Proceedings of the International Symposium on Music Acoustics

(Associated Meeting of the International Congress on Acoustics)

25-31 August 2010, Sydney and Katoomba, Australia

Parallel Monitoring of Sound and Dynamic Forces in Bridge-Soundboard Contact of Violins

Enrico Ravina (1)

(1) University of Genoa, MUSICOS Centre of Research, Genoa, Italy

PACS: 43.75. –z; 43.75. Yy

ABSTRACT

The paper refers on an original experimental activity oriented to correlate sound and internal forces generated in violins. In particular static and dynamic forces generated in the contacts between bridge and soundboard-playing instruments belonging violins family are analysed respect to the generated sound. A classical violin has been instrumented with two force sensors, wireless interfaced to PC. Simultaneously acoustic acquisitions are detected. The violin is played following different techniques (pizzicato, vibrato) and applying several methods of attack with the bow (detaché, martelé, collé, spiccato and legato). The experimental approach is described in the paper with reference to violins, but the method is been conceived to be applied to different stringed instruments, changing calibration: in particular it can be successfully applied to the whole family of bowed instruments.

INTRODUCTION

The role played by bridge in stringed instruments is well known: its geometry, stiffness and damping strongly influence the dynamic actions induced on the soundboard and consequently the acoustic behaviour of the instrument. In the case of violins the bridge transfers some of the energy of vibration of the string to the body of the violin, at frequencies where the ear is most sensitive. This is one of the reasons for the bright timbre of the violin. The action of the violin bridge is essential to the tone of the instrument. Its shape and function have been developed over centuries (Figure 1).

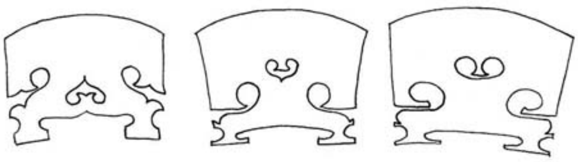


Figure 1. Baroque, classic and modern bridges

Underneath the treble side of the bridge (where the E string rests) is the sound post, which extends from the front to the back plate of the instrument. Since this side of the bridge rests on this post, it is essentially fixed and acts as a pivot for the rocking motion of the remainder of the bridge. It does, however, couple the sound energy from the top plate to the back plate of the instrument.

The bridge supports the loads generated by the strings and its relative position with the soundboard and the nut defines the vibrating length of the strings. Through the bridge string vibrations reach the soundboard: its mechanical behaviour is one of the fundamental factors for a good sound performance of the instruments.

The mechanical structure of the bridge must be able to support maximum forces without deformations. Its geometry changes with the evolution of the violin. The importance of the bridge shape and dimensions and of its dynamic response is proved by a wide theoretical studies developed by different authors in various periods.

Dynamic forces at two feet essentially represent the main mechanical actions generated by the bridge: but force measurement on contact between bridge feet and soundboard is very difficult to do in practice. Specific experimentations have been developed involving both conventional and innovative transducers placed between bridge and soundboard. The study is oriented to measure the dynamic force in orthogonal direction to the soundboard, being the prevalent force exchanged in contact bridge-soundboard.

SENSORING AND EXPERIMENTAL SETUP

Measurement of forces under bridge takes part of a wider research activity devoted to the evaluation of the external forces and of the mutual forces exchanged between components in a violin, taking into account possible relative motions and performing experimental methods. The basic idea is to develop measurement chains easy to be reproduced, low costing, in different environmental conditions, minimizing the intrusion of sensors and able to detect forces in specific points of the instrument also during the playing phases.

Micro-load cells

The preliminary experimental test has been implemented using micro load cylindrical cells (diameter 39 mm, thick 5 mm) adjusted under the bridge (Figure 2). The thickness of load cell produces a lifting of the bridge, modifying its relative position and, in particular, changing the string angles. In order to preserve these angles a modified bridge (height reduced bridge) must be used. Signal is monitored in real time

