Monitoring of the making process of a handcrafted electric guitar

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Even if the making process is highly standardised, handcrafted "identical" solid body electric guitars may present notable differences in their vibratory behaviours. The vibratory behaviour is usually measured at the end of the production, that is on ready-to-play instruments. In order to know where the differences originate, and with the aim of trying to make "identical" guitars more identical, a vibratory study during the making process can be done. In this paper, a handcrafted solid body electric guitar was measured at six successive stages of the production. Mode tracking is performed from early production stages with separated parts (neck, body) until later stages with the whole guitar. It is shown that the isolated neck and body modes determine the whole guitar modes. This allows the guitar maker to select or fix necks and bodies early in the making process, in order to reduce the variability between "identical" guitars.

1 Introduction

The solid body electric guitar has often been considered as a purely electronic instrument, but recent advances in musical acoustics showed that the mechanical behaviour of the solid body electric guitar also contributes to the sound. Indeed, before being transformed by the electro-acoustic chain going from the pickup to the loudspeaker, the acoustic signal is a transduction of the velocity of the vibrating strings.

Just as in the case of acoustic instruments (see [1] or [2] for example), the electric guitar string couples with the structure of the guitar. This coupling has been found to be well described with the knowledge of the vibratory behaviour of the structure [3, 4, 5, 6]. Vibratory measurements on musical instruments have almost always been performed on whole and finished instruments. One of the side results of such measurements is that nominally "identical" instruments can present notable differences in their vibratory behaviours [7, 8]. This holds naturally for the electric guitar, albeit its industrial history [9] has resulted in a highly standardised making process (standardised templates, use of machines, mass production. . .).

Though it tells that guitars differ, end-of-production measurements do not allow to conclude about the origins of the differences. Knowing the evolution of the vibratory behaviour throughout the making process could provide clues in that sense. Are the modes of the whole structure determined by those of the neck or of the body? Is a particular step in the making process decisive regarding the final result?

In order to address these questions, an electric guitar was measured at 6 different stages of the making process. The protocol and schedule of the measuring campaign is explained in section 2. The analysis of mobility measurements is described in section 3, it results in a modal identification for each production stage allowing mode tracking shown in section 4.

2 Experimental protocol

2.1 The guitar

The guitar of the study comes from a set built at Itemm by luthiers. It is made according to the specifications of the reference model *Les Paul Junior* by manufacturer *Gibson*. Its neck and body are made of mahogany, and its fingerboard is made of ebony. Frets, "wrap-around" bridge, pegs, "Kent Armstrong P-90" pickup, and the electronic parts are chosen to be as close as possible to what can be found on the original guitar model. The guitar was built by a single luthier, who used both machines and hand tools. The guitar can be seen in figure 1.

2.2 Measurement stages

The guitar was measured at 6 stages during the making process.

The object measured at 1st stage is the body of the guitar, with its final shape, including the hollows for the pickup, the bridge, and the electronic parts. The 2nd stage corresponds to a raw neck, that is a neck with angled headstock and heel, but without neck profile. The 3rd stage adds this neck profile. At the end of the 4th stage the truss-rod is put in the neck groove. Then the fingerboard is glued on the neck and the frets are set on the fingerboard. Stage 5 is a "raw" guitar, that is the complete neck of stage 4 glued to the body of stage 1. The whole guitar, excepted the fingerboard, is varnished at this stage. The 6th stage is the fully-equipped guitar: hardware (bridge, pegs), electronic parts (pickup and corresponding electric circuit), and strings. In this paper, we will call "object" either the neck or the guitar, depending on the current measurement stage. Table 1 sums up the measurement stages, and the object being measured.

Table 1: Description of the measurement stages, numbered by chronological order.

Stage	Measured object
1	body
2	raw neck
3	shaped neck
4	neck fitted with fingerboard and frets
5	raw guitar
6	fully-equipped guitar

2.3 Measurement method

The measurement of the structure's impulse response at typical coupling points with the strings is relevant for the study of the sound of a string instrument [1]. Typically, strings and structure can couple at the nut, the frets, and at the bridge. The measurements took place during the making process, so for schedule reasons only a few measurement points could be investigated. Hence in this study the measurements are done at the two points shown in figure 1.

