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Experimental modal analysis of bows

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The vibration performances of bow instruments are usually studied developing numerical and experimental modal analyses of the body of the instrument or of their parts (tailpiece, bridge, fingerboard, neck). The dynamic contribution of the bow is less considered, but the mutual actions generated between bow and strings are conditioned by the mechanical features of the bow.

The paper analyzes the dynamic behavior of different kind of bows (in particular with clip-in frog and screw-driven frog) through experimental modal analyses. Bows are instrumented with micro-accelerometers and excited by a micro-hammer. Frequency response functions up to 2500 Hz allow a good characterization of the bow and show significant differences about the modal shapes. The study is integrated with the experimental strain analysis, based on micro-strain gauges glued on the body; the very small dimensions of the transducers (2.5 mm) allow, from one side, a not intrusive analysis but, from another side, require specific contrivances of mounting. Details on the integrated experimentations are focused and discussed.

1 Introduction

Bows are fundamental components for the sound generated by different stringed instruments. The interaction between strings and bow is the subject of many specific research activities. In parallel to the evolution of violins a significant mutation is observed on the bow: that why the different performances required to violins in according to the aesthetic taste of different historical periods have been performed, not only with strong modification of the geometrical and mechanical structure of the instruments but also using bows having different geometries and made with different methods of construction.

In romantic age the musical repertoire was in continuous development together to the composition and interpretative language. Consequently standards of notation and musical signs, maintained for convenience and for traditional reasons, gradually modify your significance. That in similar way as alphabetic signs in languages like French and English, having writing corresponding to ancient pronunciation and not coherent to the recent one.

When in concert rooms the recovery of the ancient repertoire begins to be developed without philological problems, it seems obvious to read the ancient music applying modern standards and conventions. Following these criteria musical executions are defocused, their comprehension is reduced and to listen to the music becomes boring, except than genial compositions, written often in non conventional way. Some conventions are typically musical: other ones can be explained by means physiologic communication and perception laws. One of the main modern expressive conventions is the "voice sustain" ("tenuta di voce"), opposite to the ancient "messa di voce". The accentuation of the word in related to the physiologic mechanism having, as driver, muscles which slowly come in operation and acting on a deformable "inner bladder" corresponding to our lungs. The result is a sequence of "diminuendo" and "crescendo" less or more evident if applied to phrases or to syllables.

Pre-romantic songs use expressive laws modeled on the oratory expression and, consequently each note is emitted reinforcing and sudden decreasing as requested by the phrasing. This way to emit the voice, loudness then gradually loud and then loudness again was called "messa di voce"

In the course of time the song reduces its connection with the word. During the romantic period it reaches musical expressions with continuous notes ("note tenute") at constant intensity.

The history of instrumental music flows in parallel to the history of the song: an aspect of the musical taste is represented by bows for violins family. The ancient bow, essentially built like a semi-arc for war, has the stiffness of horsehairs progressively decreasing from edge to handle, allowing oscillation of the vibration strings more and more wider in the same direction and, during the alternate motion, able to generate a complete "messa di voce" (loudness-loud-loudness or "piano-forte-piano"). The mutable taste more oriented to the voice sustain conditions the bow geometry. Is becomes more flat in such a way to generate sounds with intensity more and more constant, up to reverse its curvature. The modern bow is curved if is released ad it is straight under load, generating sound with very constant intensity.

Many musicians and musicologists suggested geometries of bows from 17th to 18th century: Fig 1 shows the most known proposals, precursors of the modern bows.

Fig 1: Proposal of bows.

The transition from "messa di voce" to sustained sound involves two other significant components of the musical expression: the inequality and the "vibrato". Today the basic rule is that a series of notes written with sign of the same value must be executed as homogeneous way as possible; in renaissance and in baroque period the same series was bright up by impulses generated playing alternate notes with different duration (one long and one short that is unequal). By degrees the intensity modulation ("messa in voice") and the duration modulation (inequality) trend to be flattened, a particular frequency modulation arises: the "vibrato". This term defines the typical oscillation of the voice, more evident emitting long notes, and emulated also by musical instruments. This component of the voice, typically emotional, is today a stabile component of any instrument able to generate it, influencing the timber and selecting the modern sound. Under psycho-acoustic point of view, reinforce and attenuate a note, increase the duration and modulate it like a vibrato allows to continuously recalling the attention of the ear, reducing the effect of addiction.

Other aspects related to bows concern also the grip technique: Fig. 2 recalls French and German methods.

