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VIBRATION REPLICATION OF NATURAL GUITAR PLAYING BY INVERSE STRATEGY

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Abstract

Many musicians agree that extensive playing improves the sound quality of stringed instruments, such as violins and guitars. To find a scientific evidence of this effect, we consider applying a long-term vibration treatment to a test guitar, and here address the issue of developing a mechanical set-up using an electrodynamic shaker, in order to impart natural-playing vibrations to the instrument. From acceleration signals measured on the instrument during normal playing conditions, we solve the inverse problem of computing the drive signal to be sent to the shaker in order to reproduce the soundboard motion at the bridge. The identification procedure was implemented numerically, and then validated experimentally, providing useful voltage control signals and resulting in realiable replications of the prescribed motions. The proposed approach could benefit to other studies of stringed instruments, specifically when properly controlled playing-test conditions are required.

1 Introduction

The influence of long-term playing on the tone quality of string instruments has long been debated by musicians [1]. If the prevalent belief is that guitars and violins improve with regular playing, the phenomenon has not been clearly established in the scientific studies available so far. The question has however frequently been investigated from different points of view, vibrating instruments and wood samples, considering different mechanical excitations, and as final evaluation, using objective and subjective tests [2, 3, 4, 5, 6, 7]. If the phenomenon surely well depends on various factors, a likely justification could be that intense vibrations cause dynamical responses different from the original ones, possibly more satisfactory. It cannot however be ruled out that sufficiently large amplitude vibrations may also alter - reversibly or not -

the mechanical properties of the wood material, which is an organic, non-homogeneous and anisotropic material, particularly sensitive to several factors such as temperature and humidity, and for which any mechanical change affects the instrument response.
In search of scientific evidence on the effect of playing, we are currently designing a long-term experiment which aims at providing quantitative data on the phenomenon, specifically by tracking the modal parameters of a test guitar subjected to a vibration treatment. Rather than go through tests involving musicians, we consider developing a method to artificially vibrate the guitar according to natural playing conditions, using an electrodynamic shaker. In this work, we first address the inverse problem of computing the drive signal to be sent to the shaker in order to produce body accelerations that match with measurements acquired during playing and then, validate the method experimentally. An inherent difficulty of the problem is the inversion of the system transfer function, which can lead to very unstable inverse solutions [8]. To overcome ill-conditioning, we apply a regularization technique which is both simple to implement in the frequency domain and quite effective [9, 10]. The experimental implementation of the reproduction strategy shows that accurate signals of the body response at the bridge location can be achieved. Also, by simple replay, the technique offers a high degree of repeatability, and consequently, seems particularly adequate to be used in other studies of stringed instruments requiring properly controlled playing conditions.
In this paper, the first stages of this research project are presented, including the experimental modal analysis of the test guitar, the formulation of the inverse problem and its regularization and finally, the experimental implementation of the technique, for which original and reproduced acceleration signals are compared.

2 Experimental modal identification of the test guitar

The test guitar is a hand-crafted 8-string classical guitar, with a spruce soundboard, which has not been played for almost 20 years. For the measurement, the guitar was suspended in a vertical position by means of rubber bands fixed at the head, with all the strings damped but tuned to the notes C_5, D_5, E_4, A_4, D_3, G_3, B_2, E_2 (see Figure 1). Frequency response functions were measured by impact testing and estimates of the modal parameters, i.e modal frequencies, modal damping values and mode shapes, were extracted by a sophisticated modal identification algorithm. Light-weight accelerometers (B&K model 4375) were attached to the instrument body by means of a thin film of mounting wax to measure the vibratory guitar motion, two on the soundboard and one on the backplate. For the excitation, a miniature instrumented impact hammer (PCB model 086E80) was used. A mesh of 178 test locations was defined on the soundboard, and impacts were performed at all the point locations. Both inputs and response signals were recorded using a SigLab/Spectral Dynamics, at a sample rate of 5120 Hz.

Figure 1: Set-up for modal analysis of the guitar.

