Influence of the instrumentalist on the electric guitar vibratory behaviour

J.-L. Le Carrou[a], B. Chomette[b] and A. Paté[a]
[a]LAM/d'Alembert, UMR CNRS 7190, UPMC Univ. Paris 06, Sorbonne Universités, 11, rue de Lourmel, 75015 Paris, France
[b]MPIA/d'Alembert, UMR CNRS 7190, UPMC Univ. Paris 06, Sorbonne Universités, 4 place Jussieu, 75005 Paris, France
jean-loic.le_carrou@upmc.fr

The sound of the electric guitar is based on the conversion of the string vibration into an electrical signal. The string vibration may be affected by couplings with the body, mostly when there is a frequency coincidence between the modes of each sub-structure (strings and body). These kinds of coupling are generally analysed in experimental conditions far from playing conditions. The aim of this paper is therefore to quantify the influence of the guitarist on the guitar vibratory behaviour. Particular modes of the guitar's structure are therefore studied for different classic instrumentalist positions. The modal frequencies and dampings of the instrument are identified using an operational modal analysis. This method, based on the natural excitation technique using the analysis of inter-correlation functions of different sensors measuring at the same time the instrument vibration, is adapted to take into account the string as a particular excitation of the body. Experimentations are therefore performed while playing. The influence of the left hand holding the guitar neck, of the fingers pressing the string against the fingerboard, and of the right hand and the stomach touching the body are then quantified in terms of body modal parameters.

1 Introduction

The sound of the electric guitar is based on the conversion of the string vibration into an electrical signal. The string vibration may be affected by couplings with the body, mostly when there is a frequency coincidence between the modes of each sub-structure (strings and body) [1]. It was notably shown that, for the electric guitar, this coupling is mainly located at the neck. However, in the classic way of playing of this instrument, the left hand holds the neck and the finger presses behind the fret the string against the fingerboard [2]. Thus, this left hand may have consequences on the neck vibrations. Similarly, the instrumentalist stomach and thighs touch the instrument's body and may also modify the global body vibration. This playing situation is not classically taken into account for most of mechanical or vibratory studies of musical instruments [3]. Indeed, it is easier to compare experimental results to theoretical or modelling ones when the instrument's boundary conditions are well understood [4]. However Fleischer and Zwicker performed vibratory measurements on electric guitars with a player sitting on a chair with the guitar was resting on his right thigh. His left hand held the neck near the location where the conductance was determined. Measurements were done with a shaker with an impedance head directly fixed on the neck [5, 6]. Although the instrumentalist's effect is included in their conductance measurements, they can not quantify his damping contribution. In another study, Fleischer compares two modal analyses of the same electric bass guitar: laid on a stand, or resting on instrumentalist's thigh [7]. Due to the damping by the body and the arms of the player, the amplitudes of the bass vibrations are principally not as large as those measured in the guitar stand. In detail, global modes are the most affected by the instrumentalist. But the influence of the instrumentalist is not once again quantified in terms of additional damping. These studies show that this kind of measurements (shaker fixed on the neck with a player holding the guitar) can not be set up to analyse a large set of instruments, or to carry out studies with non-invasive constraints. Therefore, it could be interesting to quantify the instrumentalist's influence on the modes, in order to complete the results obtained for other boundary conditions. In order to identify the modal parameters of instruments in playing condition, an operational modal method can be used, as recently done on the concert harp [8]. By using the harmonic excitation of the strings, modal frequencies and damping may be obtained by using a modified Least Square Complex method (mLSCE) [9, 10].

The aim of the study is therefore to quantify the player's effect on the electric guitar modes. In Section 2, the operational modal analysis is presented, particularly the modified LSCE method. Then, the experimental setup is described with the instrumentalist configurations in section 3 and finally results in terms of modal parameters of the electric guitar coupled to the instrumentalist are given in section 4.