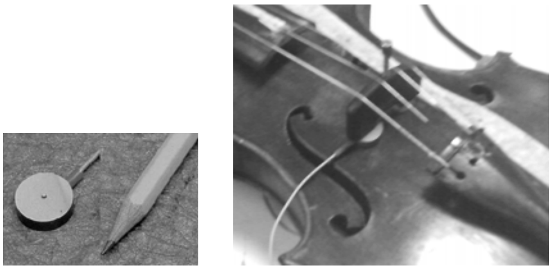
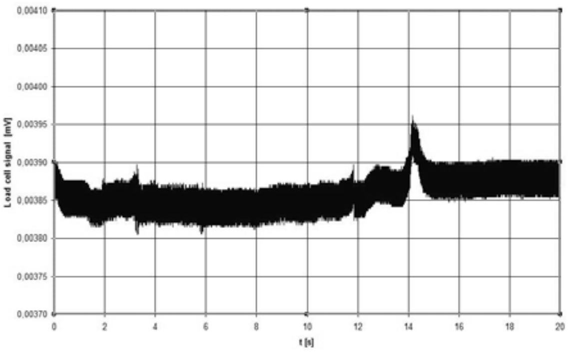
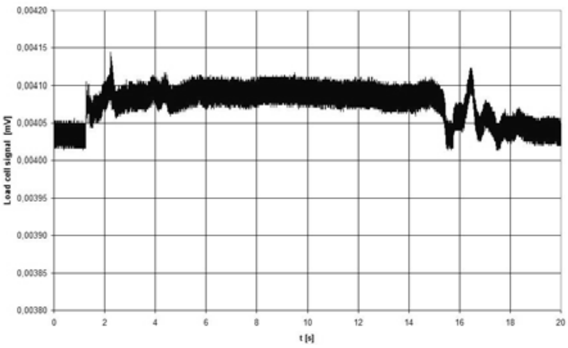


Figure 2. Micro load cell under the bridge

The influence of different kinds of bridges and of different tilt angles of the string, characteristic for modern and baroque mounting, is in particular analyzed. To avoid variations of the tilt angle of the strings (due to the thickness of the transducer) an adjustable bridge is used. The violin is played with different musical techniques: in particular continuous notes ("*tenute*") and ghost notes ("*strappate*"). Hereafter a comparison of results is reported: Figure 3 (a, b) collects the response of the same modern violin equipped by gut strings and metallic strings and played on D4 continuous note. Load cell output voltage vs. time is reported:



a) gut strings



b) metallic strings

Figure 3. Force vs. time: continuous note

Acquisition frequency is 1 kHz. The force is practically constant but the intensity is greater in presence of metallic strings (45,34 N instead of 39,5 N). Modifying the play technique (ghost note, "*nota strappata*") the actual signal changes as shown in Figure 4, reporting the example of E note (metallic and gut string) (respectively up to 55,8 N for metallic and up to 46,5 N for gut strings).

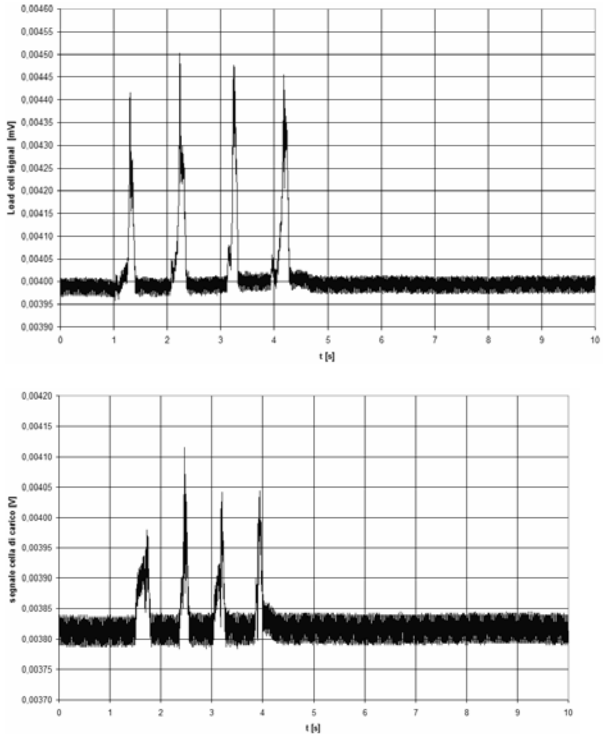


Figure 4. Force vs. time: E note on metallic (upper) and gut string (lower)

The proposed approach is easy to be implemented but the significant disadvantage is related to the modified bridge. For these reasons more reliable solutions are searched and achieved.

Thin-film micro-sensors

An improved and enhanced approach of measurement of the experimental analysis involves innovative thin film force sensors (Figure 5).

