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DETERMINATION OF DYNAMIC STIFFNESS OF MATERIALS USED UNDER FLOATING FLOORS USING ELECTRODYNAMIC ACTUATORS

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ABSTRACT

Dynamic stiffness is a parameter of great importance in materials used under floating floors because it determines the sound insulation of such floors in dwellings. ISO 9052-1 is commonly used to determine this parameter from the frequency of free oscillation of a mass-spring system composed of a loading slab of steel and a sample of the material under test. In the test method described in that standard, a vibration sensor and either an impact excitation or an attached vibration exciter that emits a white noise signal are used. This work proposes an alternative approach for determining dynamic stiffness using an electrodynamic actuator both as the vibration sensor and the exciter. To this end, the electrical impedance frequency response of the actuator coupled to the mass-spring system is measured, being the dynamic stiffness retrieved using basic circuit analysis theory. Results show a good agreement when compared to those obtained using the standard for different test materials, thus encouraging its use for acoustic characterization purposes.

RESUMEN

La rigidez dinámica es un parámetro de gran importancia en los materiales utilizados en suelos flotantes porque determina el aislamiento acústico de los mismos en las viviendas. La normativa ISO 9052-1 se usa comúnmente para determinar este parámetro a partir de la frecuencia de oscilación libre de un sistema masa-resorte compuesto por una losa de carga de acero y una muestra del material bajo ensayo. En el método descrito en esa norma se utilizan un sensor de vibración y un martillo de impactos o un excitador de vibraciones que emite una señal de ruido blanco. Este trabajo propone un enfoque alternativo para determinar la rigidez dinámica utilizando un actuador electrodinámico tanto como sensor de vibración como excitador. Para ello, se mide la respuesta en frecuencia de la impedancia eléctrica del actuador acoplado al sistema masa-resorte, obteniéndose la rigidez dinámica utilizando la teoría básica de análisis de circuitos. Los resultados muestran una buena correlación cuando se comparan con los obtenidos utilizando el estándar para diferentes materiales de prueba, lo que alienta su uso con fines de caracterización acústica.

1. INTRODUCTION

Impact noise is a problem of major concern for the well-being and comfort of people in buildings [1]. In this context, the use of floating floor solutions constitutes an excellent option both to dissipate these sound vibrations and to improve the habitability thereof. The soundproofing capabilities of these materials depend majorly on the dynamic stiffness of the materials used as resilient layers in these solutions [2].

ISO 9052-1 [3] specifies a test method for the determination of the dynamic stiffness of resilient materials used under floating floors in dwellings. Although initially intended for comparing production samples of similar materials used in a continuous layer under floating floors in dwellings, this method has been extensively used for the analysis of many different materials [4-7]. For this purpose, the fundamental mode of vibration of a mass-spring system consisting of a loading slab placed over the resilient material under test is excited using a suitable impulser. Once this resonance frequency is determined, it is straightforward to calculate the dynamic stiffness of the specimen using fundamental dynamics formulas [8]. In this method, the measurements are typically performed through a contact (e. g. piezoelectric sensor or accelerometer) or contactless (e. g. laser vibrometer or microphone) transducer [9], an impact hammer or a vibration shaker being used as impulser. Torres et al. [10] showed that the resonant modes of beam-type structures may be analysed by exciting these using an electrodynamic actuator, results showing a good agreement when compared with well-known analytical solutions and the utility of this type of transducers for characterization purposes being highlighted. In a recent work by the authors [11], electrodynamic actuators were used to determine the dynamic elastic modulus of materials under a state of simple stresses in beam-type mechanical elements. By generating a random signal excitation, the fundamental flexural mode of vibration of a beam-type cylindrical element was identified in the electrical input impedance of the actuator and its dynamic elastic modulus was then determined using classical beam theory [12].

In this work, an experimental approach that follows this methodology is proposed to determine the dynamic stiffness of resilient materials commonly used under floating floors. Experiments were performed over two different resilient materials, the results showing a good agreement when compared to those obtained following the ISO 9052-1. A discussion on the advantages and limitations of the proposed experimental procedure along with some remarks on its applicability was also given. In general, the proposed approach not only reduces the instrumental requirements for characterization but also encourages the development of compact and simplified characterization methods.