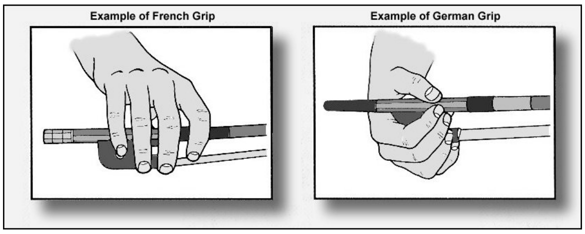


Fig. 2: French and German grip methods.

About frog, today two main technical solutions are proposed, diversified for the method of construction: clip-in frog (Fig. 2) and screw-driven frog (Fig. 3).

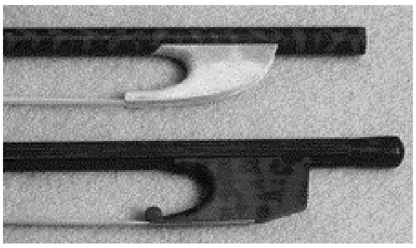


Fig 2: Clip-in frog bow.

Fig 3: Screw-driven frog bow.

Lute makers and bow-makers take care to optimize details of the bows and many research studies are oriented to optimize the geometry and the choice of type and number of horsehairs. But the actual dynamic behavior of the bow is often less studied, and, in particular, experiments devoted to evaluate the modal shapes are rarely subject of analysis.

Today a wide variety of bows, diversified, for shapes, mechanical solutions and materials, are made available on the market: some examples are collected in Fig. 4.

Fig. 4: Examples of bows, available on the market.

The bow is difficult to be studied from structural point of view, because its geometry is very complicated (wide number of profiles with different thickness), its mass is low and the effects of mechanical deformations (curvatures, local bending, pre-load conditions...) define its actual stiffness characteristic. The proposed study analyses the different dynamic behavior of clip-in and screw-driven bows through experimental modal analyses.

2 Experimental modal analysis

The experimental tests are oriented to compare the dynamic behaviour of different kind of bows and to search correlations between their mechanical performances and acoustic response, when are used to play violins having different mounting.

The experience, still under development, is based on an impact technique, involving micro-accelerometers connected to the body of the bow by means bees-wax and a micro-hammer (roving hammer technique). During the test the bow is elastically suspended to the frame and the mathematical relationship between the impact force on a generic point of the body and the acceleration response in another point defines the frequency response function (FRF) of the system. The result is a compared analysis based on the bow inertance.

In order to show the main aspects of the research activity some particular analyses are described hereafter. Figure 5 reports three bows under test, labelled A, B, and C. Bows A and B are very similar, having the same drawing and shape, and also the same design solutions. A comparison between these bows allows appreciating scattering in structural features of similar bows. Bow C is different to the other ones, in particular about the shape of the top.

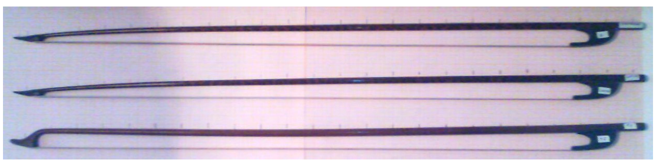


Fig. 5: Three bows under test (by A. Airenti, Genoa)

The reference geometry for the modal analysis in a line following longitudinally the body of the bow; it is defined by 24 points. The 24th point is located on the top of the bow and the micro-accelerometer is mounted at point no. 7. A detail of the instrumented bow is shown in Fig 6: the seismic mass of the accelerometer is 0.4 g and its sensitivity is 10 mV/g.

Fig 6: Reference detail for modal analysis.

The micro-hammer used for dynamic tests is shown in Fig. 7: the size of its instrumented head is very small and consequently the experimental test is absolutely not intrusive.

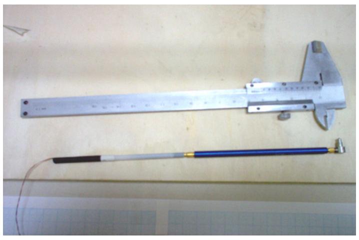
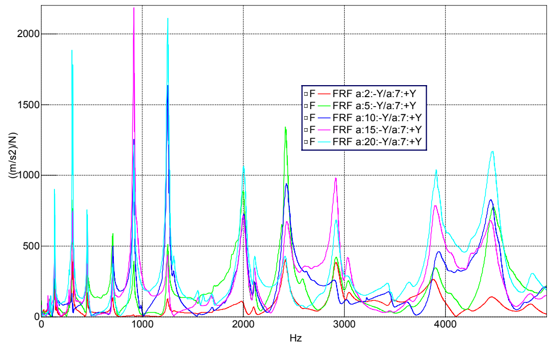


