Chapter 21
Parametric Experimental Modal Analysis of a Modern Violin Based on a Guarneri del Gesù Model

Elvio Bonisoli, Marco Casazza, Domenico Lisitano, and Luca Dimauro

Abstract Mechanical effects and dynamic behaviour of a modern violin, built on a Guarneri del Gesù model, were examined via parametric experimental modal analysis. The soundpost, a mobile component of a violin, has a particular relevance for the final acoustic performance, even if its dimensions are extremely small. Therefore, the aim of this first research is to understand the violin sensitivity to the soundpost position considering its influence on the overall structural-vibrational behaviour.

Experimental modal analysis was performed in six different configurations, related to different positions of the soundpost inside the violin, including both the outer possible locations and optimal position, generally defined by the violinist according only to the perceived best acoustic performance. Six "Signature" modes were identified and tracked in all configurations, comparing mode shapes, damping and natural frequencies of involved modes, in order to find a correlation between mechanical vibrations and acoustic performance of the instrument.

The effects of the soundpost position on the modal properties of the "Signature" mode shapes are highlighted and discussed. Finally, the potential role of soundpost as a practical engineering tool to improve the signature and sound quality is discussed.

Keywords Soundpost parametric analysis · Structural vibrations · "Signature" modes · MAC index · Roving hammer tests

21.1 Introduction

In the last decades there has been a greater interest in the study of vibrational dynamics and acoustics performance of musical instruments with harmonic case [1–3], such as violins. Violin acoustic properties are the result of a complex vibrational phenomenon, strongly influenced by materials, geometrical proportions and construction details of the violin itself. Obviously, environmental conditions, as well as other factors, should be included to fully describe the final sound perception. However, the attention is limited here to the source of sound production, i.e. the violin and its vibrational behaviour. The instrument geometry is almost bilaterally symmetrical, except for the presence of bassbar and soundpost, which are embedded into the instrument body. In particular, the bass bar is a shaped piece of wood placed under the top plate, whose position is fixed during the building process, while the soundpost is a small and mobile spruce wood cylinder, linking the top and the back plates. The former introduces a linearly distributed constraint, while the latter element is responsible for a punctual modification on the instrument acoustics. Shelleng in [1] described the acoustic functions of the two components. The bassbar introduces a dissymmetry and tones are increased. However, its main acoustical aim is to keep the upper and lower bouts of the top plate in step with the left foot of the bridge. From a mechanical point of view, it enhances the distribution of forces generated by the tensed strings. The soundpost is necessary to transmit the top plate motion to the back, or better, to reduce locally the cancelling motion of the top plate [4]. Its displacement around a neutral and theoretically best position, related to instrument proportions and defined along centuries of violin-making art, allows to balance the sound power among the strings, contributing partially to the definition of the final instrument tone quality. Violin makers 'learn', through a learning-by-doing process, how to adapt the shaping of the bassbar and to find the appropriate position for the

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soundpost, in order to obtain the desired acoustical performance, depending on the quality of materials. Moreover, violin makers fix the position of the soundpost on the basis of the sound output perceived by the violin player. Apart from an ideal best position for the soundpost, which is defined only on the basis of the instrument proportions, no practical indications were ever defined for violin-makers in order to support the building and set-up process in a more rigorous way.

Recently, Bissinger proposed an analysis of the mechanical and acoustical consequences of removal of the soundpost, using an Experimental Modal Analysis (EMA) applied to a violin with and without soundpost [5–6]. The obtained experimental results were used to define a very simple acoustic model of the violin, considering both the radiative properties of the violin normal modes and its mechanical properties. Marshall numerically evaluated the modal properties of a violin without strings [7], analysing not only bending modes, but also air and plate modes. In [5] was shown how the soundpost location produces a phase difference for both top and back plates. In [8] Bissinger focused his attention on modal-acoustic radiation measurements on several quality-rated violins, in order to find any evident difference in the five "signature" modes below 600 Hz, but no evident differences were found among very fine and the worst violins. Zhang et al. [9] studied the effects on modal behaviour of the cello bridge due to soundpost characteristics and position. In particular, they discussed the modification of the bridge centre of rotation at different frequencies. This work showed that the instantaneous centre moves from the soundpost side of the bridge at low frequency toward the bass bar side at higher frequencies.

As concern new millennium research activity, it is of particular interest the computational Finite-Element Analysis (FEM) to investigate the effects of material and isotropic properties on plates modes [10], as well as the possibility of using composite materials as substitutes for traditional wood in making top plates [11].

Gough showed how the violin acoustic quality is related to the vibrations and acoustic properties of the body shell of the instrument [12–14]. He detected an evident difference in natural frequency consequently to a transverse offset of soundpost position.