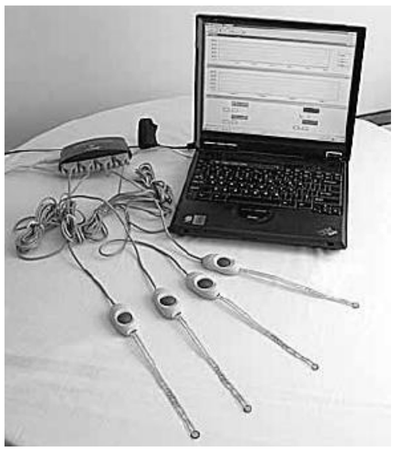


Figure 5. Thin film force sensors

Sensors used are thin film tactile force sensors (Flexiforce, produced by Tekscan, Inc.). These extremely thin, less than 0,1 mm, and their flexible grid-based device are advantageous, allowing for minimally intrusive measurements, resulting in the least disturbance to the true pressure pattern.

Each sensor consists on of a matrix of rows and columns of a semi-conductive material that changes its electrical resistance when force is applied to it. The dynamic response is very fast (< 5 μs) and the force ranges (from 0 to 440 N) cover the field interest. This solution applied to violins allows the use of standard bridges, because the relative positions and inclination of the string are not influenced by the presence of the sensors. A couple of sensors are interposed between bridge and soundboard, in order to detect the also the differential force under the inches.

The proposed solution is cheaper, non intrusive and good repeatable. Sensing area consists on a circle of 9.3 mm of diameter. Sensors can be connected to PC through electronic interface: also wireless connection has been tested. One sensor is placed under each bridge foot (Figure 6): foot surface is geometrically different to the sensing area. This problem has been solved implementing an original calibration procedure, as described hereafter.

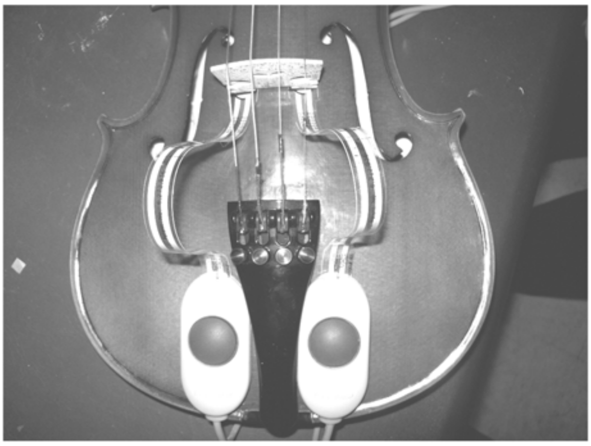


Figure 6. Thin film sensors assembled on a violin

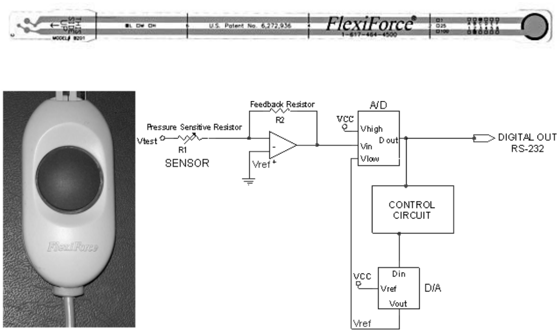


Figure 7. Ultra-thin sensor and electronics

The force sensor used (FlexiForce A201, by Tekscan Inc. U.S.A.) is an ultra-thin, flexible printed circuit. It is constructed of two layers of substrate (polyester) film (Figure 7). On each layer, a conductive material (silver) is applied, followed by a layer of pressure-sensitive ink. Adhesive is then used to laminate the two layers of substrate together to form the force sensor. The silver circle on top of the pressure-sensitive ink defines the active sensing area. Silver extends from the sensing area to the connectors at the other end of the sensor, forming the conductive leads. Sensors are terminated with male square pins, allowing them to be easily incorporated into a circuit. The two outer pins of the connector are active and the centre pin is inactive. The single element force sensor acts as a force-sensing resistor in an electrical circuit. When the force sensor is unloaded, its resistance is very high. When a force is applied to the sensor, this resistance decreases. The resistance can be read by connecting a multimeter to the outer two pins, then applying a force to the sensing area. The conductance curve is linear, and therefore useful in calibration.

