GUITAR SOUNDBOARD MEASUREMENTS FOR REPEATABLE ACOUSTIC PERFORMANCE MANUFACTURING

L Ausiello Solent University, Southampton
L Yule Solent University, Southampton
G Squicciarini University of Southampton
C Barlow Solent University, Southampton

1 INTRODUCTION

Over the past two hundred years, acoustic guitar manufacturing has changed both in terms of the accuracy of processes and in terms of the time dedicated to the construction of each single instrument. If we trace back the history of some relevant brands we can witness how small family businesses have mutated into large multinational companies, thus requiring structural and strategic changes to survive. Good examples are Martin & Co. [1] or Gibson [2] who, starting from traditional counterparts that used gut strings, have enriched the spectrum of acoustic instruments by creating and diffusing the modern steel strings guitar, offering a plethora of new designs.

Nonetheless, in both scenarios of a small shop curated by a master luthier and his/her apprentices or of a large factory employing automated machinery and strict quality control, one fundamental assumption remained un-challenged: once a specific design was found to be interesting and desirable for customers, its geometry and mechanical features were reproduced in larger and larger numbers. With mechanization almost completely replacing manual labor in the few decades after the Second World War, this approach was even more systematically flawed by intrinsic characteristics of wood, namely its anisotropy and the relatively large variation of its key parameters such as density, stiffness and damping.

Gore and Gilet correctly pointed out this problem in their work [3]. In their analysis the authors suggested a method to measure the impulse response of several parts of an acoustic guitar, which, according to them, would give sufficiently repeatable data for plates, braces and other key components. Their approach could be summarized as follow: a small number (between 5 and 10) of impulses generated by tapping a fingertip on the selected part are recorded with a microphone and, consequently, processed with a Fast Fourier Transform (FFT) to produce a frequency response.

This method is an empirical mixture of the traditional one used by luthiers to "voice" a guitar soundboard [4], and the much more accurate one adopted for example by Giordano, who assesses the mechanical impedance of a piano soundboard by the use of force actuators and acceleration sensors [5]. The main difference with the former is to not rely on the operator's listening skills (and preference), but rather to employ FFT graphs to show where the main resonances of a soundboard are located in the frequency domain.

With respect to the latter, the main limitation of the approach found in [3] is strict repeatability; due to the uncertainty of the applied force of each tapping, the recorded information of a soundboard frequency response is not correct in terms of absolute magnitude, thus impairing the capability to truly compare two different instruments or two manufacturing stages of a component still under development. Furthermore, the use of impulsive stimuli for acoustic measurements is more susceptible to ambient noise than the use, for example, of Maximum Length Sequences (MLS) or sine sweeps [6].

This paper presents an application of the sine-sweep method, commonly used to retrieve impulse responses of acoustic spaces or electro-acoustic devices, to perform a fast, accurate and objective assessment of the time-frequency response of guitar soundboards.

2 METHOD

In order to analyse the appropriateness of the proposed sine-sweep method, it was first necessary to compare its performance to more established methods, in this case the impact hammer one.

2.1 Impact hammer method

There are several possible approaches to retrieve the impulse response of a soundboard, and for the purpose of validating the suggested new methodology we'll briefly present the impact hammer technique, which will be used as initial reference. This approach was derived from stress-wave testing systems [7].

As described in [8], if we inject energy into our Device Under Test (DUT) by using an impact hammer, we can at the same time measure the force that was exerted on the system. By doing so, we can have information of both the input excitation and the output response, by simply attaching one or more accelerometer in some strategically selected points. As per [5], velocity could be calculated by integration, thus also offering the chance to measure the mechanical impedance, if needed.

The measurement system consisted of a PC running National Instrument LabView 2014 software, connected to a National Instruments PXIe-1062Q Chassis with PXI-4461 and PXI-4497 Data Acquisition Cards (DAQ). A PCB 086C03 Impact Hammer, an MMF KS901.100 accelerometer and A Brüel & Kjær Type 4190 microphone connected to a Type 2829 signal conditioner were attached to the DAQ via BNC connectors.

The system was configured to acquire signals from the impact hammer, accelerometer, and microphone simultaneously; an example is shown in Figure 2.1.

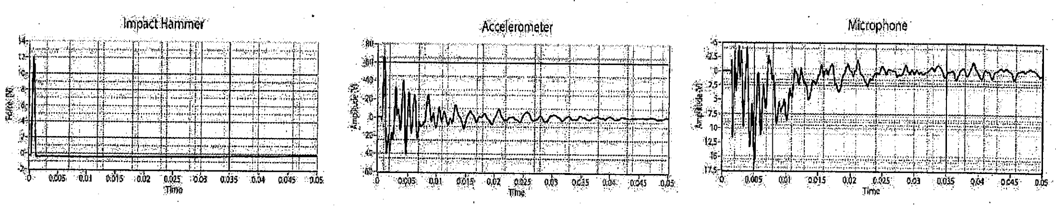

Figure 2.1. Multiple data acquired simultaneously; from left, force, acceleration and sound pressure; 0.05 seconds of recorded signals are shown.