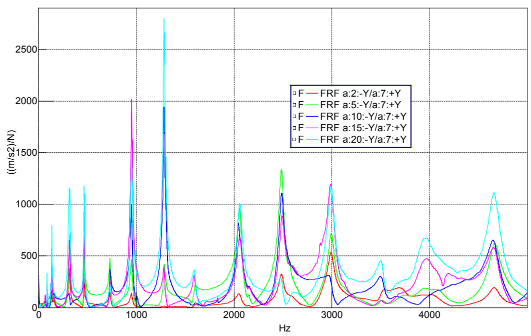
Fig 7: The micro-hammer.

The test procedure is organized on a series of impacts on the defined reference points, with acquisition in each point of the impact force and the measurement of the acceleration in a single point of the bow (roving hammer technique). The use of a mono-axial accelerometer is justified by the prevalent interest to analyze the modal shapes in the longitudinal plane of vibration of the bow and by the limitation of added masses to a very slim structure.

Fig. 8 (a, b) collects the results of frequency response functions (FRF), respectively for A and B bows, in the frequency range 0 – 5000 Hz.



a)



b)

Fig. 8: FRFs of A and B bows.

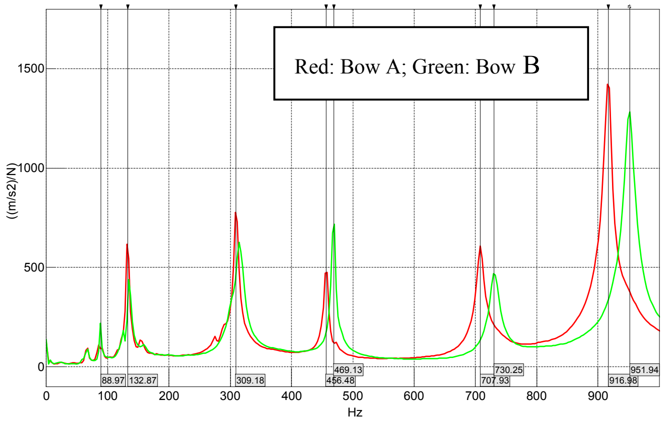


Fig. 9: Sum FRFs for A and B bows.

	f_A *[Hz]*	d_A *%]*	f_B *[Hz]*	d_B *%]*	*Shape*
Mode 1	87.18	1.22	88.67	1.06	1a
Mode 2	132.38	1.45	135.14	2.51	2a,1f
Mode 3	308.60	1.24	312.84	1.90	3a,2f
Mode 4	456.08	0.71	468.36	0.64	4a, 3f
Mode 5	708.79	0.96	730.53	0.86	5a, 4f
Mode 6	915.34	1.26	953.88	1.13	6a,5f
Mode 7	1251.09	0.87	1283.60	0.84	7a,6f
Mode 8	1992.76	1.51	2055.22	1.26	8 a,7f
Mode 9	2419.69	1.44	2483.20	1.16	9 a,8f
Mode 10	2920.31	1.26	2987.89	1.19	10b,9 f
Mode 11	3903.98	1.80	3949.94	2.25	Spatial aliasing
Mode 12	4469.31	1.34	4664.17	1.31	Spatial aliasing

Tab. 1: Frequencies of vibration modes for A and B bows. (a: antinode; f: flexure)

Fig. 9 compares the overall frequency response functions of two (very similar) bows: the uncertainty on the frequencies of the corresponding peaks is less of 5%.

Selected experimental modes for A and B bows, in the frequency range 1000 – 5000 Hz, are collected in Tab.1: the parameter *d* represents the percentage of the critical dumping. The component is clearly under dumped.

Mode No.	f [Hz]	M1 (A)	M2 (A)	M3 (A)	M4 (A)	M5 (A)	M6 (A)
M1 (B)	88.7	78.6	0.37	3.55	4.92	4.83	5.79
M2 (B)	135.14	1.39	97.32	8.97	0.43	0.25	1.54
M3 (B)	312.84	0.41	6.16	96.65	8.34	1.38	0.12
M4 (B)	468.36	1.34	0.49	2.57	97.82	12.58	1.92
M5 (B)	730.50	1.61	0.19	0.04	6.60	96.88	21.4
M6 (B)	953.80	6.86	1.12	0.79	0.10	6.13	95.16

Tab. 2: MAC analysis of A and B bows.