Residing within the plastic handle is the data acquisition hardware with USB connection. This interface ensures optimal performance by simple insertion of sensor. The electronics adjust the device sensitivity to best fit the dynamic range of the specific application. This allows to "fine tune" the single element sensors for optimal performance. Calibration procedures can deliver accuracies of + 5% up to + 3% following more controlled procedures. The electronics provide high quality signals at distances of up to 30 feet from the PC. Wireless architecture enables computer to capture and store force data wirelessly from distances of up to 200 feet. This solution offers greater flexibility in present application.

Settings

The most significant problem related to sensors setting concerns the different shape of areas (Figure 8): sensitive surface is a circle (9.5 mm of diameter), while the bridge foot is a rectangle (typically 12.5 x 5 mm). In order to develop a low cost approach the option to require customized sensors, tailored on particular surfaces it is not followed.

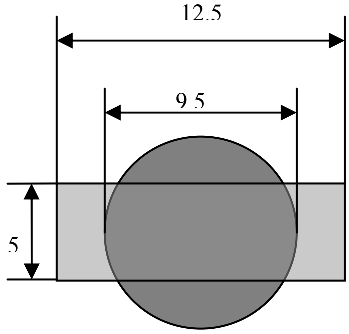


Figure 8. Sensor and bridge foot areas

Using standard setting an incorrect force measure is generated. In order to solve this problem a specific procedure of correction based on the effective sensor and feet areas is implemented. Being:

A_s = sensor area;
A_e = effective area;
F_{app} = applied force;
F_{ril} = detected force;
P = pressure
$P= F_{app} / A_s$; $Fril = P A_e = (F_{app} / A_s) A_e$

In order to obtain $Fapp = F_{ril\ during}$ the setting it is necessary to introduce a correction factor corresponding to A_s / A_e .

Effective area (Figure 9) A_e is the sum of two circular sectors and the rectangle inserted with height of 5 mm

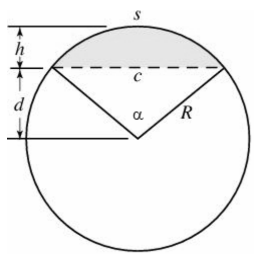


Figure 9. Geometric references

$c = 2\ R \sin(\alpha/2)$
$A_s = 0.5\ R^2\ [\alpha\text{-}\sin(\alpha)]$
$R = h + d$
$d = R \cos(\alpha/2)$
$A_e = 5\ (9.5 - 2h) + 2\ A_s$

In present application the correction factor is $A_s / A_e = 1.53$.

Applying this correction to standard procedure of setting right and left feet are set as shown in Figure 10.

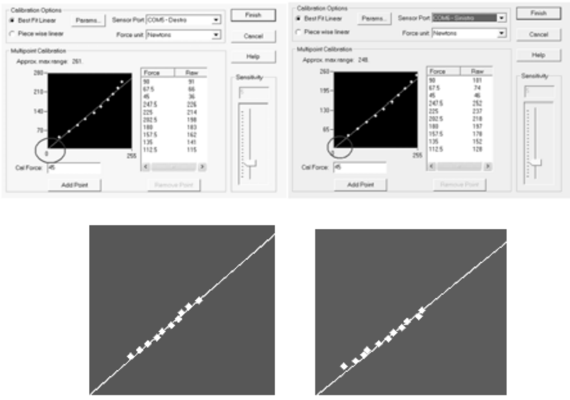


Figure 10. Right and left setting, with calibration details

During the setting of the sensors the known forces are applied with original pneumatic equipment able to load the sensor acting a pneumatic linear actuator: the air pressure is proportional to the actual force generated. On these values the correction factor has been applied: good results are obtained, checked also following the classical procedure of violin tuning. Correction factors can be evaluated for other geometries of bridges (violas, cellos...).

DETECTION OF STATIC AND DYNAMIC FORCES

Forces generated by the bridge on the soundboard are both static and dynamic. Static forces are related to the instrument tuning: in this phase the forces generated by strings tensioning increase from the undeformable condition; the resulting forces under right and left feet depend on the mechanical actions on the strings. As well known the tuning procedure requires progressive adjustments on tensioning.

Static forces

The proposed calibration method has been tested detecting these static forces: Figure 11 reports the time histories of forces under bridge feet (light grey line corresponding to right and dark grey line to left foot) during the complete tuning of a violin.