A classic impact testing method is used for the measurement of the driving-point impulse response. The excitation is provided by an impact hammer equipped with a force sensor (PCB Piezotronics 086C01). The acceleration of the structure is measured with an accelerometer (PCB Piezotronics 352A73). Excitation and acceleration are

Figure 1: The guitar of the study at stage 6 (fully-equipped guitar). The two crosses indicates the two measurement points: one close the nut (A), the other close to the bridge (B).

required to be applied and measured at the same point. The hammer excitation is checked to have a flat spectrum up to 1000 Hz, so the frequency range of the study is [0 Hz – 1000 Hz]. In this frequency range, the accelerometer signal therefore represents directly the impulse response of the structure. Free boundary conditions are provided for each measured object.

This impulse response measurement is performed at each of the 6 stages of the making process. The analysis method of the impulse response measurements is described in section 3.

3 Analysis

3.1 Modal frequencies extraction

Assuming that the excitation force is small enough to stay in the linear approximation, the impulse response of the structure can be written as a sum of damped sinusoids [10]. This suggests the use of the ESPRIT method [11], which is known to give accurate results for measurements on musical instruments [12].

The impulse response writes as:

$$h(t) = \sum_{n=1}^{N} a_n sin(2\pi f_n t + \phi_n) e^{-2\pi f_n \xi_n t} \quad (1)$$

where a_n, f_n, ξ_n, and ϕ_n are the modal amplitudes, frequencies, damping ratios, and phases respectively. Details of the present use of ESPRIT algorithm are given in [5, 13].

Only the modal frequencies f_n and damping ratios ξ_n are investigated in this paper. They are extracted from the impulse response measurement at each measurement stage.

3.2 Modal shapes identification

The knowledge of the modal shapes is required in order to perform a mode tracking. Indeed, identified modal parameters at two measurement stages can be connected together only if one has checked that they correspond to the same mode. This paper proposes a direct and classic modal analysis for the whole guitars, based on a large number of measurements (mesh). The isolated parts measurements aim at being quick and not disturbing for the luthiers' work. Therefore the mode shape identification for isolated parts (neck and body) is done with an alternate method.

3.2.1 Whole guitar modal shape

A modal analysis is carried out on the guitar at stage 6. Transfer functions measured on a 54-point mesh are analysed with the LSCF method implemented in the software MODAN [14]. The identified modal frequencies are checked to correspond to the extracted modal frequencies of section 3.1.

3.2.2 Neck and body modal shapes

A finite-element model is used in order to determine the mode shapes related to the modal parameters identified in section 3.1. The software CAST3M [15] is used for the numerical simulation. The neck of stages 2 and 3 is modelled as a simple beam. The body of stage 1 is modelled as a simple plate. Both beam and plate have the mechanical properties of mahogany. The dimensions of the plate and beam roughly correspond to the actual dimensions of the guitar. An extra thin beam is attached to the beam of stages 2 and 3 to get the model of stage 4. This extra beam has the mechanical properties of ebony. All dimensions are given in table 2. All mechanical properties are given in table 3. The densities ρ are measured on wood samples. Because the protocol is intended to be quick and reproducible in a workshop, no proper identification on the woods of the study is done, the material properties of the woods (mahogany and ebony) are taken from the literature: [16] for all mechanical constants except E_L for ebony that is taken from [17].

Table 2: Dimensions of the beam, plate, and additional beam, used for the finite-element simulation of the vibration of the neck, the body, and the fingerboard respectively.

	Plate (body)	Beam (neck)	Add. beam (fingerb.)
Width (m)	30×10^{-2}	5×10^{-2}	5×10^{-2}
Thickness (m)	4.42×10^{-2}	1.5×10^{-2}	5.5×10^{-3}
Length (m)	36×10^{-2}	71.1×10^{-2}	46.3×10^{-2}

Table 3: Material properties of mahogany and ebony.