The sampling rate was set to 90 kHz, and each measurement was triggered by an excitation from the hammer, which captured a block of samples for each channel and saved them into an array.

Due to the variability of the excitation force provided by the impact hammer, it was necessary to record multiple impacts, which had to be processed and normalized. The acquisition ran until a user-defined number of excitations (5-10) were captured. Just as a visual feedback during the acquisition, a FFT was calculated for each block of samples being recorded.

Figure 2.2 shows the calculated FFT from raw accelerometer data. The individual measurements and any possible anomaly can be seen along with a temporary average, shown as a thick black trace. At this stage some variance is always visible.

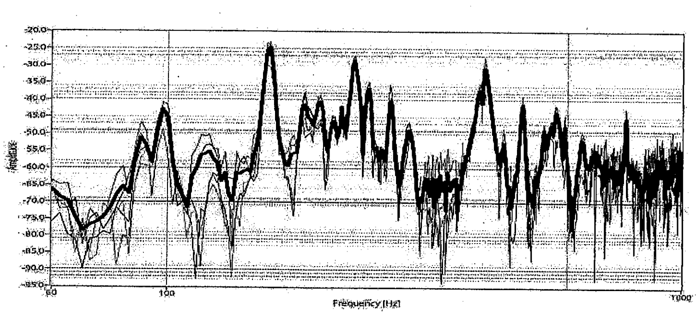

Figure 2.2. Real time FFT from multiple acceleration data recorded (several colors); average computed and plotted in black.

The following processing consisted of calculating an auto-spectrum for each input channel:

$$\text{Auto Spectrum} = \frac{\text{FFT*(Signal)} \times \text{FFT(Signal)}}{n^2}$$

Where FFT* is the complex conjugate of the FFT, and n is the number of FFT bins.
Then the cross-spectrum was computed between the impact hammer and accelerometer's signals, and also between the impact hammer and microphone's signals.

$$\text{Cross Spectrum} = \frac{\text{FFT*(Input Signal)} \times \text{FFT(Output Signal)}}{N^2}$$

Where N is the length of the signals. Once the cross-spectrum and auto-spectrum were calculated, the transfer function H(f) was calculated as the ratio between the two. Figure 2.3 shows an example of H(f) between force and acoustic pressure.

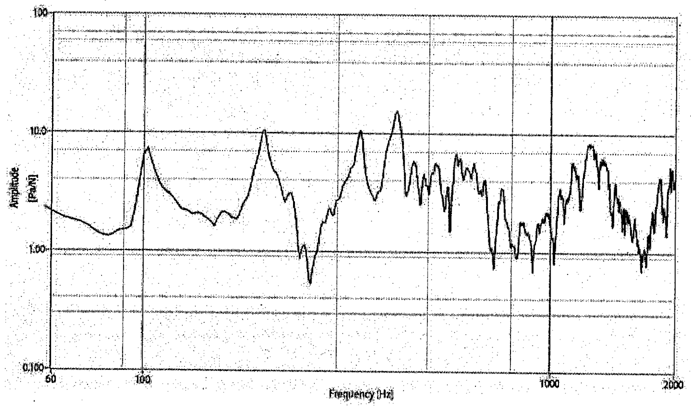

Figure 2.3. Transfer function H(f) between the auto-spectrum of force and cross-spectrum of force and sound pressure. Mark the clear presence of the main coupled air resonance at 100Hz and the main coupled top resonance at 194Hz.

Coherence was also calculated for both transducer combinations.

$$\text{Coherence} = \frac{\text{Cross Spectrum}^2}{\text{Auto Spectrum (Input)} \times \text{Auto Spectrum (Output)}}$$

The coherence function is frequency dependent and has values in [0,1]: a higher value indicates a good linear correlation between the input excitation and vibration or acoustic output.

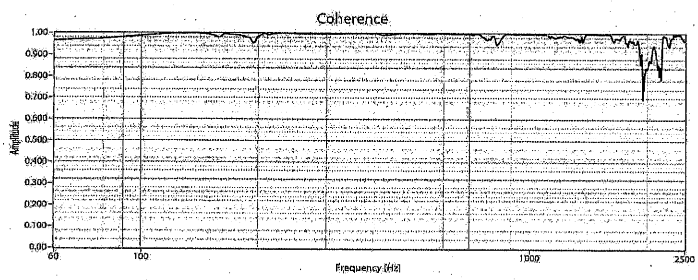

Figure 2.4. The coherence function provides information about the correlation between force and acceleration or force and sound pressure.

Figure 2.4 clearly shows that coherence is not constant over frequency and it is crucial for evaluating the frequency range in which the performed measurements are valid and consistent. In the case of a guitar soundboard, the impact hammer couldn't be equipped with a hard metal tip, because this would have permanently cut into the wooden surface under test.