2 Operational Modal Analysis

In order to identify modes on the electric guitar in playing condition, a recent method is used: the operational modal analysis and in particular the Modified Least Square Complex Exponential algorithm (mLSCE) [8, 9, 10]. Modal parameters may be obtained with the vibratory responses of the instrument only. This is explained in this section.

2.1 Natural Excitation Technique (NExT)

The modified LSCE method (mLSCE) is based on the NExT technique [11] which makes the assumption that the inter-correlation functions $R_{ij}(t)$ between the vibratory signals i and j for each instant t is similar to the vibratory response of the structure at i due to an impulse excitation at j:

$$\begin{aligned} R_{ij}(t) &= \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} q_i(\tau) q_j(\tau - t) dt \\ &= \sum_{r=1}^{N} \frac{\phi_{ri} A_{rj}}{m_r \omega_r^d} \sin\left(\omega_r^d t + \theta_r\right) e^{-\xi_r \omega_r^n t}, \end{aligned} \qquad (1)$$

where ϕ_{ri} is the ith component of the rth eigenmode, A_{rj} is a constant associated to the jth vibratory signal, m_r is the rth modal mass, ω_r and ξ_r are the rth eigen-pulsation and modal damping respectively, ω_r^d is the rth damped pulsation, θ_r is the phase associated to the rth component and N the order of the mathematical model associated to the mechanical system. Eventually, the inter-correlation functions between different vibratory signals measured on the structure simply corresponds to the sum of damped oscillations having damping coefficients and frequencies equal to the modal parameters of the structure.

2.2 mLSCE method

Equation (1) clearly shows that modal identification techniques in the time domain can be applied. Thus, the

Least Square Complex Exponential method seems to be particularly well adapted.

The inter-correlation function R_{ij} can be written in terms of complex modes Ψ_{ri} of the structure with the sampling period Δt

$$R_{ij}(k\Delta t) = \sum_{r=1}^{N} \Psi_{ri} C_{rj} e^{s_r k\Delta t} + \sum_{r=1}^{N} \Psi_{ri}^{*} C_{rj}^{*} e^{s_r k\Delta t}, \qquad (2)$$

where

$$s_r = -\xi\omega_r \pm \jmath\omega_r \sqrt{1-\xi_r^2} \qquad (3)$$

are the complex poles of the system and C_{rj} a constant associated with the rth mode for the jth vibratory signal chosen as a reference. $*$ denotes the complex conjugate. Due to the complex form of the poles, the $e^{s_r k\Delta t}$ are the roots of a $2N$ polynomial equation named Prony's polynomial equation:

$$\beta_0 + \beta_1 V_r^1 + \cdots + \beta_{2N-1} V_r^{2N-1} + V_r^{2N} = 0 \qquad (4)$$

where $V_r = e^{s_r \Delta t}$. The poles are finally obtained by using

$$s_r = \frac{1}{\Delta t}\left[|V_r| \pm \jmath arg(V_r)\right]. \qquad (5)$$

The mLSCE [9] includes the harmonic components of known pulsation Ω of the string harmonics as being virtual modes having zero damping whose poles can be written

$$s_r^{\Omega} = \pm \jmath\Omega, \qquad (6)$$

and the Prony's polynomial equation has two complex conjugate extra roots

$$V_r^{\Omega} = e^{s_r^{\Omega}\Delta t}. \qquad (7)$$

In the case of $L > 2N$ time instances, m harmonic components and p sensors, the Prony's equation can be written in symbolic form including the harmonic excitations Ω_1 to Ω_m as follows

$$\begin{cases} \mathbf{A}\ \mathbf{b}_1 + \mathbf{C}\ \mathbf{b}_2 = \mathbf{E} \\ \mathbf{B}\ \mathbf{b}_1 + \mathbf{D}\ \mathbf{b}_2 = \mathbf{F} \end{cases}, \qquad (8)$$