While the bassbar effects were widely studied, almost no experimental work has been developed to investigate the effects of soundpost position on the global vibration behaviour of violins. Since millimetric changes of the soundpost position produce surprising modifications changes in the acoustic of the instrument, as known from the empirical experience of violin makers and players, a correlation between different modal parameters and violin acoustic behaviour could be expected. Usually, depending on the sound perception, violin players require to the violin maker to slightly modify the sound post position. Therefore, the main aim of the present work is to analyse how the position of this element influences mode shapes, natural frequencies and damping ratio of the instrument. Nonetheless, until now no references are available to violin makers to show in the simplest possible way how the position of sound post can affect the violin vibrational behaviour.

The paper is organised as follow: in §21.2 the experimental setup adopt for the EMA is presented. In §21.3 the experimental modal parameters for the "Centre" configuration are presented and compared with the other configurations. The effects of the soundpost position on the "Signature" modes are discussed. Finally, some considerations are highlighted in the conclusion.

21.2 Experimental Setup

The instrument, object of the parametric EMA, is a contemporary violin, handcrafted by the violin-maker Enzo Cena (Torino, Italy, 2011) on a 1730 Guarneri del Gesù model. The mass of the violin is 0.33 kg (Fig. 21.1).

Several wood kinds were used in the production of the various components. In particular, karst spruce for the top plate and the soundpost, maple for the back plate, ribs and neck, and ebony was used for the fingerboard. The use of different density woods, along with their anisotropy and non-homogeneity, lend violin a mechanical and acoustic behaviour, strongly correlated and influenced by properties of each single component.

All the tests were performed in free-free conditions, suspending the violin with an elastic band (Fig. 21.1). Roving hammer test for modal analysis was performed for the six configurations. The violin is excited with a soft plastic tip and its response is measured using six accelerometers. Mono-axial accelerometers were positioned above the plates lungs and a tri-axial accelerometer was placed in the neck of violin (Fig. 21.2).

The violin was excited in 49 points in one direction (except for the point on the scroll excited in two directions). The points were chosen to obtain a good compromise between geometry representation and expected violin modal behaviour. Some perimetric points (three nodes for each arching, the corners and the centre of the c-rib) were selected approximating the real geometry in the best possible way. Some points are added on the lungs of front and back plates and other two nodes at the bridge base in order to identify modes of the thinnest part of plates. Few other points were selected on the fingerboard and neck. The reference geometry for the EMA tests is shown in Fig. 21.3.

Fig. 21.1 Violin and setup

Fig. 21.2 Accelerometers locations

The violin is analysed in six different configurations related to the position of the sound post. The soundpost of the actual violin is a 50 mm-long movable spruce cylinder of approximately 0.7 g and 6 mm diameter. It is placed just behind the E-string bridge foot, between the top and back plates of the violin.

The different configurations (Table 21.1) were defined with respect to a reference point, centred under the right foot of the bridge, i.e. the reference point used by violin makers as ideal position for the sound post.

According to Fig. 21.4, other four configurations were obtained shifting the soundpost position respectively on the left, top, right and below with respect to the reference point. An additional configuration is the "Optimal" point from an acoustical point of view. The position of the soundpost is accurately manually changed by the violin-maker (Fig. 21.5). The

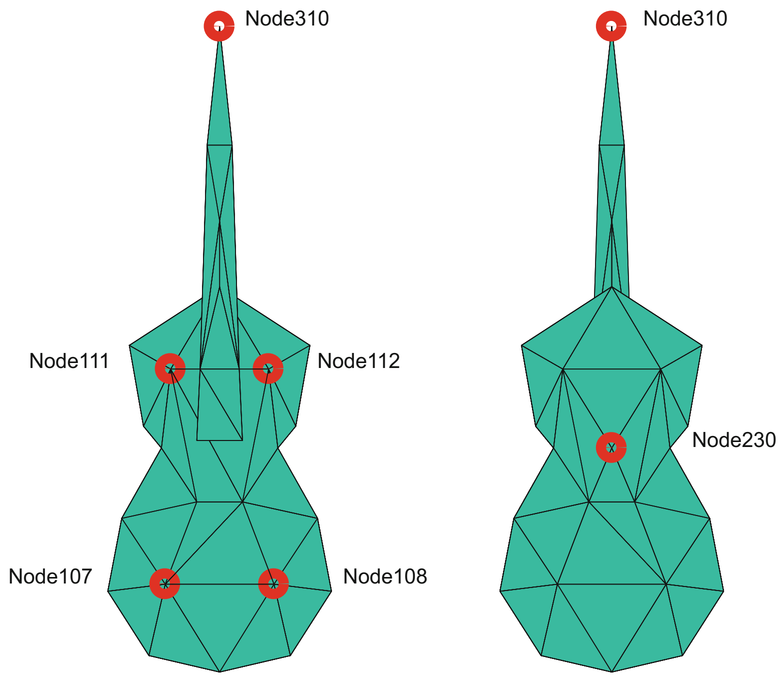

Fig. 21.3 Reference geometry for experimental tests: front view (left) and bottom view (right)

Table 21.1 Soundpost position

Configuration	Soundpost ref. system	
	X [mm]	*Y* [mm]
Central, C	0.0	0.0
Optimal, O	+1.0	0.0
1	+2.0	0.0
2	0.0	+2.0
3	−2.0	0.0
4	0.0	−2.0