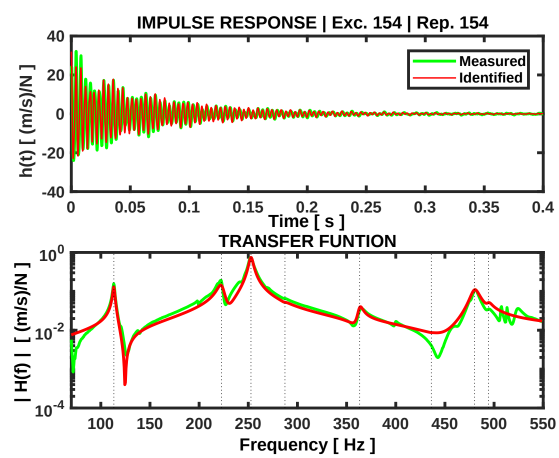


Figure 2: Measured (green) and reconstructed (red) impulse responses and transfer functions at the bridge. Dotted lines stands for the identified modes.

The modal identification was based on processing the force and acceleration time-domain signals. Computed the impulse responses in terms of velocity and force, the modal parameters were extracted using a parametric multi-degree-of-freedom technique called the Eigensystem Realization Algorithm (ERA) [12], which can support several reference channels. Based upon concepts of control theory, the idea behind ERA is to reconstruct the system responses from the experimental data using the minimum order of the state space formulation, which is obtained by SVD filtering of the zero-order Hankel matrix, built from the system outputs. In this work, the modal identification was carried out by considering three reference channels and the entire set of measured impulse responses. We used the first 0.4s of each impulse response, and limited our analysis within the frequency range 0-500 Hz. The model reduction was obtained by the analysis of a stabilization diagram built by repeating the identification process with an increasing number of modes each time. To show the reliability of the modal extraction technique, a typical impulse response and corresponding transfer function of the reduced-order model (using 8 modes) are compared with the measurement in Figure 2. Finally, Figure 3 shows the identified principal low-order modes of the guitar, with the values for the modal frequencies and modal damping values, together with the mode shapes. Despite the slight asymmetry in the instrument design, the body shapes, at least in the low-frequency range, are very similar to those described in previous investigations [14, 15], with modes involving motion either on the soundboard (modes 3 and 7) or the back plate (mode 4), or the coupled motion of the plates and the air inside the cavity (modes 1, 2, 5, 6 and 8).