where $\mathbf{A}$ is a $(L \times 2m)$ matrix, $\mathbf{b}_1$ a $(2m \times 1)$ vector, $\mathbf{C}$ a $(L \times 2N - 2m)$ matrix, $\mathbf{E}$ a $(L \times 1)$ vector, $\mathbf{B}$ a $(2m \times 2m)$ matrix, $\mathbf{D}$ a $(2m \times 2N - 2m)$ matrix and $\mathbf{F}$ a $(2m \times 1)$ vector. $\mathbf{A}$ and $\mathbf{B}$ are defined as follows:

$$\mathbf{A} = \begin{bmatrix} R_0^1 & \dots & R_{2m-1}^1 \\ \vdots & & \vdots \\ R_{L-1}^1 & \dots & R_{L+2m-2}^1 \\ \vdots & & \vdots \\ R_0^p & \dots & R_{2m-1}^p \\ \vdots & & \vdots \\ R_{L-1}^p & \dots & R_{L+2m-2}^p \end{bmatrix} \mathbf{B} = \begin{bmatrix} 0 & \dots & sin(\Omega_1 (2m-1)\Delta t) \\ 1 & \dots & cos(\Omega_1 (2m-1)\Delta t) \\ \vdots & & \vdots \\ 0 & \dots & sin(\Omega_m (2m-1)\Delta t) \\ 1 & \dots & cos(\Omega_m (2m-1)\Delta t) \end{bmatrix}, \qquad (9)$$

and $\mathbf{C}$ and $\mathbf{D}$ as

$$\mathbf{C} = \begin{bmatrix} R_{2m}^1 & \dots & R_{2N-1}^1 \\ \vdots & & \vdots \\ R_{L+2m-1}^1 & \dots & R_{L+2N-2}^1 \\ \vdots & & \vdots \\ R_{2m}^p & \dots & R_{2N-1}^p \\ \vdots & & \vdots \\ R_{L+2m-1}^p & \dots & R_{L+2N-2}^p \end{bmatrix}$$

$$\mathbf{D} = \begin{bmatrix} sin(\Omega_1 2m\Delta t) & \dots & sin(\Omega_1 (2N-1)\Delta t) \\ cos(\Omega_1 2m\Delta t) & \dots & cos(\Omega_1 (2N-1)\Delta t) \\ \vdots & & \vdots \\ sin(\Omega_m 2m\Delta t) & \dots & sin(\Omega_m (2N-1)\Delta t) \\ cos(\Omega_m 2m\Delta t) & \dots & cos(\Omega_m (2N-1)\Delta t) \end{bmatrix} \qquad (10)$$

The vectors $\mathbf{b}_1$, $\mathbf{b}_2$, $\mathbf{E}$ and $\mathbf{F}$ are defined as follows

$$\mathbf{b}_1 = \begin{bmatrix} \beta_0 \\ \vdots \\ \beta_{2m-1} \end{bmatrix}, \mathbf{b}_2 = \begin{bmatrix} \beta_{2m} \\ \vdots \\ \beta_{2N-1} \end{bmatrix}, \mathbf{E} = \begin{bmatrix} R_{2N} \\ \vdots \\ R_{L+2N-1} \end{bmatrix},$$

$$\mathbf{F} = \begin{bmatrix} sin(\Omega_1 2N\Delta t) \\ cos(\Omega_1 2N\Delta t) \\ \vdots \\ sin(\Omega_m 2N\Delta t) \\ cos(\Omega_m 2N\Delta t) \end{bmatrix} \qquad (11)$$

$\mathbf{b}_1$ can be computed with the first line of equation (8) using $\mathbf{b}_2$, and $\mathbf{b}_2$ is finally obtained from the second line of equation (8) as a least-square solution.

2.3 Stabilisation diagram

As shown in equation (8), the modal identification is clearly dependent on the order N of the mathematical model. Thus, the stabilisation diagram is generally used to select physical poles of the model. In this diagram, the evolution of the order allows to identify stable poles, through convergence criteria in frequency and in damping. These poles are then selected and defined as results of the modal identification. In this paper, stable poles have variations smaller than 1% in frequency and smaller than 20% in damping.