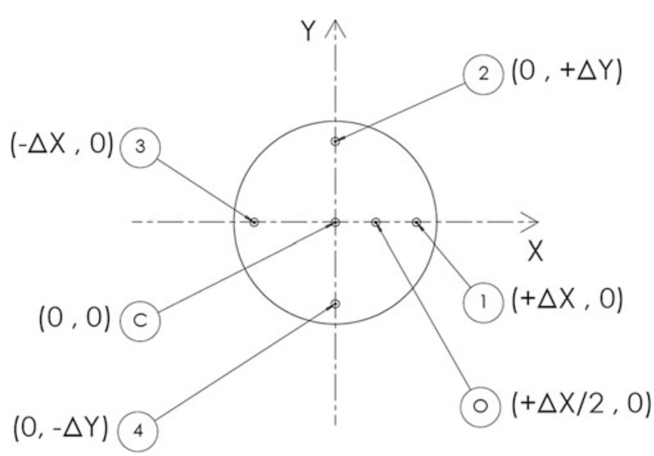

Fig. 21.4 Soundpost locations

Fig. 21.5 Soundpost position measuring

location of the soundpost in the different configurations, shown in Fig. 21.4, is expected to have the following effects on the instrument:

- C (0, 0): reference point for the manufacturer;
- $(+\Delta X/2, 0)$: optimal point for instrument performance;
- 1 $(+\Delta X, 0)$: increment of soundpost stress (due to minor space between the two plates), with a perceived sound more intense toward acute strings (E and A strings);
- 2 $(0, +\Delta Y)$: the perceived sound is less loud, with an effect that might result closer to the vowel "U" (International Phonetic Alphabet: ʉ);
- 3 $(-\Delta X, 0)$: decrement of soundpost stress (due to major space between the two plates), with a perceived sound more intense toward lower-frequency strings (D and G strings). Usually this configuration is not adopted, since it increases the bass bar effect;
- 4 $(0, -\Delta Y)$: louder sound, with a perceived effect usually compared to a "more open" sound, close to the open vowel "A" (International Phonetic Alphabet: a).

21.3 Identification of Modal Properties and Configuration Comparison

For all the analysed configurations, the identifications were performed on the frequency range $0 \div 1024$ Hz, using PolyMAX algorithm [15]. In the reference configuration, i.e. the Centre configuration, 59 modes were identified (Table 21.2).

To compare the mode shapes, the well-known Modal Assurance Criterion (MAC) is adopted. It is defined as the normalised scalar product between two modes j, and k:, hence it results equal to 100% if two modes are parallel, while it reaches 0% if they are orthogonal:

$$MAC_{j,k} = \frac{\left[\varphi_j^T \ \varphi_k\right]^2}{\left[\varphi_j^T \ \varphi_j\right]\left[\varphi_k^T \ \varphi_k\right]} \tag{21.1}$$

The Auto-MAC matrix shown in Fig. 21.7, hence the comparison between the family of modes of the same configuration, proves that the mode shapes are quite orthogonal and the synthetized FRFs (Fig. 21.8) results quite near to the experimental ones. Therefore, the dynamics behaviour of the violin is well represented with this set of mode shapes.

In this work, we focus our attention only on the "Signature" mode shapes and their tracking between the configurations. In particular, six "Signature" mode shapes are detected (bold in Table 21.2). Modes 25 and 26 are respectively is the breathing of right and left bottom lung of top plate (Fig. 21.6 2–3). Modes 28 and 44 are two bending modes, including also the fingerboard, on x-z plane (Fig. 21.6 4–5). Modes 15 and 49 could be considered as two torsional mode shapes (Fig. 21.6 1 and 6). The former involves mainly the zone of the violin bridge and the C-rib, while the latter is the torsional mode of the

Table 21.2 Experimental identified modes conf. Centre

Mode	Freq. [Hz]	ζ [%]	Mode	Freq. [Hz]	ζ [%]	Mode	Freq. [Hz]	ζ [%]
1	0.75	0.08	23	319.55	1.90	45	686.65	0.81
2	0.75	0.01	24	342.26	2.97	46	702.23	1.18
3	0.75	0.07	**25**	**352.57**	**3.37**	47	715.23	1.41
4	2.24	0.02	**26**	**366.64**	**0.17**	48	720.35	1.08
5	2.98	0.02	27	393.21	3.36	**49**	**733.92**	**0.19**
6	6.75	0.09	**28**	**423.33**	**2.16**	50	737.45	0.21
7	71.14	22.04	29	445.69	7.54	51	740.03	1.98
8	92.98	7.01	30	461.78	1.78	52	755.45	1.53
9	99.52	2.86	31	469.88	2.35	53	798.12	2.47
10	125.23	7.36	32	490.15	2.38	54	807.95	2.85
11	136.37	0.86	33	506.57	2.44	55	827.00	1.92
12	152.29	0.90	34	521.27	1.97	56	856.72	2.74
13	158.02	2.97	35	527.36	3.27	57	868.64	0.16
14	162.32	5.97	36	536.53	1.99	58	870.81	0.08
15	**182.91**	**0.05**	37	551.40	0.09	59	876.11	0.09
16	204.72	0.76	38	582.21	0.11	60	893.84	1.11
17	245.57	0.79	39	598.87	1.86	61	918.74	0.16
18	269.05	2.96	40	620.23	1.29	62	920.25	3.41
19	276.88	2.03	41	645.69	0.52	63	950.13	2.55
20	282.87	3.91	42	658.17	1.61	64	971.92	1.48
21	291.17	0.37	43	677.29	4.08	65	995.66	2.38
22	313.24	3.44	**44**	**682.68**	**1.30**			