The use of a plastic tip, or a hard rubber one, had a profound impact on the usable frequency range of the recorded data [7]; in this example it limited the validity of this method up to approximately 2 - 2.5 kHz. Above this frequency, the coherence showed consistently values below 0.8.

2.2 Sine-Sweep method

The sine sweep method is a general purpose measurement methodology that can assess all types of linear and non-linear (although time-invariant) systems [6]. Its robustness against periodic noise and its simplicity made this technique very popular especially in room acoustics regulation (e.g. estimation of the reverberation time according to ISO 3382-3:2012) and electro-acoustics measurement systems [9].

Normally, the DUT is stimulated with an exponential sine sweep, which is a signal of constant amplitude and exponentially rising frequency. For the work described here, once the frequency range of interest is selected, a test signal is created using the Aurora audio plugins developed by Farina, running on a Digital Audio Workstation (e.g. Audacity or Adobe Audition 3.0). When a sine sweep is created, its corresponding inverse filter is also automatically generated [6].

The theory shows that when convolving the original sine sweep with its corresponding inverse filter, a Dirac-like function (with its intrinsic bandwidth limitations) can be retrieved [6]. When injecting a sine sweep into a DUT, the real system is expected to produce an output in forms of vibrations or acoustic waves. This actual output should be recorded and then convolved with the original inverse filter. The convolution product will results in the DUT's impulse response [6]. Afterwards, FFT analysis can be applied to the computed impulse responses.

This technique relies on an actuator to inject energy in the DUT; the actuator of choice was an electromechanical exciter (Fig.2.1). By mechanically connecting its voice coil to the guitar bridge, a solid contact surface could be created, allowing repeatable measurements to be performed.

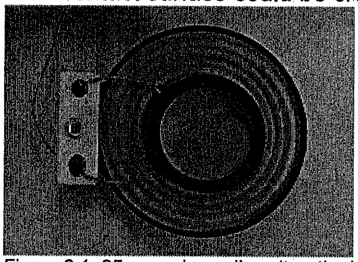

Figure 2.1. 25mm voice-coil exciter: the black ring is the bottom of the voice coil, which is glued to the soundboard, in yellow the spider, on the left the transducer's terminals.

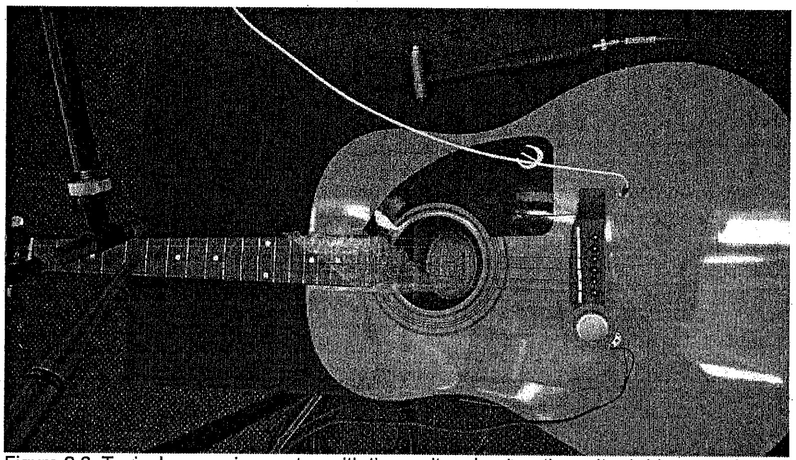

Figure 2.2. Typical comparison setup with the exciter glued on the guitar bridge, accelerometer placed on the soundboard, Earthworkds MD30 mic (bottom), Brüel & Kjær Type 4190 mic (top), and impact hammer in the background (top).

The whole signal chain, depicted in figures 2.2 and 2.3, consisted of:

1. DAW (Audition 3.0), which generates the sine-sweep with a start frequency 45 Hz, and an end frequency 8 kHz
2. M-Audio Fast track 600 USB Audio Interface connected to the PC providing both output for sine-sweep signals and input for the microphone sensed ones.
3. Earthworks MD30 omnidirectional microphone connected to the M-Audio soundcard
4. Calibrated power amplifier (NORSONIC 280)
5. 25mm voice-coil exciter (made by ASK)
6. Guitar under test [DUT]

