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ACOUSTICS 2012

Simulated and experimental force analyses in the bridge-soundboard contact of string instruments

E. Ravina

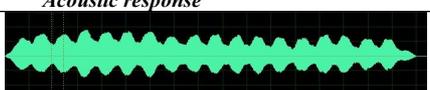
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The paper describes a theoretical and experimental research activity oriented to analysis of static and dynamic forces generated in the bridge-soundboard contact of string musical instruments. This contact area is fundamental for the transmission of mechanical actions generated on the strings by the player and the corresponding vibration response on the acoustic parts of the instrument, like soundboard. In particular static and dynamic forces generated in these contacts areas are analyzed with respect to the generated sound. Forces in bridge-soundboard contact are theoretically modelled and the model is validated by experiments, acquiring the components along the normal to the contact surfaces by means non-invasive thin film micro-sensors, wireless interfaced to PC. The detected forces are significant to investigate on the friction forces generated in the contact. Simultaneously acoustic acquisitions on the played instrument are detected. Different playing techniques are related to several methods of attack on the string by the player. The proposed approach is actually used to study the influence of different kinds of bridges. Different tilt angles of the string on modern and baroque assembling are subjects of analysis. Preliminary correlations between forces and acoustic sound levels have been focused and discussed.

1 Introduction

The aim of design and construction of musical instruments is, of course, the achievement of desired sound results in terms of amplitude, tone, timbre and, more in general, of sound quality. Performances of a violin depend both to the intrinsic physical and mechanical features of the instrument and to the player. Experiments and tests on stringed instruments need musicians to play: the result is consequently related to the characteristics of the player, because repeated actions are necessarily influenced by the human response. In particular, bowed instruments are played putting in relative motion the bow on the strings: different bowing gestures or *articulations* give the violin a range of different sounds. The differences are chiefly in the transient sounds at the beginning and end of the notes, and in the envelope: the way the sound varies over time.

Table 1: Time histories of different articulations.

Articulation	Acoustic response
Vibrato	
Tremolo	
Sul tasto	
Sul ponticello	
Spiccato	
Pizzicato	
Collé	
Col legno	

In the middle of a long, sustained note, each vibration of the violin string and each cycle of the sound it produces are nearly identical to the one that preceded it. The string undergoes Helmholtz motion (steady state condition). However, much of the interest in violin sounds comes from

the transients: the short lived effects at the beginning and end of each note. To the violinist, these are achieved by different articulations or bowing styles. As well known several nomenclatures maintain Italian idioms, in particular:

- Vibrato;
- Tremolo;
- Sul tasto;
- Sul ponticello;
- Spiccato;
- Pizzicato;
- Collee';
- Col legno.

Examples of acoustic responses corresponding to different articulations are collected in Table 1. Relative motion between bow and strings is related to the attacks of the bow. In addition, instantaneous velocities and accelerations are variables unconsciously activated by players.

2 Instrument variables

Articulations depend from the player. But the produced sound strongly depends to physical and mechanical variables of the violin and of the bow. Mechanical actions responsible to the produced sound arise from the contact between strings and bridge and finally are transmitted from bridge to soundboard.

Bow motion is not only related to the musical technique but to mechanical and physical phenomena related to the contact between horsehairs and violin strings: these phenomena depend on the size and shape of bows and violins, and to the local forces applied by the player by means its wrist and indirectly from bow to string. The main problem is the governor of the bow, including structural, kinetic and dynamic aspects. Figure 1 sketches the fundamental variables: force applied on the string (F), distance between bridge and contact (x) and bow velocity (v).

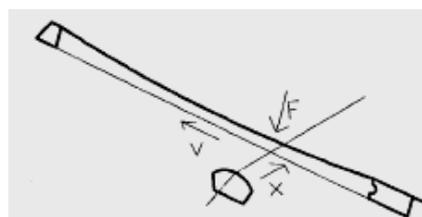


Figure 1: Fundamental variables

Distance and velocities depend on the articulation of the bow on the strings. Force is imposed by the wrist of the musician. In order to define the low motion it is necessary to know the 3D trajectories of the bow: Hodgson plots are used in the present study [1]: these plots are usually available in orthographic back projection (xz-plane and x-y plane). Figure 2 reports an example of these plots.