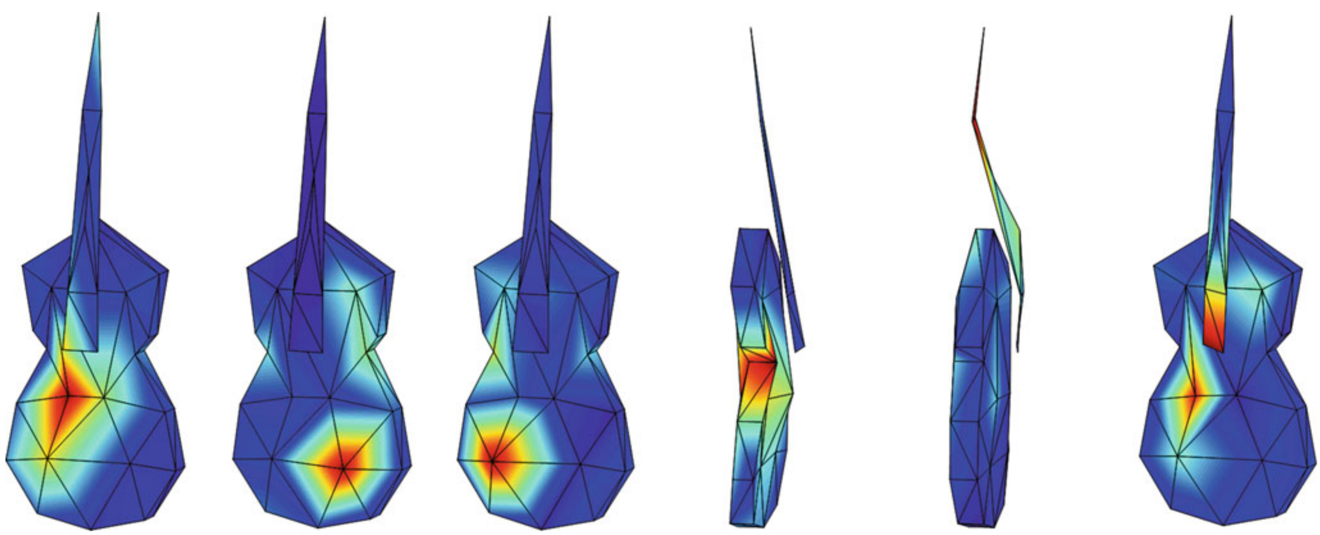

Fig. 21.6 Experimental "Signature" modes (from left to right): (15) f_n=183 Hz; (25) f_n=353 Hz; (26) f_n=367 Hz; (28) f_n=423 Hz; (44) f_n=683 Hz; (49) f_n=734 Hz

whole structure, including the fingerboard. Mode 49 is found close to the bridge 'squat' mode (i.e. 710 Hz), which is related to non-linear bridge behaviour [16].

The Auto-MAC of the Centre configuration is shown in Fig. 21.7. Some 2 × 2 pattern along the diagonal are observable. They are the results of very similar mode shapes with different local behaviour. In particular, several modes involving the top and back plates are highly correlated.

In Fig. 21.8 the auto-inertance of the node corresponding to the right bottom lung of the top plate is shown. The frequencies related to the "Signature" modes are highlighted with coloured vertical lines.

The major peak for the experimental FRF at 350 Hz corresponds to the second "Signature" mode. The synthetized dash-dot red curve is obtained through:

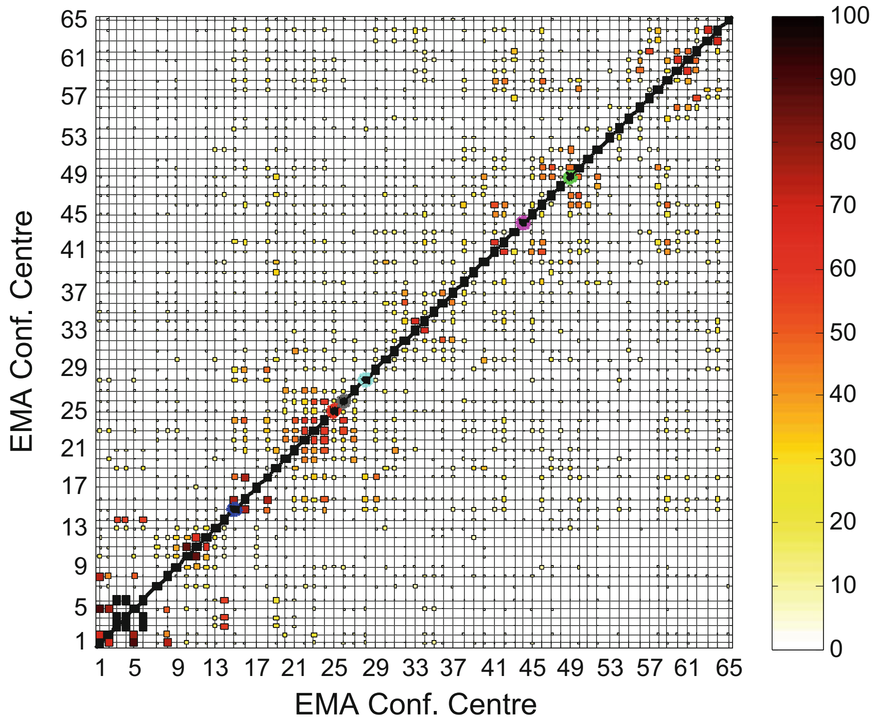

Fig. 21.7 Experimental mode shapes Auto-MAC

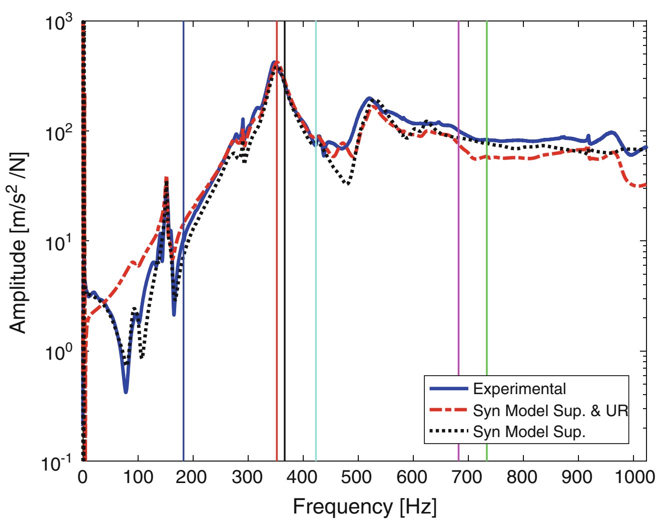

Fig. 21.8 Auto-inertance right bottom lung on front plate

$$A_{j,k}(\omega) = \frac{\ddot{x}_j(\omega)}{F_k(\omega)} = -\omega^2 \frac{x_j(\omega)}{F_k(\omega)} = \sum_{r=1}^{n} \frac{-\omega^2 \phi_j^{(r)} \phi_k^{(r)}}{\left(\omega_r^2 + 2\,\mathrm{i}\,\zeta_r\,\omega_r\,\omega - \omega^2\right)} - [LR] + \omega^2 \; [UR] \tag{21.2}$$

where $[LR]$ and $[UR]$ are respectively lower and the upper residuals [15]. The dot-dot black line was obtained using the same Eq. (21.2), but neglecting terms related to the residuals. This last curve is obtained coupling the modal superposition with the rigid body modes of the violin, this lets to fit, at low frequency, the synthetized FRF with the experimental one.

The identification of modal parameters extraction was performed also on the other configurations.