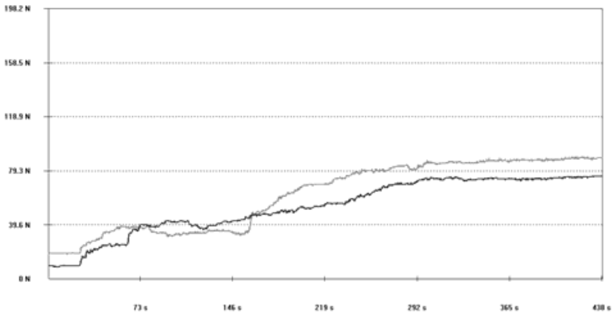


Figure 11. Forces distribution during the tuning phase

Overall forces increase during the time showing bedding phases corresponding to temporary relaxations of the string submitted to tensioning.

Dynamic forces

Dynamic forces induced by the bridge on the soundboard are related to strings playing. In this phase a correct setting of sensors is fundamental to detect reliable measurement of dynamic forces generated in the contact between bridge feet and soundboard.

Dynamic actions depend on the attack imposed to the player. Different playing techniques can be followed (*pizzicato, vibrato…*) and several methods of attack with the bow can be applied (*detaché, martelé, collé, spiccato* and *legato*). In order to investigate on the actual forces generated unde different paying conditions a violin is equipped with two sensors (one for each foot) and played on different attacks. An example of results are shown in Figure 12, reporting the time histories of left and right forces playing A string in *pizzicato* (light grey line corresponding to right foot and dark grey line to left foot), sampled to 4 µs.

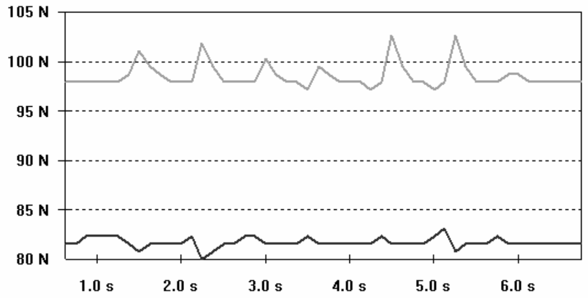


Figure 12. Forces time histories on A stringT (*pizzicato*)

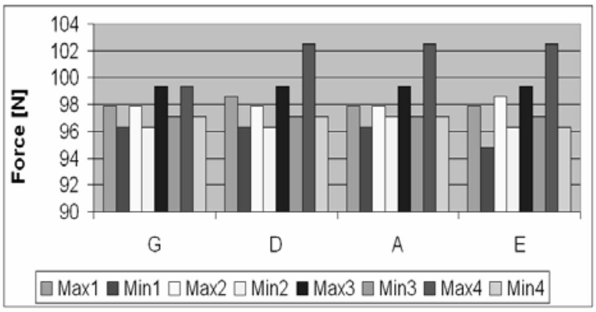


Figure 13. Forces at right foot

This test has been repeated for different played notes and in different attack conditions. Synthesis of results are collected hereafter: Figures 13 and 14 reports respectively minimum vs. maximum forces detected at right and left feet playing notes A, D, E and G under four different attacks: *continuo* (1), *saltato* (2), *strappato* (3) and *pizzicato* (4).

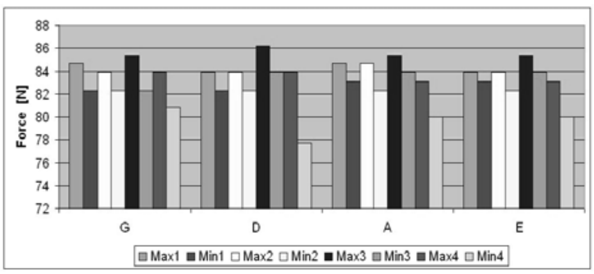


Figure 14. Forces at the left foot

The knowledge of theses forces is significant also to investigate on the friction forces generated in the contact. The detected forces act along the normal to the contact surface: friction forces can be evaluated as function of the friction factor depending on the soundboard and bridge materials.

ACOUSTIC RESPONSES

In parallel to the forces detection the sound generated by each played string is recorded. The purpose of this measurement is to attempt correlations between forces generated in the instrument and the corresponding acoustic level. Time histories of the acoustic level for different notes and attacks are collected in Table 1.

Maximum forces are compared to maximum acoustic levels: for A, G, D and E notes correlations expressed by 4[th] order polynomial curves are reported in Figure 15.