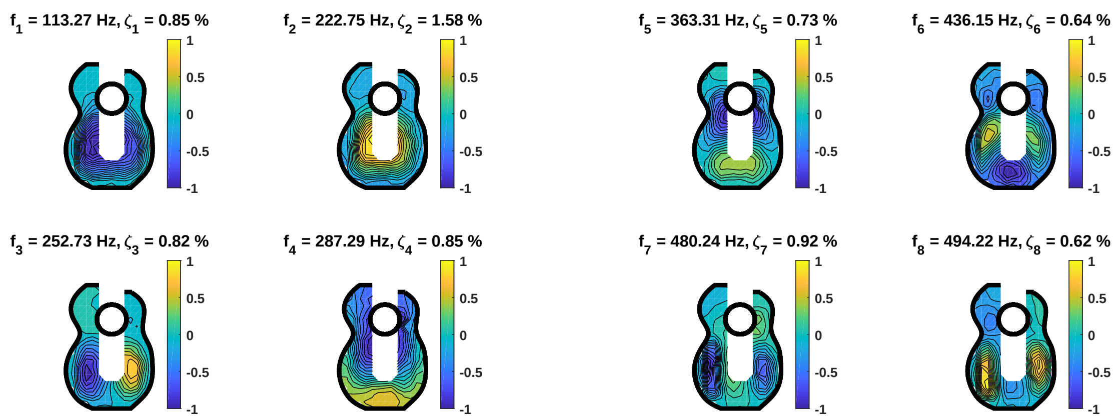
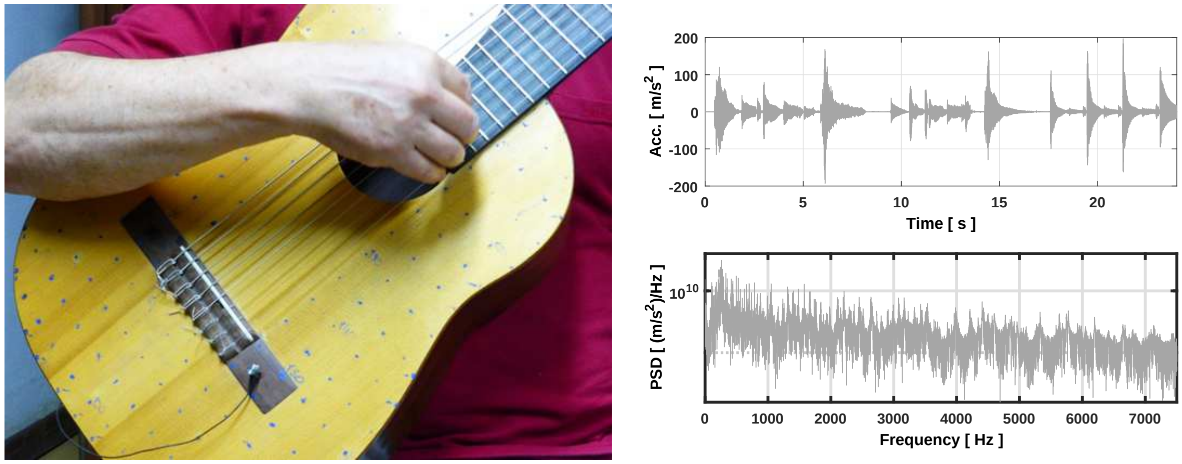


Figure 3: Modal frequencies, modal damping value and mode shape for the principal lower-order modes.

3 Live playing recording

Several short musical excerpts were played by one of the authors (P.V.C.) on the test instrument, and the vibratory responses were recorded by using a small accelerometer (B&K model 4375), mounted close to the bridge (see Figure 4a). Objective of the test was to provide some reference acceleration signals to be reproduced by the vibrating device, and built a data base for providing the instrument a vibration process having the same effect as normal playing. The musical excerpts were therefore intended to cover the frequency range and natural dynamics of the guitar. It included excerpts of the classical guitar repertoire such as the opening of *Asturias* by Issac Albéniz and *Grand Overture Op. 61* by Mauro Giuliani, as well as scales and other melodies played by plucking low-pitched to high-pitched strings, for different dynamic levels and including a variety of playing techniques (*apoyado*, *tirando*, vibrato, harmonics, etc...). Signals were recorded through the SigLab/Spectral Dynamics acquisition board, with a sampling frequency f_s=51200 Hz. Figure 4b shows a representative acceleration waveform of one recording, with its corresponding auto-spectrum.



(a) (b)

Figure 4: Live playing recording (a) and representative acceleration signal measured at the bridge (b).

4 Identification problem formulation and inverse problem regularization

An important issue when designing any vibration test is the choice of the excitation to be used to create a response in the test structure. This can include controlled force input as in laboratory modal test, or environmental or operational inputs as in seismic assessment of structures or transportation vibration. For simulating long-term playing artificially, a similar approach to vibration control is sought, in a way aiming at recreating the vibration undergone by the instrument from data recorded during playing. Technically, this requires to solve an inverse problem, where the specific issue is to compute the input signal of a shaker in order to produce an output that match a pre-recorded time-history response. The control problem is thus a problem of response deconvolution, when working in the time domain, or response inversion, by working in the frequency domain.