2. METHODS

2.1. ISO 9052-1

ISO 9052-1 [3] is a standard that proposes the use of a resonance method for the determination of the dynamic stiffness of resilient materials with smooth surfaces. From the resonance frequency of a mass-spring system as that depicted in Fig. 1a, which is composed of a loading slab (i. e the mass) and a sample of the resilient material (i. e. the spring) mounted on a rigid floor, the dynamic stiffness of the material under test can be calculated. For that purpose, the vertical vibratory response of the loading slab when subjected to an external excitation is obtained in terms of the transfer function response. The dynamic stiffness of the material can then be obtained from the resonance frequency of the single-degree-of-freedom system as

$$s = 4\pi^2 m f_0^2 \tag{1}$$

where s is the dynamic stiffness, m is the mass of the whole system, and f_0 is the resonance frequency in the transfer function response.

2.2. Proposed approach

The proposed approach uses the same slab-material arrangement that the standard, the major difference being the coupling of an electrodynamic actuator to the loading slab. An electrodynamic actuator consists of a coiled wire embedded in a uniform magnetic field so that when an electrical current is flowing a mechanic force is produced in its moving assembly. This mechanic force depends on the mechanical load coupled to the transducer so that by measuring its electrical input impedance this coupling effect can be captured. Consequently, instead of using an accelerometer and an impact hammer, the electrodynamic actuator is used both as an impulse exciter and a vibration sensor simultaneously.

To this end, let us first consider the mechanical system shown in Fig. 1b, which is composed of two masses, m_1 and m_2, and two springs with stiffness s_1 and s_2. Such a system can be linked to the proposed measurement system as follows: m_1 and s_1 correspond to the mass and suspension of the electrodynamic actuator, respectively, m_2 stands for the mass of the loading slab, and s_2 represents the dynamic stiffness of the resilient material under test. For the free vibration analysis of such a two-degree-of-freedom system, the equations of motion of each mass can be written as

$$m_1 \frac{d^2 \xi_1}{dt^2} + s_1 \left(\xi_1 - \xi_2 \right) = 0 \tag{2}$$

$$m_2 \frac{d^2 \xi_2}{dt^2} + s_2 \xi_2 + s_1 \left(\xi_2 - \xi_1 \right) = 0 \tag{3}$$

where ξ_1 and ξ_2 are the displacements from the equilibrium of masses m_1 and m_2, respectively.

The above linear differential equations can be written in terms of a matrix product as follows

$$\begin{bmatrix} -m_1\omega^2 + s_1 & -s_1 \\ -s_1 & -m_2\omega^2 + \left(s_1 + s_2 \right) \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{4}$$

The eigenvalues of that matrix system can therefore be obtained for those values of ω^2 for which the determinant of the matrix is equal to zero

$$\left(-m_1\omega_{1,2}^2 + s_1 \right)\left(-m_2\omega_{1,2}^2 + \left(s_1 + s_2 \right) \right) - s_1^2 = 0 \tag{5}$$

The frequencies corresponding to these eigenvalues (i. e. the natural frequencies of vibration, $\omega_{1,2}$) can thus be easily obtained by identifying the resonance peak frequencies on the measured electrical input impedance spectrum of the actuator when an electrical voltage is applied to it (see [11] for details on the measurement principle). Given that these frequencies correspond to the solutions of the so-called characteristic equation (Eq. (5)), after some basic algebraic manipulations it is straightforward to obtain the dynamic stiffness of the tested material as

$$s_2 = \frac{m_1 m_2 \omega_{1,2}^4 - \left(m_1 + m_2 \right) \omega_{1,2}^2 s_1}{m_1 \omega_{1,2}^2 - s_1} \tag{6}$$

Note that to obtain the dynamic stiffness using the previous expression, the mechanical properties of the remaining elements must be known beforehand. In this latter regard, a simple weighing procedure can be used to determine m_1 and m_2, while the stiffness of the actuator, s_1, can be easily obtained by substituting m_1 and the resonance frequency of its electrical input impedance when coupled to a rigid floor (w/o resilient material) in Eq. (1).