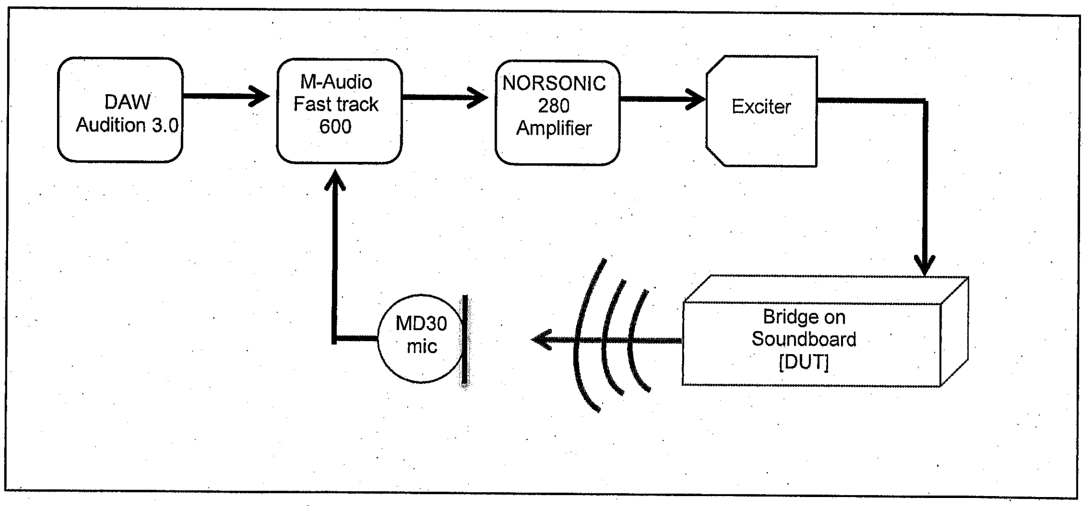

Figure 2.3. Block diagram of the signal chain setup. Sine sweep signals flows from DAW to soundcard to amplifier and final transducer, which injects energy into the soundboard. The microphone then records the acoustic energy.

The original sine-sweep signal is depicted in figure 2.4 in which both its time behavior and spectrogram are presented. On the horizontal axis two sweeps of 10 seconds each, interleaved by 5 seconds of silence, can be seen; the spectrogram's vertical axis clearly shows the limit of 8kHz of the end frequency. Note that due to the time-frequency resolution, it is not possible to show in the spectrogram the exact starting frequency at 45Hz.

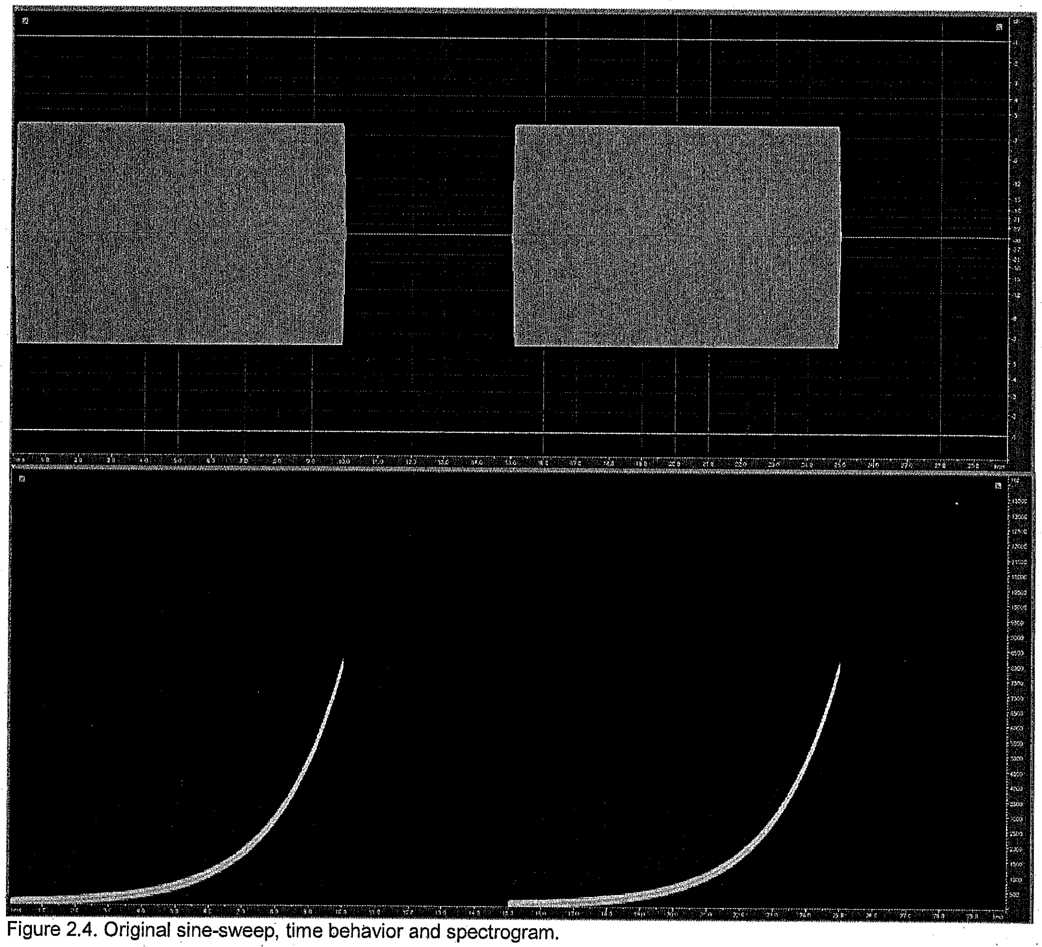

Figure 2.4. Original sine-sweep, time behavior and spectrogram.