From a Fourier perspective, the problem of inversion is more pratical and remarkably straightforward. The basic identification procedure of the input voltage signal of the shaker $v(t)$ from the acceleration measured at the bridge $\ddot{x}(t)$ can be summarized as:

$$\ddot{x}(t) \quad \overset{FFT}{\Longrightarrow} \quad \ddot{X}(\omega) = H(\omega)V(\omega) \Longleftrightarrow V(\omega) = \frac{\ddot{X}(\omega)}{H(\omega)} \quad \overset{FFT^{-1}}{\Longrightarrow} \; v(t) \tag{1}$$

where $H(\omega)$ is the electromechanical transfer function of the global system, including the guitar. In practice, care must be taken when computing the inverse of the system transfer function, because $H(\omega)$ may include near-zero values at some frequencies. Such singularities make the inverse solution very unstable, and usually demand the use of regularization techniques for achieving useful solutions [8, 11].

In previous works concerned with the identification of nonlinear interaction forces [9, 10], the authors explored several regularization techniques, including Tikhonov inspired methods and SVD filtering. In the present paper, a simple and effective regularization of the transfer function is performed, using the so-called *water level regularization* [13]. The basic idea is to employ a filtered version of the transfer function before computing the inversion in Eq. (1). The so-called *regularized* transfer function is then defined as:

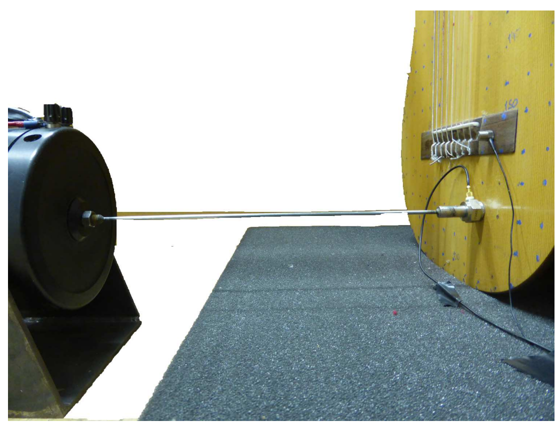
$$H_{REG}(\omega) = \begin{cases} H(\omega), & \text{if } |H(\omega)| > \varepsilon \\ \varepsilon H(\omega)/|H(\omega)|, & \text{if } |H(\omega)| \leq \varepsilon \end{cases} \tag{2}$$

where ε is the regularization parameter which acts as a lower boundary beyond which filtering of the inverse problem is enabled. To ensure stability and recover useful solutions, selecting an appropriate ε is of fundamental importance. To that end, several methods have been proposed, amongst others the widely used L-curve method [16], which seeks to balance the trade-off between fitting the data and the solution stability. Asssuming a set of values for ε and plotting on a log-log scale the norm of the residual $||H(\omega)V^{\star}(\omega) - \ddot{X}(\omega)||$ versus the norm of the solution $||V^{\star}(\omega)||$ (or its high-order derivatives), the optimal regularization parameter is expected to be near the corner of the curve, which corresponds to the point of maximum curvature.

5 Experimental set-up

Figure 5 shows the open loop control system developed for vibrating the tested guitar. An electrodynamic shaker (B&K model 4809) is connected to the guitar, close to the bridge, using a stinger and a piezoelectric force transducer (B&K model 8200), and a small accelerometer (B&K model 4375) is used to measure the bridge response, at the same location as during the recording session, on the bridge. A power amplifier (B&K model 2712) operates the shaker, and a National Instrument acquisition board (USB-4431) is used to generate the drive signal.
Before performing the identification, a swept sine test was conducted to measure the electromechanical transfer function of the system in accordance with Eq. (1). It is defined as the ratio between the soundboard response at the bridge (accelerometer signal) and the supply voltage, thus including the influence of all the system parts, i.e. the amplifier, the shaker, the guitar and the transducers. Results are plotted in Figure 6. If a near constant value would normally be expected for the amplifier/shaker system because of their rather flat frequency response in such operating frequency condition, one can observed in Figure 6 several resonances, which fall near the resonance frequencies of the guitar, and thus evidence the load of the guitar on the system and its interaction with the shaker.

(a)



(b)

Figure 5: Experimental set-up for vibrating the guitar. (a) Global view with the PC controler, the acquisision module, the amplifier and the shaker; (b) detail of the shaker mounting with the force transducer and accelerometer.