Ebony		Mahogany	
E_L	15.50×10^9 Pa	E_L	11.60×10^9 Pa
E_R	$E_L/8$ Pa	E_R	1.24×10^9 Pa
E_T	$E_L/13.5$ Pa	E_T	0.74×10^9 Pa
G_{LR}	1.26×10^9 Pa	G_{LR}	1.00×10^9 Pa
G_{RT}	0.37×10^9 Pa	G_{RT}	0.33×10^9 Pa
G_{LT}	0.97×10^9 Pa	G_{LT}	0.76×10^9 Pa
ν_{LR}	0.39	ν_{LR}	0.39
ν_{LT}	0.46	ν_{LT}	0.46
ν_{RT}	0.67	ν_{RT}	0.67
ρ	1180 kg.m^{-3}	ρ	528 kg.m^{-3}

3.3 Matching experimental identification to numerical simulation

For each measurement stage, the finite-element simulation provides a modal basis (frequencies and shapes) of a conservative system. Because of the expected difference between the wood mechanical properties of table 3 and the actual ones, the modal frequencies f_n are not the same in the simulation as in the measurements. However, because of the similar geometry between the measured objects and the corresponding models, the modes are expected to appear in the same order, with identical frequency ratios f_n/f_1, where f_1 is the lowest modal frequency.

For each measurement stage, the frequency ratios from the finite-element simulation are compared to the frequency ratios from the experiment. These ratios, as well as the corresponding frequencies and mode shapes, are shown in table 4. The relative error between the frequency ratios of the simulation and the experiment never exceeds 13.03%, so the extracted experimental frequencies and corresponding damping ratios can be associated to the frequencies and mode shapes from the simulation.

4 Results

Modes are identified for each stage independently. The next step is to link the modes from one stage to another. Figures 2 and 3 show the result of the modal frequency and damping ratio tracking throughout the making process. In these figures, the crosses indicate either the modal frequencies, or the modal damping ratios. Mode tracking allows to connect (solid lines) the neck frequencies (or damping ratios) of stages 2, 3, and 4, as well as the whole guitar frequencies (or damping ratios) of stages 5 and 6. In the following, the numbering of the neck, body, or guitar modes is made according to increasing frequency order.

Concerning the frequencies, a clear trend can be observed: they decrease from stage 2 to 3, and increase from stage 3 to 4. They decrease between stages 5 and 6. The trends in neck frequencies may be explained by changes in the geometry (cross-sectional area and second area moment) at stage 3, or in the mechanical behaviour (the simple beam becomes a composite beam) at stage 4. The decreasing whole guitar frequencies can be a result of the additional mass due to the electronic parts and hardware.

No such very clear trend is found in damping ratios. Anyway it can be noticed that damping ratios tend to increase between stages 2 and 4 and between stages 5 and 6. The latter increase could be due to the guitar fitting out with various parts like bridge, pegs, etc.

Dashed lines in figures 2 and 3 indicate supposed relationships between modes of separated parts and modes of the whole guitar.

Indeed, at stage 4, the neck modes seem to have reached a final frequency close to these of guitar modes with similar mode shape. This is particularly clear for the first two neck modes: their mode shape is very similar to the mode shapes of guitar modes 2 and 3. Furthermore, the 1st (resp. 2nd) neck mode and the 2nd (resp. 3rd) guitar mode have close frequencies. This tendency can be seen as well between 3rd neck mode and 5th guitar mode. Body modes can also be associated with guitar modes. The 1st body mode shows the same torsional behaviour as the 4th guitar mode, and the 2nd body mode shows a very similar mode shape as the 5th guitar mode. Isolated body modal frequencies are quite close to those of corresponding guitar modes.

The relationship between isolated part damping ratios and whole guitar damping ratios is even clearer. The modes keep being numbered by increasing frequency. The three identified neck modes at stage 4 have damping ratios close to 2nd, 3rd, and 5th guitar modes at stage 5, showing a similar neck shape. Moreover, the 1st body mode has a damping ratio very close to the one of 4th guitar mode at stage 5. The same is observed for the 2nd body mode and 5th guitar mode. Stage 6 introduces a dispersion in damping ratios that could be due to the additional electronics and hardware.

As a provisional result, it is found that all guitar modes at stage 5 are determined by the modes of the separated parts. This is true with the exception of the lower guitar mode, that is a bending mode of the whole guitar, whose origin can not, by definition, be attributed to the separated parts.

5 Conclusion

Vibratory measurements were carried out at 6 stages during the making process of a solid body electric guitar. Separated parts (body, and neck at different states of progress), as well as the whole guitar, could be measured. A method was described for the mode identification and tracking throughout the production stages. There are systematic trends in the modal frequencies from one measurement stage to another. These systematic trends may be related to changes in mechanical and geometrical parameters like shape, mass, etc. Modelling those trends is the purpose of ongoing work.