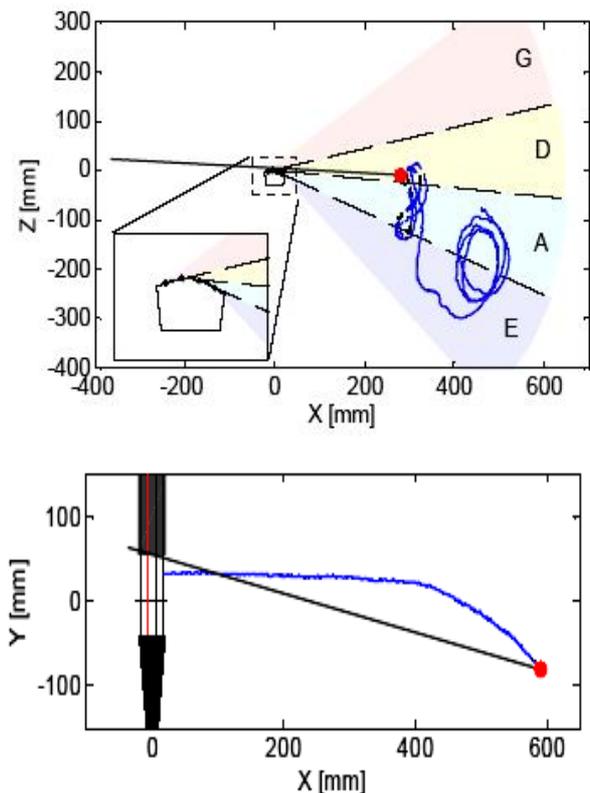


Figure 2: Examples of Hodgson plots

The red dot indicates the position of the frog at the “present” moment (i.e., at the end of the selected time interval). The black line corresponds approximately to the bow-hair ribbon from the frog to the tip, ignoring the bending of the hair at the bow-string contact point. The trajectory history of the bow frog is indicated by a blue line, shown when the bow was in contact with the string, thin and dotted otherwise. In the background, the bridge, string positions and string crossing angles are shown, defining the functional context of the displayed bowing gestures. The string crossing angles (dashed lines) subdivide the space into four angular zones associated with the bowing of the different strings. The zones are indicated with different colours: blue (E string), green (A string), yellow (D string) and red (G string). This approach has been followed in various specific researches involving gestures in musical events [2, 3, 4, 5, and 6].

From the mechanical point of view, the string displacement can be modelled through the equation:

$$y(x, t) = \sum_{n=1}^{\infty} a_n \sin \frac{n\pi x}{L} \sin n\omega t \quad (1)$$

Maximum string displacement y_m and maximum force on the bridge are related to the ratio v_b/x_b :

$$y_m = \frac{1}{8f} \frac{v_b}{x_b} \quad (2)$$

$$F_m = \mu c \frac{v_b}{x_b} \quad (3)$$

where v_b is the bow velocity, x_b is the distance between the contact point of bow and string from the bridge, f is the frequency, μ the mass for unit length, c the wave velocity propagation and the product μc represents the characteristic string impedance.

Other variables responsible to the generated sound in a violin are introduced modifying the instrument mounting. Modern and baroque violins playing the same music by the same player with the same bow generate a different sound. An example is show in Figure 3, comparing the acoustic spectra (in logarithmic frequencies) corresponding to two very similar violins differently mounted. (B. Bassano piece is played recorded on 20s).

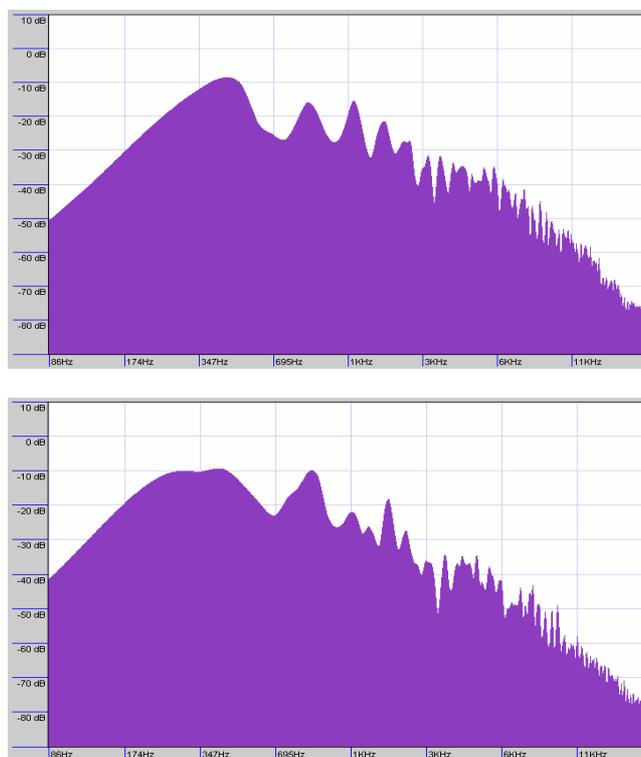


Figure 3: Acoustic spectra comparison (up baroque mounting, down renaissance mounting).