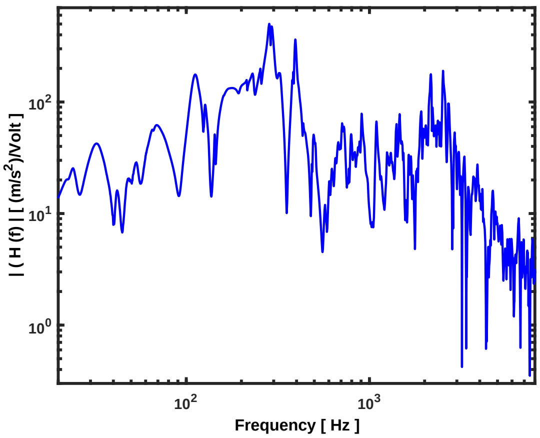


Figure 6: Electromachanical transfer function of the full experimental system.

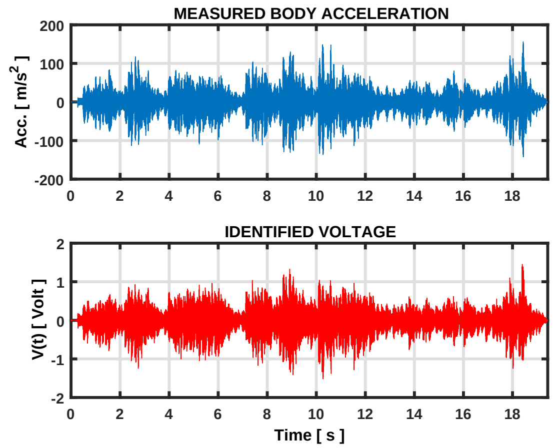


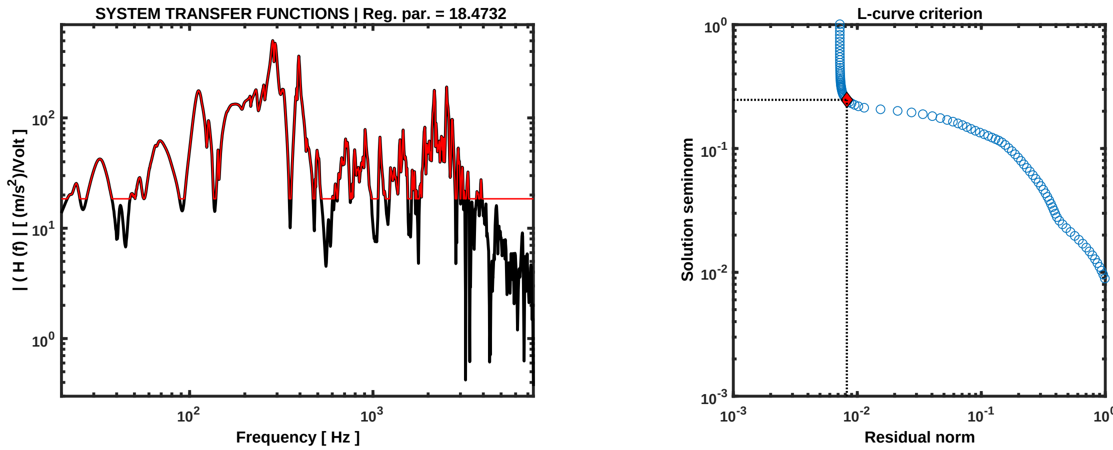
Figure 7: Measured acceleration and identified drive voltage. Opening of *Asturias*.