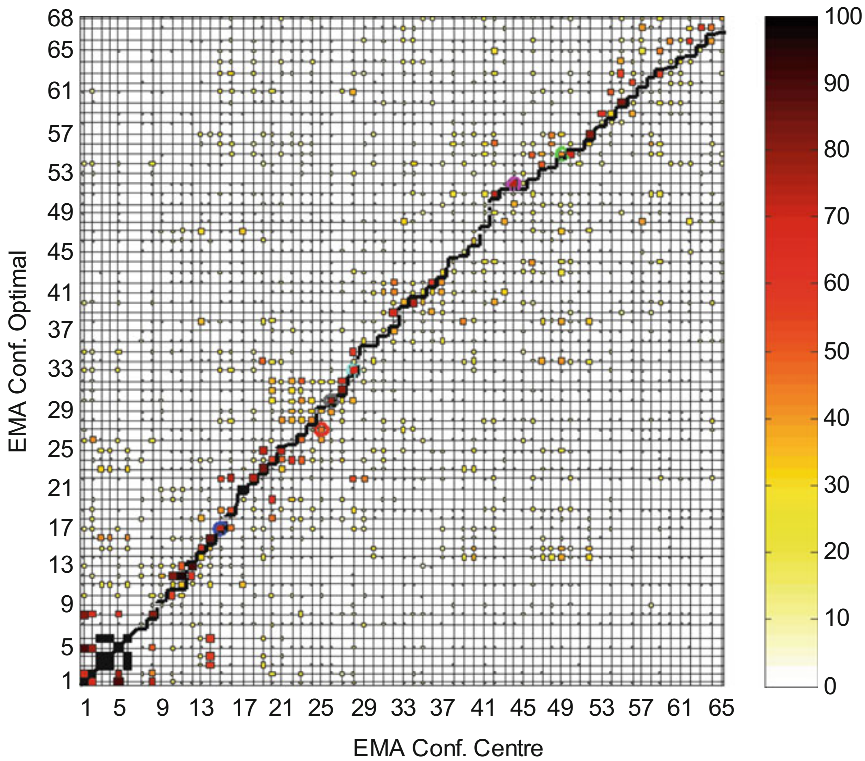

Fig. 21.9 MAC Centre vs Optimal

For all other configurations 59 mode shapes are identified, except for conf. Optimal in which 68 modes were detected. As example the MAC between configurations Centre and Optimal is presented in Fig. 21.9. The presence of a marked diagonal indicates that the two configurations are not too much different. Most of the modes are correlated very well, especially the six "Signature" mode shapes.

In Fig. 21.10 a MAC detail focusing only on these "Signature" modes is presented. It is possible to see a stiffer behaviour of the Optimal configuration with respect to the Centre one for five of the six "Signature" modes. The breathing mode of right bottom lung on the top plane presents a low MAC value; this is a confirmation that the soundpost has a relevant effect in the structural vibroacoustic behaviour of the instrument.

Figure 21.11 shows the experimental inertances of right bottom lungs on top plate for all six analysed configurations. The vertical thick coloured lines indicate the natural frequencies of the six "Signature" modes detected in the configuration corresponding to the central position of soundpost, while the rectangular areas represent the "Signature" natural frequencies variation ranges among the six configurations. The soundpost seems not to have any visible effect on the experimental FRF up to 400 Hz, especially for the peaks of the first two "Signature" modes. At higher frequency the response of the violin is quite different.

The extracted "Signature" mode shapes of the six configurations are compared in Fig. 21.12. The mode shapes of each configuration are grouped in relation to their behaviour and compared. The correlation inside the group is quite high for the first three "Signature" mode shapes and slightly lower for higher frequencies mode shapes. The correlation outside the group is very low, as expected. The fourth "Signature" mode, namely the bending mode in the longitudinal plane, presents an evident correlation with the bridge torsional mode and the breathing mode of right bottom lung on top plate.

The trend of natural frequencies along x direction of soundpost positions (Fig. 21.13) seems to have a common behaviour: for horizontal movements of the soundpost the frequency decreases from left (conf. 3) to the centre; while, moving to the optimal one, it increases for five of the six "Signature" modes. Instead, in the y direction, no particular trends were detected.

Figure 21.14 shows the trend of damping ratios. For each "Signature" mode the damping ratio changes within a range of 0.2–2%. A decrement in damping ratio involves five of the six "Signature" modes, when the soundpost is moved from the central position to the optimal one. This can be correlated with an improvement in the acoustic power of the instrument.