The DUT output was recorded on a separate track of the DAW, and its original time behavior can be seen in figure 2.5. Even in the time domain large amplitude variations are clearly noticeable; these are also shown in the spectrogram analysis in terms of color variations and correspond to resonance of the board.

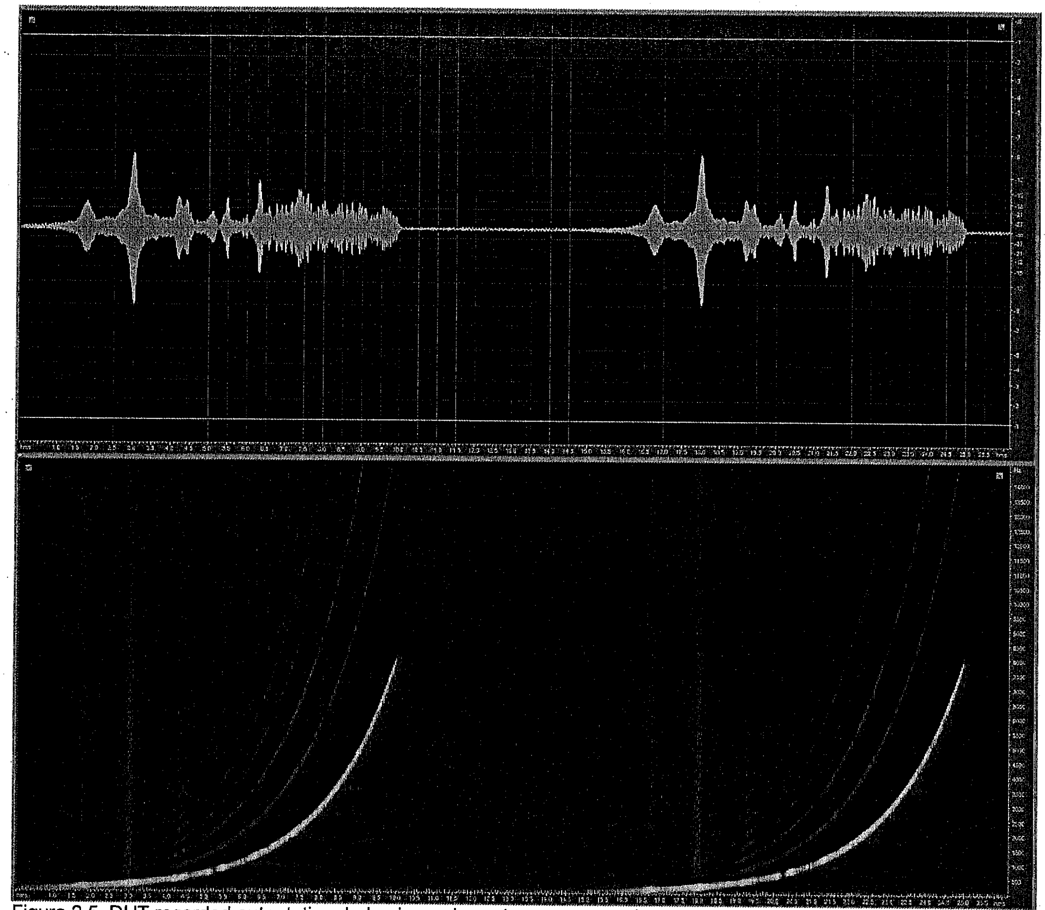

Figure 2.5. DUT recorded output, time behavior and spectrogram.

Once convolved with the inverse filter, the DUT's impulse responses were saved as audio files, to be post-processed and validated against the ones found using the impact hammer method.
It is to be noted that in this approach the force at the shaker/board interface was not measured and the output is therefore not normalized by the input.

2.3 Results for method validation

To verify the measurement procedure, the sine-sweep results were compared with the impact test ones (Fig. 2.6). Along with the different test approach, the added mass of the exciter was another reasons for expecting differences in the results.

To investigate this, various set-up were tried:

- Sine-sweep injected using the exciter (continuous red curve)
- Impact hammer hitting the bridge near the position of the exciter, with the latter still attached to the bridge (dashed blue curve)
- Impact hammer hitting the bridge where the center of the exciter voice-coil was originally positioned (thus no exciter was attached to the bridge) (dashed green curve)

All results are presented in Figure 2.6; despite the setup differences, they are in good agreement, indicating that the information contained in the impulse responses is consistent.