6 Experimental results

We now illustrate the procedure to compute the control voltage by considering the recording of the opening of *Asturias*. Figure 7 shows the acceleration signal measured during performance and the corresponding control voltage signal, computed by inversion. The comparison shows the underlying trend that the input acceleration and control voltage are very similar, but include differences of detail because of the variations of the frequency response of the experimental set-up with frequency. For illustration, Figures 8a shows the original and the regularized transfer functions, obtained for an optimal regularization parameter of $\varepsilon = 18.47$, which effectively lies at the corner of the L-curve plotted in Figure 8b.
Generating and sending the voltage signal to the shaker, the resulting acceleration signal measured at the bridge is shown in Figure 9, superimposed with the target acceleration measured during normal playing. As can be seen, there is an overall good agreement between the two signals, with respect to both amplitude and frequency content. The observed slight differences are the manifestation of the regularization process, which results in some kind of filtering. A measure of the difference between the original and reproduced accelerations can be given by the correlation coefficients, which is a measure of their linear dependance. For uncorrelated signals, the coefficient is zero while equivalent signals result in correlation coefficient of 1. For this example, a value of 0.86 has been calculated, thus confirming strong similarities between the original and reproduced signals.
In its present stage, the experimental implementation proves efficient for reproducing a large set of recorded acceleration signals. The technique surely benefits from using a measured version of the transfer function of the system, with a high signal-to-noise ratio (measurements were done using a slow sine sweep), which may limit the perverse effect of noise and modelling errors during the inversion.

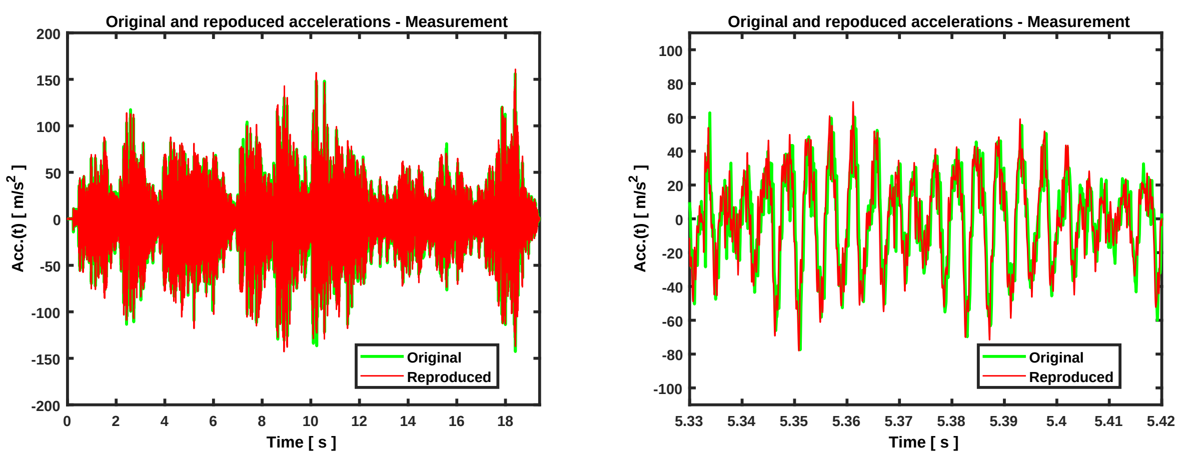
7 Conclusions

We developed a simple control strategy to vibrate artificially stringed instruments, which has the merit to achieve closely accurate reproductions of real vibratory response. Based on inverse techniques, we successfully computed the drive signal to be sent to a shaker in order to match a pre-recorded time-history vibratory response, and paid specific attention to the regularization of the electromechanical transfer function of our set-up. The experimental validation was then presented from accelerations signals recorded during normal playing, and results showed the reliability of the procedure. Interestingly, by simple replay of the drive signal, the developed technique offers a high degree of repeatibility which can benefit to studies of stringed instruments when properly controlled playing conditions are required. Using the data base of acceleration signals measured at the bridge in real playing conditions, we are currently imparting a long-term vibration



(a) (b)

Figure 8: (a) comparison of the original (black) and regularized (red) electromechanical transfer functions. (b) corresponding L-curve for a logarithmically distributed range of regularization parameter.



(a) (b)

Figure 9: Experimental results. Comparison of the target and measured acceleration. Global time history (a) and temporal zoom (b).

treatment to the test guitar in order to yield quantitative data on the effect of playing on the tone of stringed instruments.

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