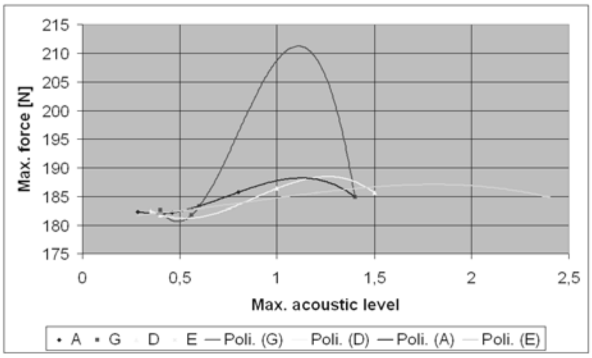


Figure 15. Maximum forces vs. maximum acoustic signal (attack *saltato*)

Significant differences have been detected between G-string and A, D and E strings.

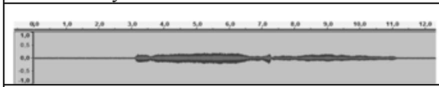
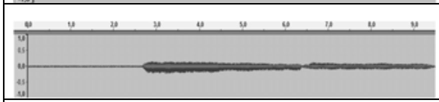
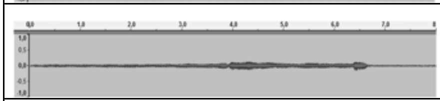
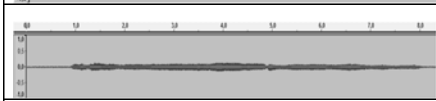
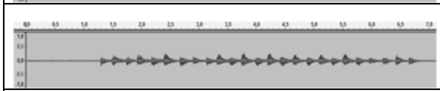
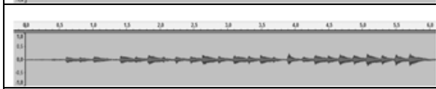
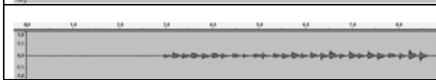
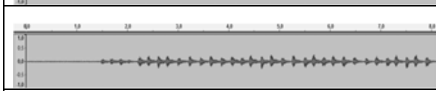
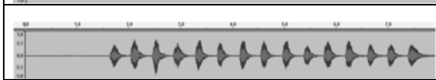
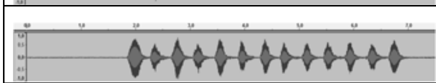
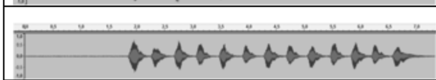
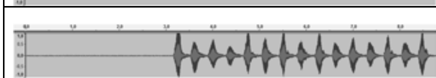
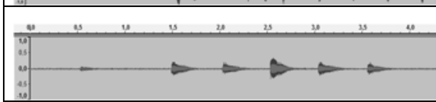
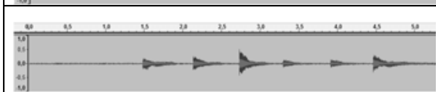
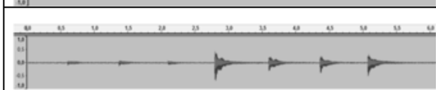
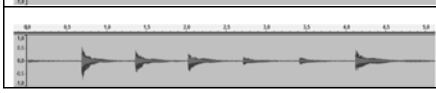
CONCLUDING REMARKS

An experimental approach attempting to correlate forces in the bridge-soundboard contact and generated sound is implemented. Static and dynamic forces generated during playing phase have been monitored: non-invasive micro-sensors allow the detection.

Force monitoring seems to be a useful tool not only for the instrument construction but also for testing in restoration and maintenance phases. Particular interesting seems the application on theoretical studies and experimental tests related to the historical transformation of the violins family, through comparative evaluations based on modal analyses, acoustic responses and tests on persistence of the sound. The same violin, mounted with metallic strings and modern assembling or with gut string and modern or baroque assembling, is instrumented and tested from structural and acoustic points of view. The influence of different kinds of bridges and of different tilt angles of the string on modern and baroque assembling is subjects of analysis.

Relationships between forces and acoustic sound levels have been focused. Further developments will be oriented to test the influence of different types of metallic strings.