Significant differences in terms of frequency distribution and levels can be easily detected.

Each component (strings, neck, tailpiece...) gives its contribution to the sound modification. Surely the bridge plays a fundamental role for the generated sound, supporting the strings above the fingerboard from the nut to the tailpiece [7, 8, and 9]. It is not only a strength component supporting static and dynamic forces generated by the strings, but also a fundamental mechanical filter to vibrations generating sound. In the violins family the bridge needs to be fitted by carving its feet to match the curvature of the violin belly. It also needs to be adjusted so that it is

the proper height for the violin, and usually it is placed even with the slash in the f-holes. The feet of the bridge are placed over the sound post and the bass bar. Geometry of violin bridges is very diversified and related to the dimensions of the instrument and to its mounting (baroque, classical, modern). Bridge is an asymmetrical component: one side is flat, the other is slightly tapered. The tapered side will face the tailpiece and the flat side will face the scroll. In this way the thickness is variable matching small contact surfaces between strings and notches with a good stability at feet. The flat side should form a right angle with the violin's belly; in addition the bridge should be tilted away from vertical so the angles from bridge and both segments of the string will be equal. This posture equalizes the tensions on the opposite side of the string.

Violin bridges are usually made in maple. This is a strong wood to withstand the forces tightening the strings. It is also a good material to carry the vibrations from the strings to the belly of the violin. Some bridges have an insert of ebony where the E-string will go to prevent its digging into the bridge.

The dynamic behaviour of bridges is subject of several studies and experiments oriented to correlate the bridge shape to the transformation of the motion of the vibrating strings into periodic driving forces applied by its feet to the soundboard of the instrument. Force transfer function of the bridge and more detailed analyses concerning the bridge and its interactions are focused in [10, 11, 12, 13, 14], [8]. The complexity of the interactions between strings, bridge and soundboard is increased by the behaviour of the materials and by its internal and contact frictions. In addition the effective input forces are related to the bowing gestures followed by the player. The differences are chiefly in the transient sounds at the beginning and end of the notes, and in the envelope: the way the sound varies over time.

3 Modeling

In the present approach the bridge is modeled using mass-spring-damper system, taking into account that the body of the violin bridge cannot move in y direction. The applied model is an improvement of the models proposed by Cremer, and Woodhouse, including dampers, rigid and elastic frictions. A sketch is reported in Figure 4.

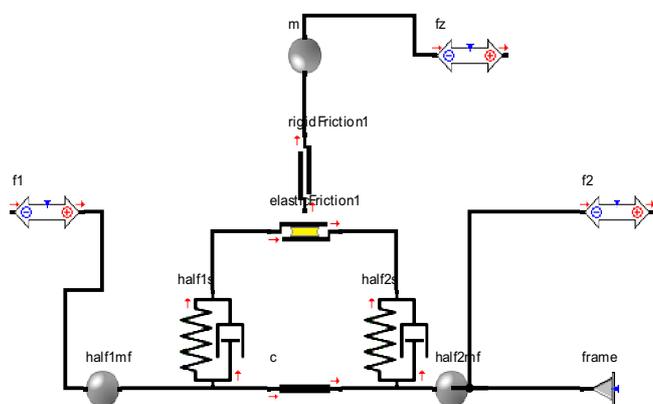


Figure 4: Simplified dynamic model of bridge.

The simulation code applied is SimulationX (by ITI, Denmark). Its flexibility allows developing interesting sensitivity analyses modifying the physical parameters. However the main information necessary to validate the model are the actual forces transmitted at bridge feet. For this reason specific experiments finalized to detect this data have been implemented.

4 Experiments

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.

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. The violin is played with different musical techniques: in particular continuous notes (“*tenute*”) and ghost notes (“*strappate*”). Starting from previous experiences, an improved and enhanced approach of measurement of the experimental analysis involves innovative thin film force sensors. Thin film tactile force sensors are used (Flexiforce A201, produced by Tekscan, Inc.). The extremely reduced thickness (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 ($< 5 \mu s$) 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.