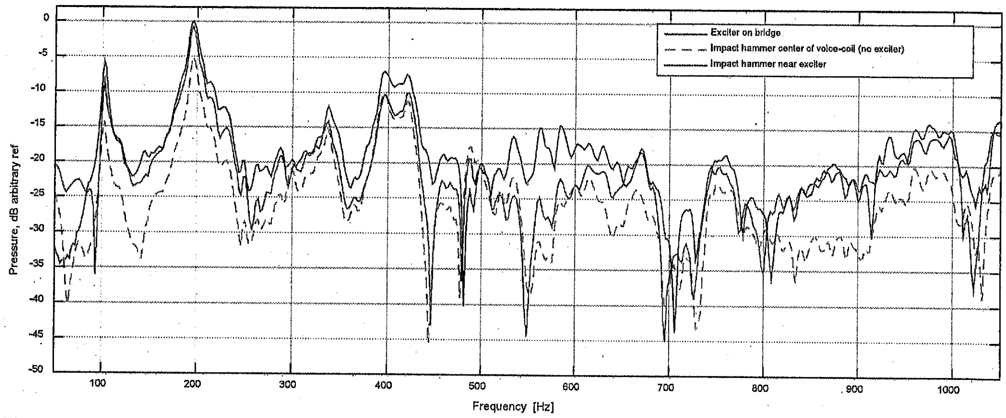

Figure 2.6. Frequency response comparison between impact hammer method and sine-sweep method.

For frequencies above 1 kHz (not shown here) the comparison between the two methods is also limited by the lack of accuracy of the impact hammer method, in particular above 2.5 kHz. On the contrary the DUT clearly responded with a sufficient signal-to-noise ratio up to 8kHz when using the sine-sweep method, opening the possibility to use this approach for any pitched acoustic instrument with fundamentals reaching 4 kHz and more, e.g. the piano.

2.4 Experimental method

To verify if the sine-sweep method can be of practical use in making guitars, three all-solid wood guitars were tested and compared. All the instruments were produced in 2017; they were steel string guitars, 00 size [1], with a 12 fret mahogany neck and Sitka spruce tops.

Two specimens had rosewood back and sides and they were supposedly identical (guitar A and B), being the same model (Blueridge BR-361), while the third one (guitar C) had mahogany back and sides (Blueridge BR-341).

Previous researchers [3, 9] based their models and evaluations criteria on a subset of the complete frequency response. Accordingly, our analysis focused on acoustic frequencies spanning from 45 Hz up to approximately 2 kHz. This was also done taking into consideration the actual extension of the DUT (whose lowest note is an E_2 = 82.407 Hz, and highest note is a C_6 = 1046.502 Hz), the usual number of upper harmonics which mainly contribute to the evaluation of timbre, and the extension of the critical bandwidth of the human hearing system [11].

Each test, comprising two consecutive sine-sweep excitations, was undertaken once per each instrument. Aurora plugins and Audition 3.0 software were used to perform analysis and plots.

2.5 Results

In figure 3.1 the frequency responses of two guitars are compared. The green trace shows the response of guitar A, with rosewood back and sides, while in red guitar C, with mahogany back and sides.

The first difference that appeared in the responses is the location of the coupled main air resonance, also known as $T(1,1)_1$ [3], which is located at 112.7 Hz for guitar A and at 108.3 Hz for guitar C. In this frequency region this difference of 4.4 Hz is very relevant, considering that one semitone is 6 Hz wide. The coupled main top resonance $T(1,1)_2$ is consistent between the two instruments.

Other differences could be clearly seen in the 370-450 Hz region, in the 600-650 Hz region, and in the 725-800 Hz region. This information could clearly be used to perform classification and/or pattern recognition, or it could be used as useful design feedback to design new bracing patterns for new models [12], once a sufficient amount of statistical data is collected.

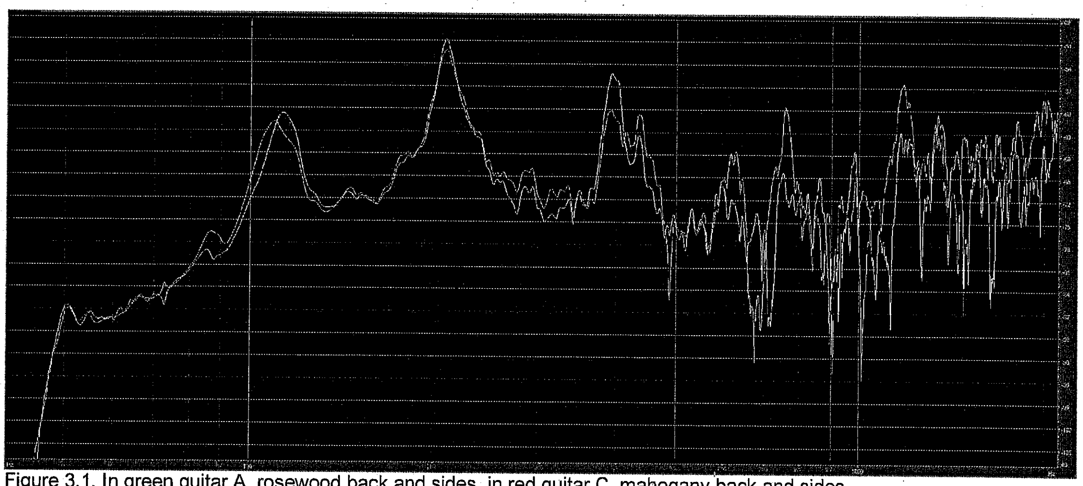

Figure 3.1. In green guitar A, rosewood back and sides, in red guitar C, mahogany back and sides.
The coupled main air resonance is clearly different between the two instruments, while it should be the same considering that this mode comes from the geometric shape and the body dimension.