3 Experimental setup

In order to investigate the influence of the instrumentalist on the electric guitar vibratory behaviour, the modal analysis of the instrument is performed when the instrument is played by using the method previously explained. Two classic playing configurations are studied in this experiment: when the instrumentalist is sitting or when he is standing, as shown in figure 1.

Previous studies [1, 4] showed that the main element affecting the string vibration of an electric guitar is the neck. In consequence, we chose to investigate its modal behaviour. Thus, nine accelerometers are glued on the neck: eight are fixed, four on each side, and one is roving on the symmetrical axis close to the played fret as shown in Figure 1. This latter accelerometer provides the reference signal (see section 2.2).

Figure 1: Experimental configurations: A sitting musician; B standing musician

In order to compare results in playing situation to those in free boundary conditions, a classic modal analysis is also performed where the electric guitar is laid on elastic straps supported by a frame. For the modal identification, the Least Square Complex Frequency (LCSF) algorithm, implemented in the Modan Software [12] developed at the Femto-st Institut, is used.

The instrumentalist is asked to play several notes along the D3-string (fundamental frequency for the open string 146,82 Hz). The left-hand middle finger presses the string against the fingerboard successively at the nut (denoted F0), the frets 2 (E3), 4 (F#3), 6 (G#3), 10 (C4), 14 (E4) and 16 (F#4, fundamental frequency 369,9 Hz). Other strings are blocked with the other fingers of the left-hand (this is a common practice for guitar players).

4 Results

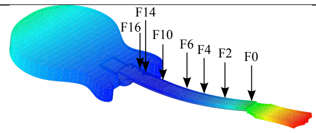
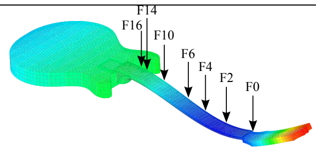
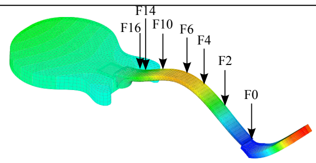
Table 1 gathers the modal parameters of the first three bending modes of the electric guitar obtained by the classical modal analysis. Results are found to be very close to those already obtained for a similar guitar [1]. In order to have a good overview of the mode shapes, it was chosen to show those computed with a finite-element model [13]. The location of each pressed fret can be shown for each mode (see table 1).

In figure 2 the modal parameters are shown for the three first modes, identified by the operational modal analysis, for the two playing configurations (sitting or standing) and for the seven notes. The first mode is a global bending motion like a free-free beam. The second and the third modes correspond to a classic quasi-clamped-free beam: the mode shape is localised on the neck.

In figure 2, the relative deviation between modal frequencies with or without instrumentalist is found to be between 1% (mode 3) to 7% (mode 1). This deviation is in the same order of magnitude of the inherent error of the identification method, as already found in [8]. Modal frequencies obtained in playing situation are not consistently found below or above the modal frequencies in free boundary conditions. These results suggest that this deviation is more due to the identification algorithm than to the instrumentalist.

On the contrary, the modal damping evolution with the note played (pressed fret) seems to exhibit a systematic

Table 1: Electric guitar's modes. Modal frequencies and dampings are obtained by the classic modal analysis. Mode shapes come from a finite-element model [13]. F_i denotes the approximative location of each fret i

N°	Mode shapes	Modal freq. [Hz]	Modal damp. [%]
1		56.3	1.3
2		169.1	2
3		370.8	1.5

behaviour, see figure 2. Indeed, this evolution is found to be directly linked to the modal shape shown in table 1: the wider the mode shape displacement is, the higher the damping is. This can be explained by the fact that the instrumentalist left hand behaves as a localised dashpot. The modal damping is all the more affected so this dashpot is localised close to the anti-node of the mode shape. When the instrumentalist left hand is close to a node of the mode shape, the modal damping is little affected as shown for mode 2, frets 10 to 16, or for mode 3, between fret 2 and 4. Neck modal dampings are modified by the finger and hand pressing the fingerboard, only if the modal displacement is large enough at the fretting point. This is particularly true for the modes 2 and 3 where only the neck vibrates. For the mode 1, the body has a significant displacement. Therefore, for this mode, the stomach touching the body also acts as a dashpot. That is why, for mode 1, the modal damping in playing configuration is found to be always above the modal damping without instrumentalist (classic modal analysis) at about 5% for F0 (close to the mode node). Note that for a sitting configuration, the thigh also touches the guitar's body (see Figure 1-B) and then increases the damping for this mode.

