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Operational modal analysis applied to the concert harp

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ABSTRACT

Operational modal analysis (OMA) methods are useful to extract modal parameters of operating systems. These methods seem to be particularly interesting to investigate the modal basis of string instruments during operation to avoid certain disadvantages due to conventional methods. However, the excitation in the case of string instruments is not optimal for OMA due to the presence of damped harmonic components and low noise in the disturbance signal. Therefore, the present study investigates the least-square complex exponential (LSCE) and the modified least-square complex exponential methods in the case of a string instrument to identify modal parameters of the instrument when it is played. The efficiency of the approach is experimentally demonstrated on a concert harp excited by some of its strings and the two methods are compared to a conventional modal analysis. The results show that OMA allows us to identify modes particularly present in the instrument's response with a good estimation especially if they are close to the excitation frequency with the modified LSCE method.

1. Introduction

Acoustic musical instruments are designed to amplify vibrations produced by an oscillator. At low frequencies, this amplification is mostly governed, for string instruments, by the structural modes of the soundboard. These modes are thus characteristic for each instrument and are often discussed to understand the operation of the instruments [1,2], for comparing instruments [3–7] or to synthesise the sound [8,9]. Classical methods are generally used to obtain structural modes: the instrument is either impacted by a hammer or excited by a shaker. These excitation methods can induce some experimental problems, such as gluing a force sensor on the soundboard or causing damage to the instrument with the hammer. An other solution is to use the instrument excitation system that is to say its strings. Therefore, the end goal is to develop a method to be used when the instrument is being played, and this paper focuses on identifying modal parameters by using recent methods such as operational modal analysis (OMA).

OMA has been extensively developed in the past decades particularly when the input of structures is unknown or difficult to measure in their ambient environments. For example, Brincker et al. [10] use a decomposition technique in a set of single degree of freedom systems to accurately identify close modes without knowing the input exciting the system. De Vivo [11] applies OMA in order to identify the modal shapes of a large structure exposed to wind excitation. Xu [12] uses OMA using non-contact excitations and sensors. Agneni et al. [13] devote a special attention to the case of structures with

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closely spaced coupled modes and propose also the use of the power spectra densities [14] to estimate modal parameters in the frequency domain and calculate the correlation function in the time domain. Peeters and de Roeck [15] propose an approach based on stochastic subspace identification in order to avoid correlation function calculation. Numerous time domain OMA can be based on the natural excitation technique (NExT) [16–18] which is conventionally used to identify modal parameters using ambient vibrations. Brincker et al. [19] propose a method to compute the cross correlation and the auto correlation function to identify modal parameters. For example, Shen and Zheng [20] experimentally use the cross-correlation technique to extract modal parameters on the response-only data in the case of an airplane model. In the NExT technique, the main assumption of the input excitation is that the excitation must be assimilated to a stationary white-noise. That is why OMA cannot be applied in theory in the case of structures characterised by the presence of harmonic excitation. In this particular case, other methods can be applied. Brincker et al. [21] propose an indicator to separate structural and harmonic modes. Harmonic components can be removed from the response or taken into account in the procedure. Manzato [22] and Agneni [23] propose to remove harmonics to improve the OMA. Mohanty and Rixen propose some new algorithms to avoid perturbations due to filters and to have a more efficient and robust procedure. These new methods are based on the least square complex exponential (LSCE) method [24,25], on the eigensystem realization algorithm (ERA) method [26] or on the single station time domain (SSTD) method [27] in order to apply OMA in the case of a disturbance including harmonic components particularly for rotating machines. These methods consider that the harmonic frequencies are close to the eigenfrequencies of the structure and include no-damped harmonic components in the identification procedure. Therefore, these methods seem particularly appropriated to identify eigenfrequencies of string instruments in low-frequencies. Indeed, instrument makers design musical instruments so that the soundboard's eigenfrequencies are close to the excitation frequencies of the string and the anti-node's locations match the strings attachment position to radiate the sound. This is particularly the case for plucked string instruments such as the guitar [28] or the harp [29,30].

This paper deals with the application of OMA methods in order to identify the modal parameters of a concert harp. This musical instrument is particularly suitable for a first practical test because the instrumentalist does not affect the structural vibration of the harp when it is played unlike some other instruments. With a classical guitar for instance, the comparison of the modal basis obtained with OMA and with a classical modal analysis method would not be possible since the instrumentalist body and arms can affect the instrument modal parameters, especially the modal damping. Therefore, in order to study the efficiency of the method, the modal basis identification of the concert harp's soundboard should be more suitable. For this instrument, the high damping values and the close modal frequencies lead to use a time domain OMA method. Moreover, it is difficult to measure the input of the instrument in playing conditions and harmonic excitations due to strings are present in the disturbance. Consequently the classical modal operational procedures can fail in the identification of modal parameters. The novelty of this study is to apply OMA on a structure with damped harmonic excitations containing low noise level. After a brief presentation of the method, the efficiency of the approach is experimentally demonstrated on a concert harp excited with different strings of different frequencies.

2. Identification algorithm

In this section, the different steps of the implementation of the LSCE and the modified LSCE are detailed. The objective is to identify modal parameters of the harp when the instrumentalist is playing.

2.1. LSCE algorithm

First, data are measured when the strings are played one after another. Consequently, a single reference can be used for each identification corresponding to each string excitation. A more complete description can be found in [16,24,25]. These two algorithms use the Prony method [31]. In the case of a white noise excitation, the correlation function R_{ij} between the signal measured at i and a reference at j is similar to the response at i of a system submitted to an impulse excitation applied at j, as shown in the NExT method [16]. In the case of a string excitation, the structure response is the sum of the solution of the homogeneous equation and the particular solution corresponding to the damped forced response due to the harmonic components of the string excitation. In the transient state, the response of the structure includes almost all the structural modes (of which the nodes are not close to the played string attachment point) and the string modes. That is why the structure response in transient state can be assimilated to the response at i of a system submitted to an impulse excitation applied at j. In this section, R_{ij} denotes the correlation function or the structure response. This assumption can be written as follows using a sampling step Δt

$$R_{ij}(k\Delta t) = \sum_{r=1}^{2N} C'_{rij} e^{s_r k\Delta t}, \tag{1}$$

where s_r denotes the complex poles of the system and C'_{rij} is the constant associated to the rth mode. This assumption is particularly verified for a structure excited by a string in free oscillations. Indeed, each decaying sinusoid is related to a structural or a string mode. Due to the conjugate complex form of the poles

$$V_r = e^{s_r k\Delta t} \tag{2}$$