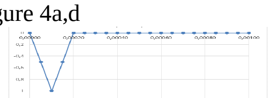


Figure 9. Violin model testing. The results of STFT analysis of the response signal presented in Fig. 5a . (where: BH is a frequency band pass of the “Bridge Hill”; τ is the shift of the time window); a) waterfall spectrum b) sonogram

5. Comparison of FEM – experiment

The basic differences between FEM and experimental testing are shown in Table 1.

Table 1. Comparison FEM - Experiment

FEM	Experiment
Structure	
The structure is divided into finite elements. All elements have the same properties.	The continuity of the structure. Local inhomogeneous density and other according to wooden properties.
Basic material properties	
Young's modules (E_L, E_R) are constant.	Young's modulus (E_L, E_R) are inhomogeneous according to local properties of the wooden plate. The average values of Young's modules are the same as in FEM
Boundary conditions	
The plate is supported on the springs and dashpots in axis directions (k_{spring} = 200 N/m) – linear – see Figure 4a,b,c 	The plate is based on the foam ankles. The foam stiffness is unknown (typical nonlinear) – see Figure 1a and Figure 4b
Load – excitation	
Impact force F = -1N (triangle, time=0.0002s) – see Figure 4a,d 	Excited by a mechanical pendulum – see Figure 1a

6. Conclusions

Experiments were made with a rectangular wood-plate with a simplified bridge and simplified f-holes. The bridge was impulse excited by a mechanical pendulum and the velocity response was measured. By FFT the velocity response was transformed into frequency response. The plate was bent in three steps, first across the fibres with maximum arch along the bridge line, secondly flattened and finally bent along the fibres with maximum arch height along the centre line. Minimum level in the 2,5 kHz, the BH range, was found for the plate with the arch along the bridge line, somewhat higher for the flattened plate and the highest level for the plate arched along the centre line. The experimental results were subjectively evaluated and need independent verification and an explanation.

The comparison of the experiment results that are shown in Figure 3b and in [1, Figure 6c] to the transformed FEM results shown in Figure 8 confirms that typical BH exists near frequency of 2,8 kHz. Despite the differences shown in Table 1 the results of the experimental investigation and FEM coincide for the flat plate.

Preliminary FEM simulations of the bent plates that are shown in Figure 1b and Figure 1c do not confirm experiment results exactly that are shown in Figure 3a and Figure 3c. Further research are planned to clarify the reasons of the differences. Perhaps the methods of bending plates used in the experiment had introduced changes in the material properties of the plates. FEM models ought to be checked beside of this.

Acknowledgment

This paper was partially financially supported in the year 2016 by research project 02/21/DSPB/3478.

References

1. F. Durup, E. V. Jansson, *The quest of the violin bridge hill*. Acustica - Acta Acustica (2004), **91** (2005) 206 – 213.
2. W. Reinicke, *Die Übertragungseigenschaften des Streichinstrumentenstegs*, Doctoral dissertation, Technical University of Berlin, 1973.
3. L. Cremer, *The physics of the violin*, chapter 9, MIT Press, Cambridge MA, 1985.
4. E. V. Jansson, B. K. Niewczyk, *On the acoustics of the violin bridge or body hill*, J. Catgut Acoust. Soc. Series **23** (1999) 23 – 27.
5. J. Woodhouse, *On the "Bridge hill" of the Violin*, Acustica-Acta Acustica, **91** (2005) 155 – 165.
6. J. Woodhouse, *The acoustics of the violin*, a review Rep. Prog. Phys. 77 (2014) 115901 (42pp).
7. E. V. Jansson, *Admittance measurements of 25 high quality violins*, Acustica - Acta Acustica, **83** (1997) 337– 341.
8. E. V. Jansson, B. K. Niewczyk, A. Knast, *An investigation of old violins in Poznan and Krakow*, unpublished report.

9. E. V. Jansson, *On the prominence of the violin bridge hill in notes of played music*, J. Violin Soc. Am. VSA papers Summer 2009 XXII, No 1, 169 – 176.
   Better ref E. Jansson, *On projection: long-time-average spectral analysis of four played violins* JVS VSA papers Summer 2006, Vol. XX, No 2, 143 – 154.
10. S. Zygmuntowicz, *Strad3D DVD*, 2009.
11. E. K. Askenazi, Anisotropy of woods and wood materials, Forest industry (*"Lesnaiia Promyslennost"*), Moscow 1978.
12. S. Qian, D. Chen, *Joint time-frequency analysis: methods and applications*, Upper Saddle River, NJ, Prentice-Hall 1996.
13. K. Dziedzich, W. Staszewski, T. Uhl, Time–*frequency analysis of time-variant systems*, Diagnostyka, **14**(1) (2013) 37 – 42.
14. R. Barczewski, *Diagnostic oriented methods of short time processing of vibroacoustical signals*, Publishing House of Poznan University of Technology, monograph, No 504, Poznan, 2013.