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A method for an accurate estimation of natural frequencies using swept-sine acoustic excitation

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ABSTRACT

Early detection of cracks in engineering structures by vibration-based methods requires monitoring systems that can evaluate natural frequencies with high accuracy. This paper introduces a method for estimating the natural frequencies using features extracted from the vibrational response of structures excited to cross through the resonance. To this aim, an open-loop acoustic system able to ensure bidirectional excitation, in swept-sine or short-time mode, with controllable parameters was developed. Analyzing the structural response at the crossing area through the resonance, two particularities on which the method is based have been revealed. The first refers to the symmetry of the frequency shift at peak amplitude from the natural frequency, if positive and negative sweep rates are applied. Therefore, the natural frequency can be found as the average of the frequency values at the resonance. Also, the necessary time to achieve the peak amplitude after passing through the natural frequency is similar, irrespective to the sign of the sweep rate. This accomplishment allows finding the natural frequency from a graphical representation. Frequency estimation made for a test structure by employing the two procedures lead to convergent results. Comparing these results to those achieved by impulsive excitation, a better precision was remarked at the swept-sine excitation. With regard the simplicity, rapidity and stability of the method, the swept-sine excitation has been proved as the most effective.

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1. Introduction

In the last decades, the study of the dynamic behavior of structures had become a major concern of mechanical, civil and aerospace engineers. To better understand the dynamic behavior, it is essential to know the modal parameters of the structure, i.e. its natural frequencies, mode shapes and damping ratios. The precise identification of these parameters can be made through the use of robust and reliable methods that belong to the field of research known as *modal analysis*. The applications of modal analysis, which is doubtless the main approach to performing system identification [1], cover a broad range of objectives, as observation of structural modification, structural integrity assessment and damage detection, model updating, etc. [2].

The modal parameters can be found from the measurements made on the structure [3]. Two approaches are possible to perform the experimental modal analysis. If the responses are measured during operation and the modal parameters are

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found assuming unknown excitations, we refer to operational modal analysis. A second option is to excite the out-of-operation structure in a more or less controlled manner. This method, also known as modal testing, provides more accurate information [4].

Procedures to perform modal analysis are widely discussed in Refs. [2,4–7], while the basic experimental equipment used in the vibration tests is analyzed in detail in Ref. [8]. A comprehensive presentation of vibration measuring techniques, concerning both instrumentation and signal analyzing aspects, is also available in the literature [9–11]. The four phases of modal testing, namely the test planning, the measurement, the analysis and the modeling, are described in Ref. [12].

Among excitation techniques, those based on impulsive forces are widely used because of their simplicity and low costs. By using those methods, a broadband excitation is produced, but the amplitudes of higher-order natural frequencies decrease rapidly [13]. Moreover, the poor signal-to-noise ratio (SNR) and repeatability limit the precision of the method. Guidelines to improve impact testing results are given for instance in Refs. [14,15].

Sine excitation ensures the repeatability of tests and is mainly used to plot the frequency response function (FRF). Since the steady state has to be achieved for each programmed excitation frequency, the method is time-consuming [16]. For multiple-degree of freedom systems, each frequency of interest has to be analyzed separately. A method to perform just one measurement per mode, possible by sweeping the stepped sine excitation around the sought frequency, is introduced in Ref. [17]. In this way, the time needed for the experiment is shortened. Another time-saving method is based on the recursive estimation of the FRF value at a given excitation frequency [18]. A simple alternative is to analyze the responses in the time domain and identify the excitation sine for which the envelope of the response best indicates resonance [19].

An overview of the most common random excitations, such as pure random, periodic random, burst random, is given in Refs. [20,21]. The latter one also proposes an excitation technique as a combination of cyclic averaging and burst random excitation. All random excitation methods were found to be relatively fast and permitting a good system approximation.

The swept-sine excitation is a good compromise between high energy input and short test duration, especially for large structures [22]. Sweeping of sinusoids can be made in a linear or logarithmic manner, depending on the rule under which the excitation frequency changes. The speed at which the frequency range is traversed, namely the sweep rate, influences essentially the structural dynamic response. For a very low sweep rate, the envelope of the response in the time domain has a shape that is quite similar to the curve representing the steady-state response amplitude versus excitation frequency [23]. If the sweep rate is not sufficiently low, the envelope is distorted. Besides the maximum amplitude decrease, the peak width increases and the loss of symmetry is observed. Furthermore, the excitation frequency at which the maximum amplitude is obtained differs from the natural frequency of the structure [24]. It is higher than the natural frequency if the excitation frequency increases and is lower if the excitation frequency decreases. Envelopes, constructed from a locus of extrema taken from time-history of the non-stationary response to a swept-sine excitation, are presented in Ref. [25] for a linear sweep and in Ref. [26] for a logarithmic sweep. An overview of the most important causes of beating in sine testing, with a particular emphasis on beatings caused by the swept-sine excitation, is presented in Ref. [27]. Since this method is the basis of the frequency estimation algorithm proposed in this paper, a detailed description of the phenomena is largely described in Section 2.

Although acoustic excitation is used in modal testing, it has not become a common approach, in spite of several advantages [28]. This non-contact excitation is proper for light structures and permits controlling the frequency range in which the energy is transferred to the structure. If the response signal is analyzed in the frequency domain, a mode-by-mode frequency evaluation is possible even for continuous structures, because the resonance peaks are visible [29]. The controlled energy transfer improves this approach by reducing the effect of noise.

In previous research, the authors have developed a method to detect transversal cracks in isotropic and composite beams [30–33], which is based on the natural frequency changes. Detecting the damage in incipient state requests an accurate evaluation of the natural frequencies for several bending vibration modes. An algorithm to post-process the signal and precisely evaluate the natural frequencies was also contrived by the authors [34,35]. It allows finding the frequencies with a precision of millihertz. Using this algorithm, we found that frequencies from vibration signals of real structures show small variations, depending on the applied excitation and the portion of signal extracted for analysis. Therefore, there is a need to find an appropriate excitation method and identify the most suited signal portion to be analyzed.

In the present paper, a frequency evaluation method considering the responses of the structure to swept-sine excitations, for both increasing and decreasing sweep directions, is introduced and its ability to extract precisely the natural frequencies is assessed. To this end, experiments are performed considering a cantilever beam. Acoustic excitation is employed, because it has the advantage of transmitting the forces without the need for contact with the structure, so no alteration is brought to its dynamic behavior. In addition, the frequency and amplitude of the excitation forces are well controllable. The results are compared with those attained from the free beam vibration, where two excitation techniques are involved: hitting the test structure with an impact hammer and applying a short-time harmonic sound pressure.

This paper is organized as follows. In the next section, the phenomenological aspects regarding the transition through resonance of beam-like structures are discussed and a methodology for natural frequency estimation based on this phenomenon is described. A simple algorithm for precise frequency extraction from short signals, involved in the methodology, is also mentioned here. The experimental set-up, designed to allow a versatile acoustical sweep sine excitation, is presented in Section 3. In Section 4, the way how the methodology is applied to a test structure is comprehensively described. Finally, the results are compared with those achieved from tests that use impulsive excitation and the improved frequency readability demonstrated.

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