The second performed test was the comparison of guitar A and B, which were the two examples of the same model. Figure 3.2 presents in green guitar A and in red guitar B. Again we can see a substantial difference in the coupled main air resonance $T(1,1)_1$ location, which is located at 112.7 Hz for guitar A and at 108.3 Hz for guitar B.

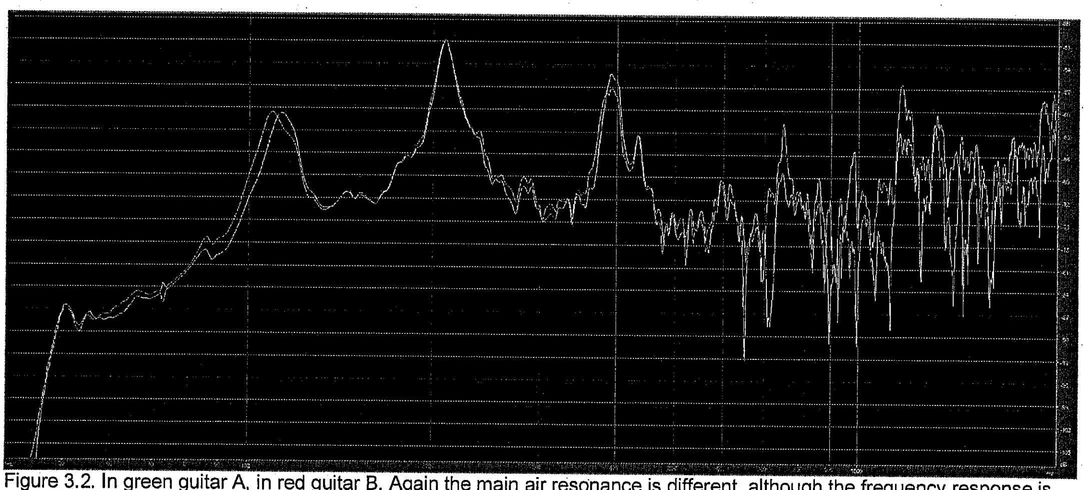

Figure 3.2. In green guitar A, in red guitar B. Again the main air resonance is different, although the frequency response is more similar up till about 650 Hz. Above this point the modal response is quite different, suggesting possible differences in the exact position of the secondary braces [11].

While guitar A and B presented similarities in the 150-500 Hz region, a detailed view of the upper part of the response was able to show substantial differences, which would be worth investigating from a manufacturing point of view. In figure 3.3 a zoomed linear view of the higher part of the frequency responses is presented: by observing the position of several important notches and peaks it would be possible to repeatedly distinguish and separate the two instruments within a production batch.

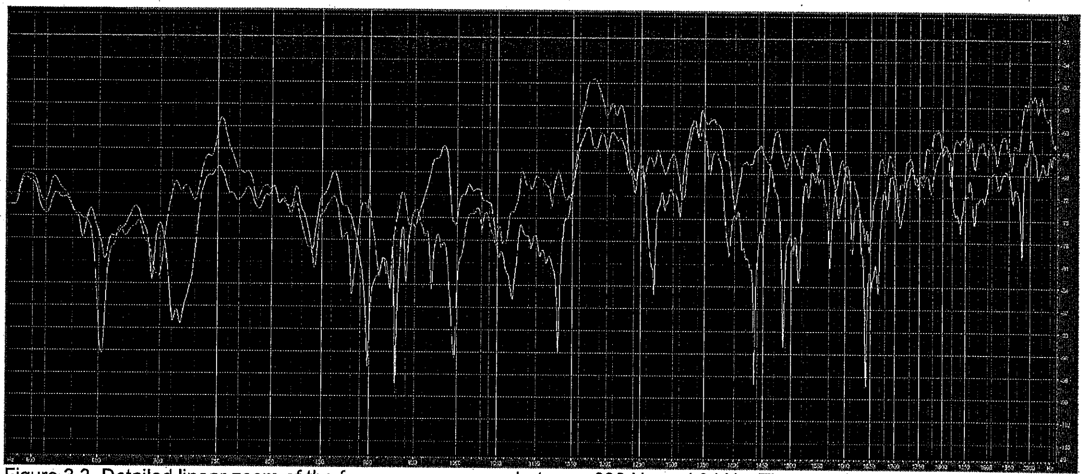

Figure 3.3. Detailed linear zoom of the frequency response between 600 Hz and 2 kHz. The position and amplitude of notches and peaks is a clear indication of a different mechano-acoustic behaviour between guitar A and B.