Table 1. Acoustic responses

Time history	Note	Attack
	G	continuo
	D	
	A	
	E	
	G	saltato
	D	
	A	
	E	
	G	spiccato
	D	
	A	
	E	
	G	pizzicato
	D	
	A	
	E	

REFERENCES

1. N. H. Fletcher and T. D. Rossing, "The Physics of Musical Instruments", 2[nd] ed., (Springer, New York, 1998) pp. 297-300
2. H. A. Müller, *The Function of the Violin Bridge*, Trans. E. Wall. Catgut Acoustical Society, pp. 19-22, (1979)
3. C. M. Hutchins, *A Note on Practical Bridge Tuning for the Violin Maker*, Catgut Acoust. Soc., pp.15-18 (1984)
4. J. Curtin, "*Bridging the Divide*", The Strad, 3, pp. 44-48, (2005)
5. O. E. Rodgers and T. R. Masino, *The Effect of Wood Removal on Bridge Frequencies*, Acoustical Society Journal, 1, 6, pp 6-10 (1990)
6. E. V. Jansson, L. Fryden and G. Mattsson, *On Tuning of the Violin Bridge*, Catgut Acoust. Soc. Journal, 1, 6, pp. 11-15, (1990)

7. L. Cremer and J.S. Allen, *Physics of the violin*, MIT Press, U.S.A, (1984)
8. L. Cremer, M.A. Heckl, and E.E. Ungar, *Structure-Borne Sound : Structural Vibrations and Sound Radiation at Audio Frequencies*, Spinger-Verlag, New York, (1973)
9. G. Bissinger, *Structural acoustics model of the violin radiativity profile*, J. Acoust. Soc. Am. 124, 4013-4023 (2008).
10. G. Bissinger, *Structural acoustics of good and bad violins*, J. Acoust. Soc. Am. 124, 1764-1773 (2008).
11. G. Bissinger, *Surprising regularity between plate modes 2 and 5 and the B1 corpus modes,: Part I*, Violin Soc. Am.: VSA Papers 21, 83-101 (2007).
12. G. Bissinger, E.G. Williams, N. Valdivia, *Violin f-hole contribution to far-field radiation via patch near-field acoustical holography*, J. Acoust. Soc. Am. 121, 3899-3906 (2007).
13. G. Bissinger, *The Violin Bridge as Filter*, J. Acoust. Soc. Am. 120, 482-491 (2006)
14. G. Bissinger, *A Unified Materials-Normal Mode Approach To Violin Acoustics*, Acustica, 91, 214-228 (2005)
15. G. Bissinger, *Contemporary generalized normal mode violin acoustics*, Acustica, 90, 590-599 (2004)
16. G. Bissinger, *Relating normal mode properties of violins to overall quality – signature modes. I*, CAS Journal, 4 (series II), 37-45 (2003)
17. G. Bissinger, *Relating normal mode properties of violins to overall quality – general trends. II*, , CAS Journal 4 (series II), 46-52 (2003)
18. G. Bissinger, *Generalized Normal Mode Violin Acoustics* , Proc Stockholm Mus. Acoust. Conf. 2003, 35-38 (2003)
19. G. Bissinger, *Modal analysis of a violin octet*, J. Acoust. Soc. Am. 113, 2105-2113 (2003)
20. G. Bissinger. *Wall compliance and violin cavity modes*, J. Acoust. Soc. Am. 113, 1718-1723 (2003).
21. G. Bissinger and J. Keiffer, *Radiation damping, efficiency and directivity for violin normal modes below 4 kHz* , Acoust. Res. Lett. Online, 4, no.1, 7-12 (2003)
22. G. Bissinger, *Modern vibration measurement techniques for bowed string instruments*, Exp. Techniq. 25(no.4), 43-46 (2001).
23. A Srikantha Phani and J Woodhouse, *Experimental identification of viscous damping in linear vibration, J.* Sound Vib. 319 832–849 (2008)
24. C Fritz, I Cross, BCJ Moore and J Woodhouse, *Perceptual thresholds for detecting modifications applied to the acoustical properties of a violin*., J. Acoust. Soc. Amer. 122, 3640–3650 (2007)
25. J Woodhouse , *On the "bridge hill" of the violin,* Acustica – Acta Acustica 91, 155–165 (2005).
26. J Woodhouse, *Plucked guitar transients: comparison of measurements and synthesis,* Acustica – Acta Acustica 90, 945–965 (2004).
27. Woodhouse and PM Galluzzo, *The bowed string as we know it today,* J Acustica – Acta Acustica 90 579–589 (2004)
28. P Duffour and J Woodhouse, *Instability of systems with a frictional point contact: Part 1, basic modeling,* J. Sound Vib. 271 365–390 (2004)