In order to compare the real dynamic performances of similar bows, more detailed analyses are performed: for instance, in Tab. 2 a MAC analysis (Modal Assurance Criterion) in the frequency range of 0 – 1000 Hz is collected. Very high values on the main diagonal suggest very similar mode shapes.

The Frequency Response Function of type C bow is reported in Fig. 10:

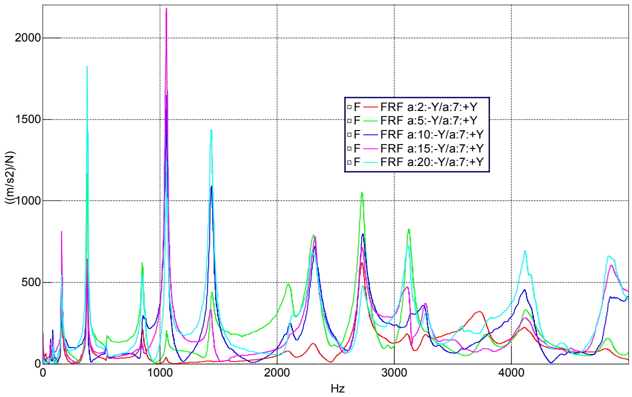


Fig 10: FRF of C bow (frequency range 0-5000 Hz).

The inertance of this bow is different with respect to A and B bows: in Tab. 3 a comparison of frequencies between B and C bows is described. Errors are expressed in Hz and in percentage.

Bow C has modes with the same shape at higher frequency with respect to bow B (except than in mode 1). The bow C seems to be more rigid. The different behaviour is evident animating the mode shapes: in Fig. 11 a schematic representation of fundamental mode (Mode 1) for B and C bows is reported.

	f B[Hz]	f C[Hz]	Error[Hz]	Error[%]
Mode 1	88.67	87.28	-1.39	-1.57
Mode 2	135.15	164.18	29.04	21.48
Mode 3	312.84	379.60	66.76	21.33
Mode 4	468.37	546.65	78.28	16.71
Mode 5	730.53	853.21	122.68	16.79
Mode 6	953.88	1056.88	102.99	10.79
Mode 7	1283.60	1438.74	155.13	12.08
Mode 8	2055.22	2317.97	262.75	12.78
Mode 9	2483.20	2723.66	240.45	9.68
Mode 10	2987.89	3125.33	137.44	4.59
Mode 11	3949.94	4124.28	174.34	4.41
Mode 12	4664.17	4830.95	166.78	3.57

Tab 3: Comparison between B and C bows.

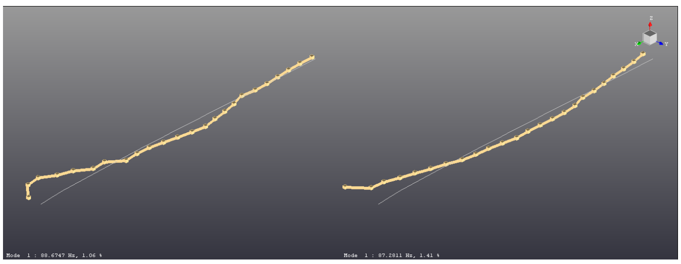


Fig 11: Mode 1 for B (left) and C (right) bows.

The mechanical response of bows is correlated to their mechanical action on the string and, consequently, to the sound generated by the played instrument. The proposed study attempts to give a contribution about this relationship: for this reason a second step of the analysis is oriented to the acoustic performances.

3 Acoustic response

The bow is the mechanical tool to generate sound on stringed instruments. The practical effect of bows having different characteristics of stiffness and damping can be detected playing a violin: the sound generated by a violin is strongly influenced by the bow used and the harmonic contents generated coupling violin with bow are influenced both by the violin and by the bow.

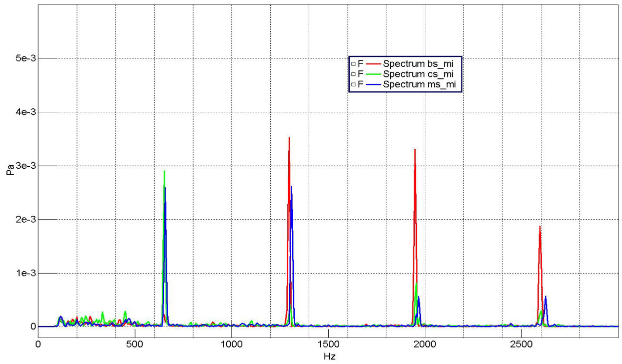


Fig 12: Acoustic response of three violins played by the same clip-in frog bow.