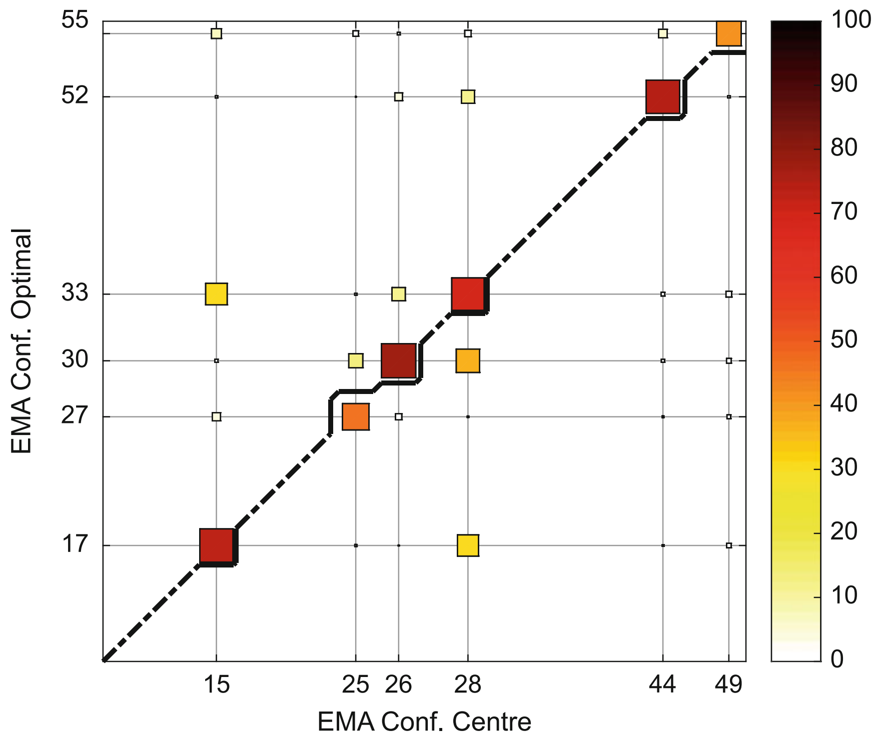

Fig. 21.10 "Signature" modes MAC detail Centre vs Optimal

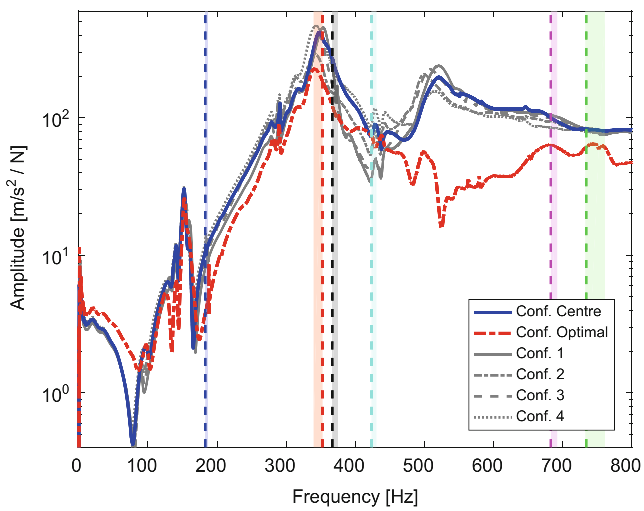

Fig. 21.11 Comparison auto-inertances of inferior right lungs on top plate

21.4 Conclusion

A parametric experimental modal analysis was performed on a Guarneri del Gesù violin. The parameter taken in consideration was the position of the soundpost, to evaluate its effect on the vibrational properties of the analysed system. Six different configurations, with different locations of the soundpost, were investigated. The adjustment of the soundpost position is very important for the acoustic performance of the instrument. Each player prefers a slightly different position of the soundpost for best exploit the instrument performances.

Six "Signature" modes of the violin have been identified in each configuration and compared, in order to understand the effect of the soundpost position of the instrument modal behaviour.

Some considerations result:

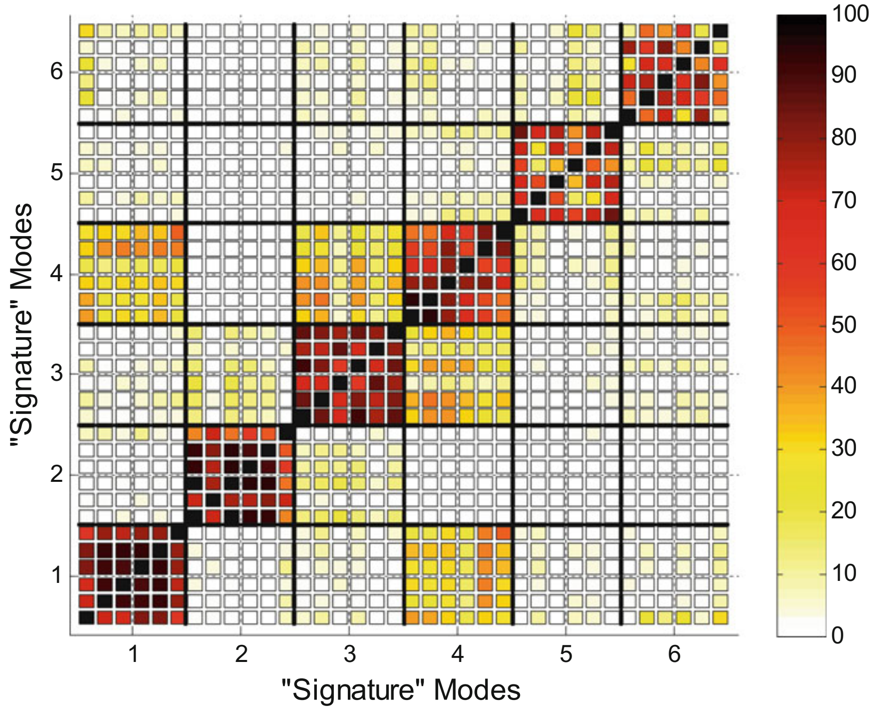

Fig. 21.12 MAC between experimental "Signature" mode shapes groups

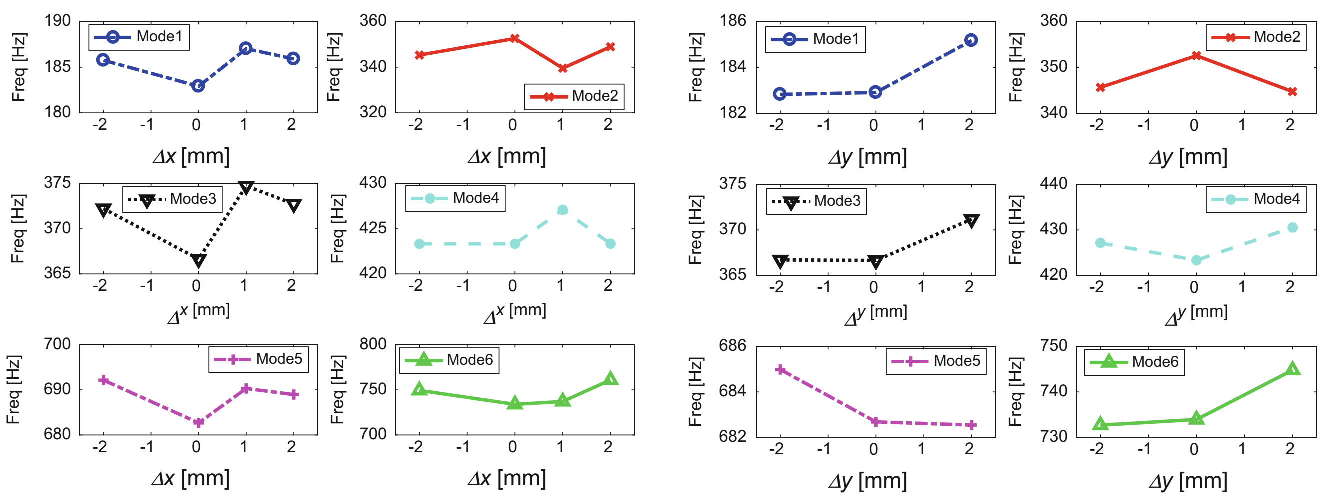

Fig. 21.13 Frequency trend in *x* (left) and *y* (right) directions

- the natural frequencies increase when the soundpost is in the optimal position,
- the damping is the lowest in the optimal position.

Both these considerations are coherent with the players' opinion, considering the "optimal" configuration the best for the instrument performances.

The optimal configuration results as the one in which the natural frequencies of the "Signature" modes are the closest to the standard music note frequencies; their correlation is shown in Table 21.3. The most interesting fact is that the frequencies related to E and F notes are the most recurring. These frequencies are close, as lower octave harmonics, to the one known as "bridge hill" (being a broad peak response of good violins in the vicinity of 2.5 kHz) [17].

It is important to stress here the fact that the violin player requirements depend on their perception, thus, further psychoacoustic considerations should be integrated in a final step, based on this research.

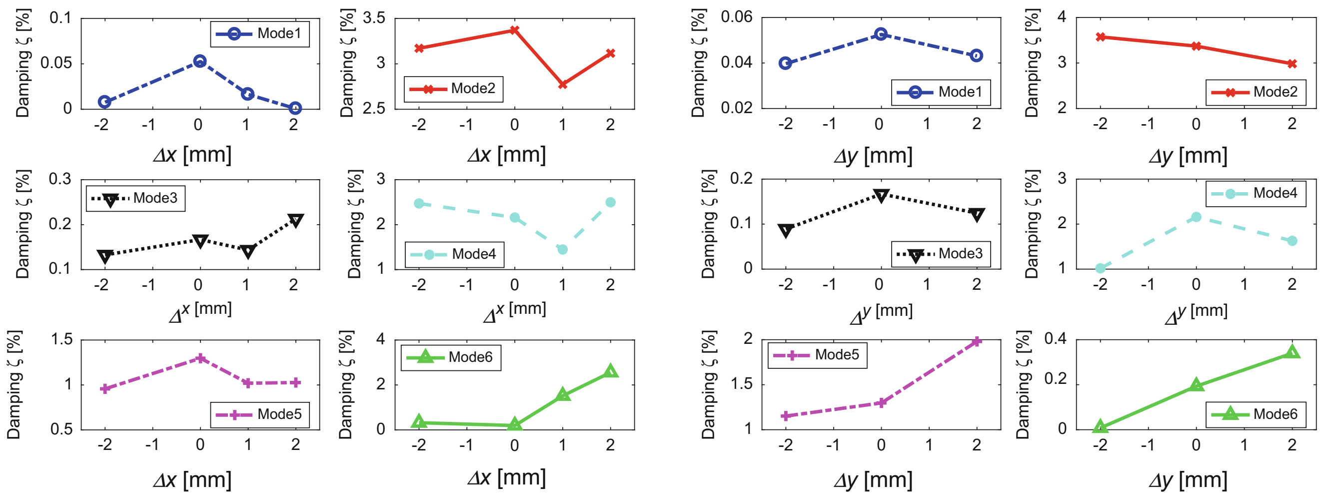

Fig. 21.14 Damping trend in *x* (left) and *y* (right) directions

Table 21.3 "Signature" mode shapes conf. Optimal and notes frequencies correlation

Mode	Frequency [Hz]	Note	Standard frequency [Hz]
17	187.03	F#3	185
27	339.55	E4 – F4	330–349
30	374.74	F#4	370
33	427.00	A4	440
52	690.78	F5	698
55	738.08	F#5	740

A numerical model of the violin, considering the involved material orthotropy, is ongoing. The present work will let to validate the numerical model and perform much more accurate parametric analysis to better understand the common trend of the modal parameters changing the soundpost location and to relate them with the acoustic performance through an objective law.

A validated parametric model of the violin could become a very useful engineering tool to predict the best soundpost location in order to shift the "Signature" modes natural frequency as much as possible close to the standard note frequencies.

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