The main result of this paper is the link that is established between isolated parts modes and whole guitar modes. The body modes at stage 1 and the neck modes at stage 4 show frequencies, damping ratios, and mode shapes close to the guitar modes of stage 5. More exactly, the 1st and 2nd neck modes seem to cause the 2nd and 3rd guitar modes. The 1st body mode seems to cause the 4th guitar mode. 3rd neck mode and 2nd body mode seem to cause the 5th guitar mode.

As a final result, it can be stated that:

- the guitar modes at stage 5 are determined by the separated parts modes, both in frequency and damping ratio,
- stage 6 however scatters the damping ratios of stage 5, so that the relationship between guitar and separated parts damping ratios is lost,
- stage 6 frequencies still may be deduced from stage 5 modes with the knowledge of the hardware and electronics additional mass: the modal frequencies of the guitar could be predicted from the only knowledge of the neck and body modal frequencies.

If confirmed with other guitars, this result may be used by electric guitar makers. The final production stage comes too late to make measurements that are useful to the makers. Vibratory control during the making process allows either the selection of some suitable necks and bodies, or the fixing of singular necks or bodies early in the making process. This could be a great help to the guitar maker in order to improve the overall quality of guitars, and to reduce the variability between "identical" guitars.

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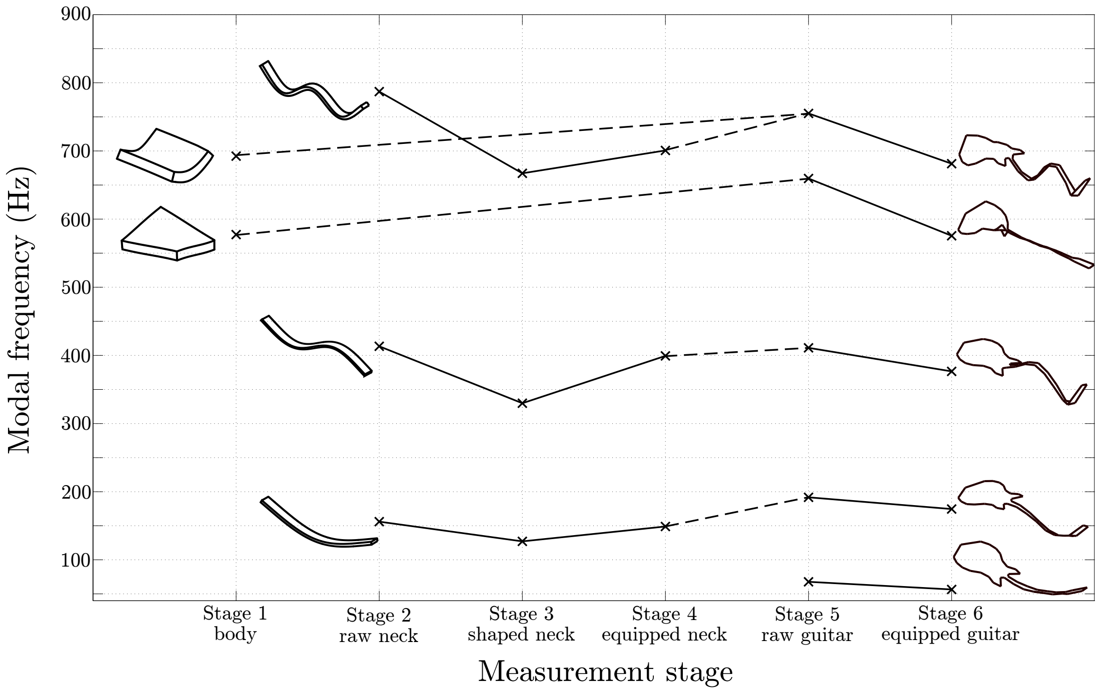

Figure 2: Modal frequency (y-axis) tracking for measurement stages 1 to 6 (x-axis). Crosses indicate the modal frequencies. Solid lines indicate identical modes accross stages. Dashed lines indicate supposed relationships between modes of separated parts and modes of the whole guitar.