Figure 5: Thin force sensors assembling.

A couple of sensors are located between bridge feet and soundboard, in order to detect also the differential force under the feet (Figure 5).

The proposed solution is cheap, non intrusive and well repeatable. Sensing area consists on a circle of 9.3 mm of diameter. Sensors are connected to PC through wireless electronic interface. Wireless architecture enables computer to capture and store force data wirelessly from distances of up to 60 m. Sensitive surface is a circle (9.3 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 sensitive surfaces is not followed. Using standard setting an incorrect force measure is generated: feet surfaces are geometrically different to the sensing areas. In order to solve this problem a specific procedure of correction based on the effective sensor and feet areas is implemented. A specific pneumatic workbench has been assembled: the sensor is submitted to known forces pneumatically generated and forces detected in contacts with geometrically different surfaces are detected.

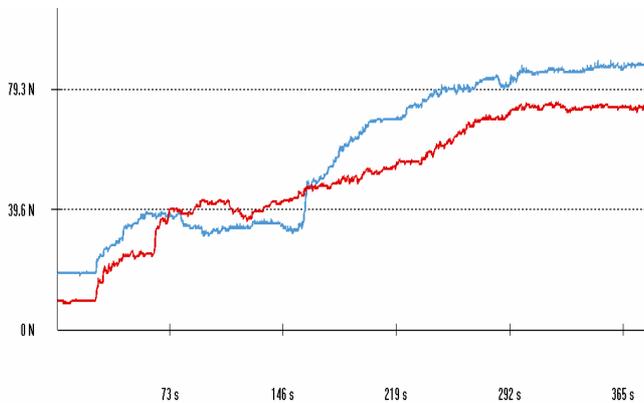


Figure 6: Tuning phase.

The proposed calibration method has been tested detecting static forces: Figure 6 reports the averaged time histories of forces under bridge feet (blue line corresponding to right foot and red line to left foot) during the complete tuning of a violin. Overall forces increase during the time showing phases corresponding to temporary relaxations of the string submitted to tensioning.

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.

Examples of A note played under *continuo*, *saltato*, *spiccato* and *pizzicato* attacks are reported in Figure 7.

This test has been repeated for different played notes and in different attack conditions. Synthesis of results are collected in Figures 8 and 9, reporting 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). The knowledge of these 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.

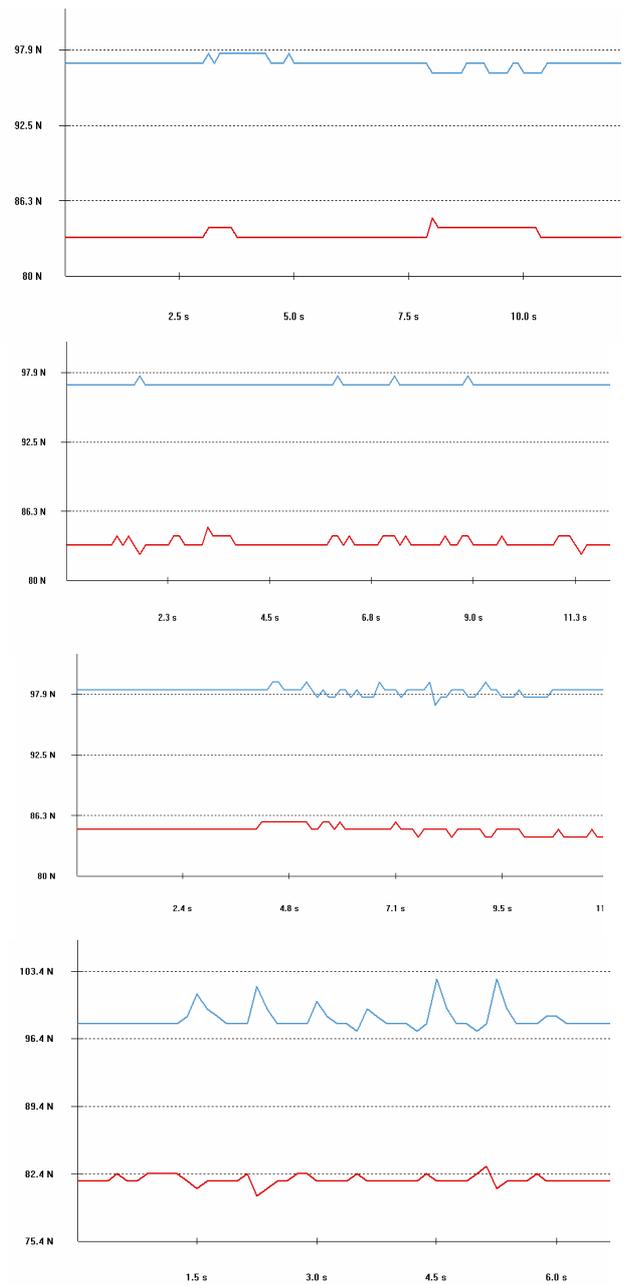


Figure 7: Forces time histories on A string.