Summarising, the method was capable of clearly identifying differences in the acoustic signature of two "identical" instruments, as well as being able to suggest classification criteria of their performance.
Furthermore, the method was able to provide quantitative date to support subjective evaluation (and therefore marketing strategies) as well as relevant data that could be feed back to the R&D process.

3 DISCUSSION

There are several possible applications for the suggested measurement method, and this section describes two of them. In section 3.1 the application of the technique as an acoustic-based quality control test is presented, while in section 3.2 the possible use of the technique to monitor the production steps of newly manufacturer soundboards is given.

3.1 Acoustic-based quality control

As long as guitar manufacturers continue to produce their instruments using quality controls (QC) based on mechanical or geometrical tolerances, the intrinsic variation of the properties of wood (e.g. stiffness, density, etc.) will naturally affect the repeatability of any production run [3]. Furthermore, by relying solely on dimensional checks, the maximum performance of acoustic instruments would be difficult to reach and maintain without the risk of either high rejection rates (caused by mechanical instability) or mid-to-long-term customer's complaints, due to the slow but inevitable permanent deformation (creep) of materials [1,2,3].

While improved mechanical tests could be implemented to direct the building process towards a desirable performance [3], any large manufacturer who wanted to keep its actual processes unchanged and still be able to grade instruments according to their acoustic performance, could effectively use the presented method to perform a very quick and affordable final QC.

By setting up a simple test station in a relatively quiet area of their shop floor, or by dedicating a special room for this purpose, any guitar would require about one minute to be tested; this could in fact represent also added value to the customers, who could receive their instruments with an original frequency response and, in the following years, ask for a new measurement to be performed to assess how their instrument had evolved with time (eventually producing quantitative data to support subjective evaluations).

The results shown in section 2.5 indicate that the sine-sweep method would form the basis of an appropriate and reliable acoustic test for QC, which would be able to assess the variability in performance of musical instruments. This would enable manufacturers to set acoustic performance thresholds for instruments in order to minimise variations between individual 'identical' instruments.

3.2 Acoustic-based manufacturing process

Details of the traditional process steps to manufacture and tune a guitar soundboard could be found in literature [3, 4], but in this section we will try to depict an innovative manufacturing method, which can extensively rely on the acoustic measurement just introduced.

As starting point boards are prepared starting from thin resonant wood plates (usually spruce or cedar), which are cut in halves (to produce a symmetric grain pattern), glued and shaped according to the guitar body shape [1,2,3].

Afterwards, the board can be placed onto a guitar-body jig and firmly clamped; mark that at this point no braces are present yet, nor the bridge and, with it, the static strings tension, but the presence of the sound-hole is necessary. A "false-bridge" can be clamped to the board, and force can be exerted in such way to emulate a part or the whole strings tension. Inside the substitute of the bridge an exciter can be placed, thus giving us the chance to inject the sine-sweep in the un-braced plate.

This way an initial acoustic response can be gathered. Despite the fact that the absence of the braces probably compels the applied static tension to be smaller than the standard one, we can use this initial response to start evaluating the main coupled plate resonance $T(1,1)_2$, and, also very important, to get a quantitative figure of the static deflection and stiffness [3].

This step can already indicate whether, for example, the guitar top needs to be sanded down a to reach a mechanic-acoustic target, which had been fixed both in terms of static deflection and $T(1,1)_2$ resonance.
In fact, in an industrial context, computer controlled machines (CNC) could perform an automated etching process of the board when it still resides on the measuring jig, while a real-time acoustic performance feedback could be used to control the machine [12].
After this step is completed, the board now thinned to acoustic specifications can be removed from the jig; over-sized braces could be glued to the top, and, after the glue has cured, the tuning process (this time involving the shape and thickness of the braces) can start again. Starting from over-sized braces is important if their stiffness was not previously assessed, as suggested by Boven in his work [12].

By using a consistent measurement method, a plethora of different designs could be quickly investigated; the use of neural networks and machine learning could effectively be helpful to recreate a specific acoustic feature or signature with a desired level of accuracy.
Furthermore, this investigation suggested that this approach can be also applied to other parts of the acoustic guitar and, in fact, to almost any acoustic instruments.

4 CONCLUSIONS

In this paper an innovative use of the sine-sweep acoustic measurement method for the assessment of acoustic musical instrument was introduced and validated against the state of the art of impulse response retrieval techniques. The method was shown to produce comparable results to that of use of an impact hammer, while being low in cost.

Tests of multiple guitars demonstrated the lack of standardisation in performance of instruments manufactured to the same tolerances and theoretically identical. In particular, variation in the location of the coupled main air resonance was shown. It is proposed that this method is therefore appropriate for application in both quality controls of finished instruments and in the process control for manufacturing of acoustic guitars.

It is suggested that there are multiple other possible uses in the manufacture of other musical instruments and these will be investigated in detail in further studies by the authors.

5 ACKNOWLEDGEMENTS

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