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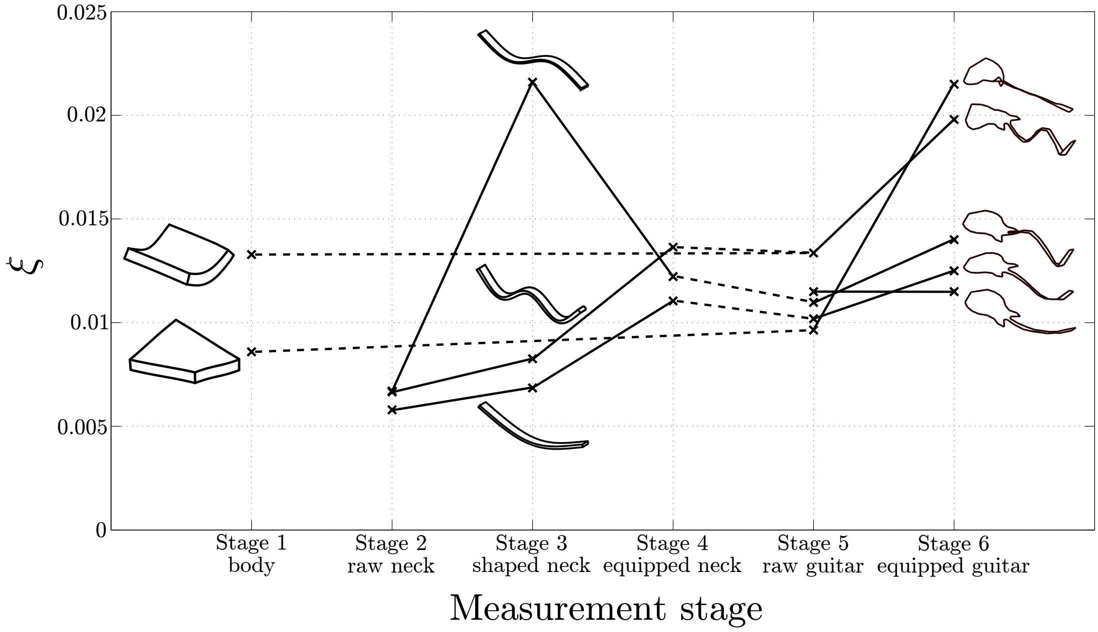
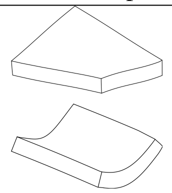
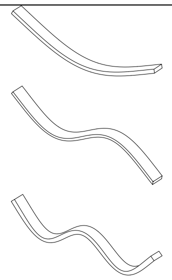
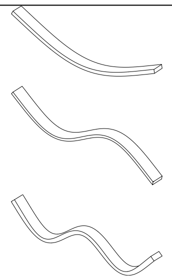
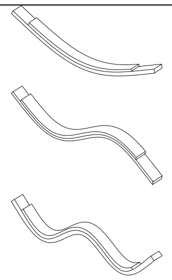


Figure 3: Modal damping (y-axis) tracking for measurement stages 1 to 6 (x-axis). Crosses indicate the modal dampings. Solid lines indicate identical modes accross stages. Dashed lines indicate supposed relationships between modes of separated parts and modes of the whole guitar.

Table 4: Result of the matching process between experimentally identified modes to modes obtained through finite-element simulation. For both numerical and experimental modes, f_n is the modal frequency, and f_n/f_1 is the ratio between f_n and the lowest modal frequency. Also shown is the relative error between frequency ratios of the simulation and the experiment.

	Num.			Exp.		
Stage	Mode shape	f_n (Hz)	f_n/f_1	f_n (Hz)	f_n/f_1	Relative error (%)
1		582.88	1	576.00	1	–
		706.74	1.21	726.93	1.26	4.13
2		142.98	1	160.5	1	–
		389.17	2.72	423.67	2.64	2.94
		748.7	5.24	816.21	5.09	2.86
3		142.98	1	117.93	1	–
		389.17	2.72	331.37	2.81	3.31
		748.7	5.24	642.57	5.45	4.01
4		200.93	1	152.70	1	–
		477.4	2.38	410.17	2.69	13.03
		882.48	4.37	709.37	4.65	6.41