5 Conclusion

In this paper, a novel technique for modal identification in playing configuration is successfully used. Modes of the electric guitar in different configurations are studied. It is shown that for the first three bending modes, structural damping is found to be increased by up to 15% for fretting cases at anti-nodes. Instrumentalist's stomach and thigh increase the modal damping by 5% for the first bending mode. Note that no significant modal frequency modifications are found with our experiment.

These results are particularly interesting for the interpretation of the conductance curves of electric guitar in free boundary conditions. Future works will include the investigation of other modes, and the modelling of the body

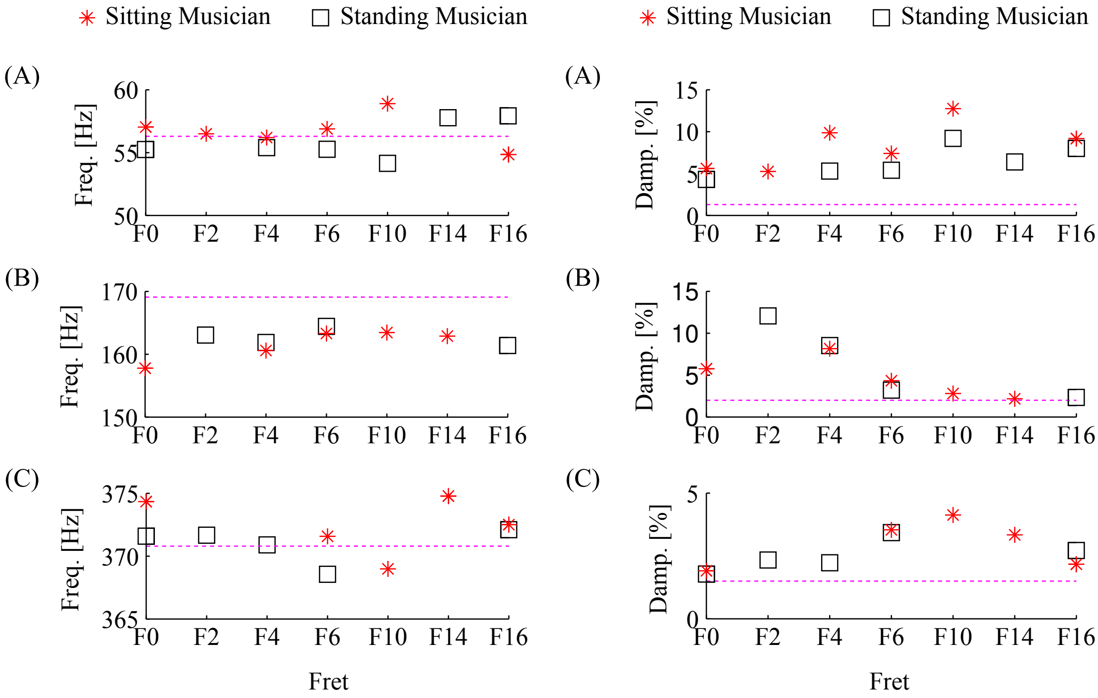


Figure 2: For each configuration, the modal parameters are identified for different played notes: at frets 2, 4, 6, 10, 14, 16 and at the nut. The dashed lines correspond to the modal parameters obtained in free boundary configuration by the classical modal analysis. Three bending modes are shown: A-Mode 1, B-Mode 2, C-Mode 3

(fingers, hand, stomach and thigh) of the guitar player.

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