Experimental tests are proposed in this field: Fig 12 shows the acoustic response function of three very similar violins, differently mounted (baroque, classical and modern), and played by the same clip-in frog bow (note E5).
The baroque violin presents significant differences at high frequencies. Playing the same violins using another kind of bow (e.g. a screw-driven frog bow) the acoustic result is significantly different. This aspect is shown in Fig. 13: the played note is always E5.

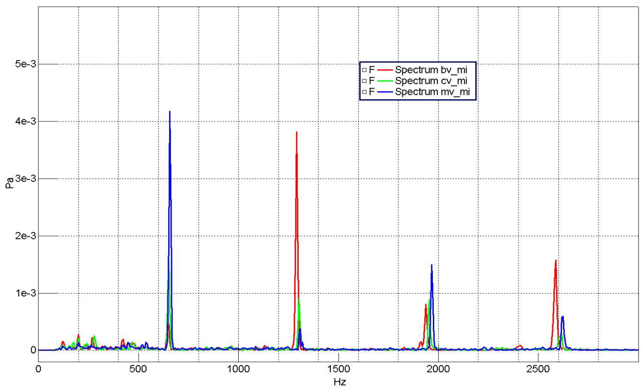


Fig 13: Acoustic response of the same violins playing with screw-driven frog bow.

5 Strain analysis

The experiments on modal analysis and on the acoustic effects are integrated with strain analyses. Experiments based on the use of micro- stain gauges are in particular under development: Fig. 14 shows a phase of experimentation of a miniaturized sensor (base 1.8 x 6 mm) glued on a test surface: the glued essentially is a cyano-achrylate (M-Bond 200, by Vishay) allowing to heavy fatigue tests (up to 60.000 micro-deformations). Particular care must be taken into the assembly phase of glued sensors: the surface must be carefully cleaned before the glue deposition.

The electrical acquisition requires a dedicated conditioned channel: Fig. 15 reports an image of the acquisition system. An approach based on virtual instrument implemented on a PC screen is proposed. Fig. 16 shows the overall front panel made available to the user and Fig. 17 reports a calibration phase of four micro-sensors under contemporary acquisition.

Fig. 14: Experiment on glued junction (magnif. 7.5 X).

Fig. 15: Acquisition system and detail of input cards.

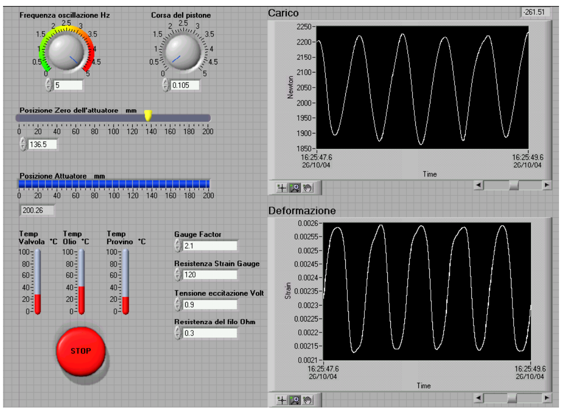


Fig. 16: Overall view of the front panel.

Specific experiments of bows are, at the moment, under development and detailed results will be presented in a next paper.

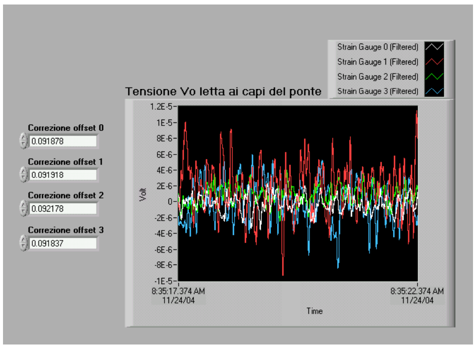


Fig. 17: Calibration phase of micro-strain gauges.

5 Conclusion

An experimental approach oriented to evaluate and compare vibratory features of different bows is presented. The research activity is focused to integrated testing of modal analyses, deformations and acoustic performances playing different kind of violins. Experiments on very similar bows show the construction differences related to handicraft; tests on different bows allow the identification of specific mechanical and structural features. The activity is still under development, testing a wide variety of bows: the goal is the realization of a systematic archive of mechanical features of bows, making available compared results to bow and lute makers.

Acknowledgments

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