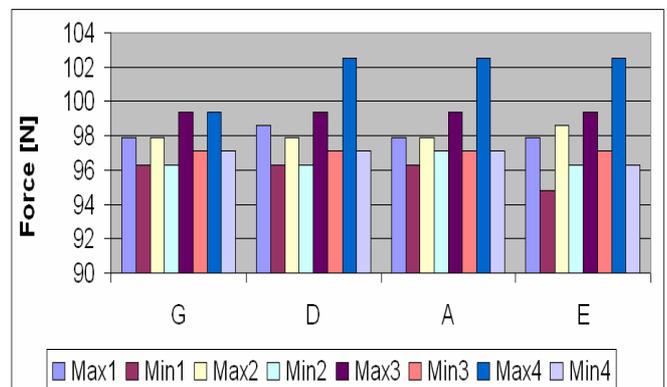


Figure 8: Forces at right foot

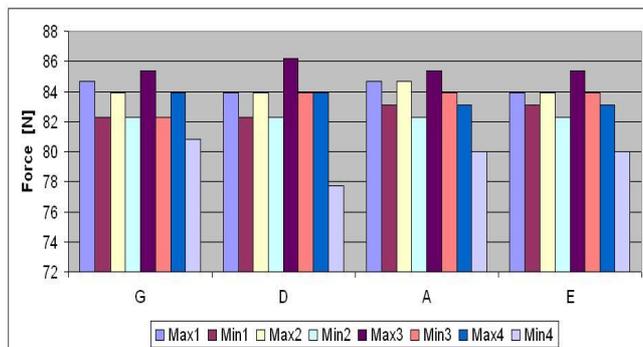


Figure 9: Forces at the left foot

Finally some particular conditions can be monitored: Figure 10 shows, for example, the force distribution under the bridge at the fracture of a string (G).

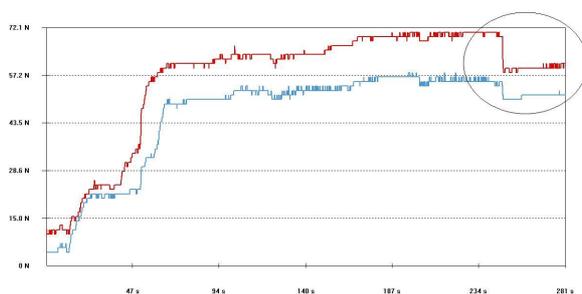


Figure 10: Fracture of G string.

5 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 4th order polynomial curves are reported in Figure 11.

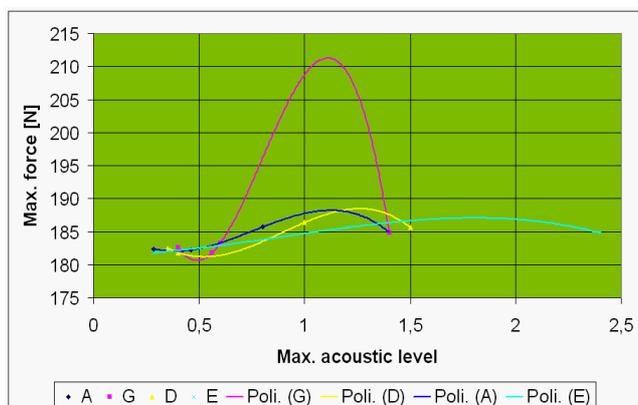


Figure 11: Forces vs. acoustic level.

Significant differences have been detected between G-string and A, D and E strings. Response is influenced also by the string type and by the bridge material.

6 Concluding remarks

A modelling and 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 to be the application on theoretical studies and experimental tests related to the historical transformation of the violins family, integrating evaluations based on modal analyses. The influence of different kinds of bridges and of different tilt angles of the string on modern and baroque assembling is further subject of analysis.

Preliminary correlations between forces and acoustic sound levels have been focused. Further developments will be oriented to improve the model and to optimize the experimental setup.

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