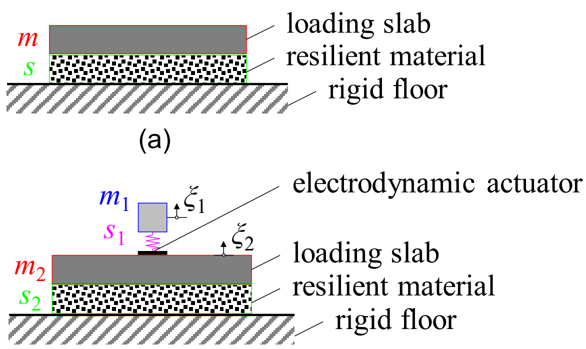


Figure 1 – Schematic representation of the mechanical systems used to determine the dynamic stiffness of resilient materials: (a) ISO 9052-1; and (b) proposed approach.

3. MATERIALS

Several resilient material samples having dimensions 200 mm x 200 mm were tested using both the procedure described in ISO 9052-1 [3] and the proposed approach. A loading slab made of natural stone 2.341 kg in weight was used for the experiments. A summary of the thickness and weight of the loading slab and analysed specimens are given in Table 1.

In the current work, the method for the determination of the dynamic stiffness of resilient materials described in the ISO 9052-1 was performed using a Brüel&Kajer contact accelerometer type 4534-B-002 connected to a Brüel&Kajer signal conditioner 1704-A-002, the impact force being produced with a Brüel&Kajer impact hammer type 8202 connected to the same signal conditioner (see Fig. 2a). The outputs of the signal conditioner were then connected to the acquisition platform OR34 Compact Analyser, which recorded the responses of each transducer and calculated the mechanical mobility necessary to identify the resonance frequency in the test arrangement. Measurements were performed three times for each specimen as specified in the standard.

As for the proposed approach, the acquisition platform used to perform the electrical input impedance measurements consisted of the USB two-channel audio interface CLIO SC-01 connected to a laptop through the PB-4281 running the software CLIOwin. This experiment was easy to perform by just connecting the transducer whose electrical impedance is to be measured (i. e. the electrodynamic actuator) to one input channel and then a random noise signal is generated to excite it. Regarding the transducer, the TEAX32C20-8 electrodynamic actuator from Tectonic was used for the measurements (see Fig. 2b).

Table 1 – Thickness and weight of the analysed specimens.

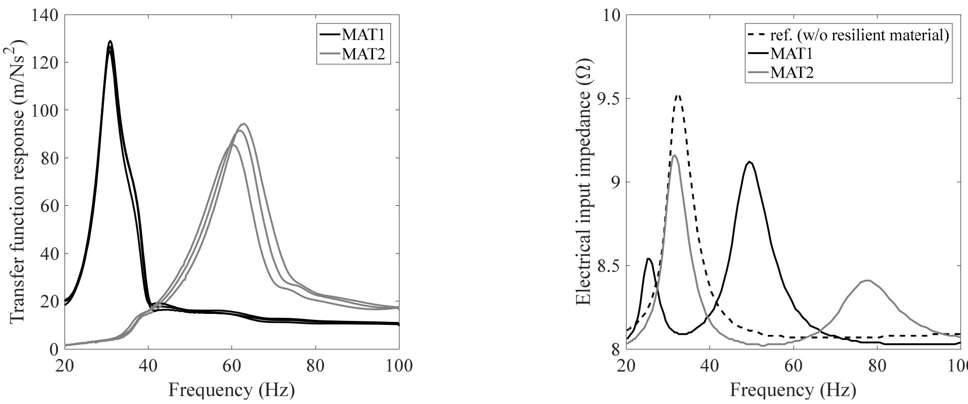
# ID	Thickness (mm)	Weight (g)
loading slab	30	2341
MAT1	20	79
MAT2	20	132

(a) (b)

Figure 2 – Pictures of the experimental setups used to determine the dynamic stiffness of resilient materials: (a) ISO 9052-1; and (b) proposed approach.

4. RESULTS AND DISCUSSION

Fig. 3a shows the transfer function response (ratio of the acceleration to the force) obtained for each of the specimens by following the standardized procedure, the resonance frequency f_0 being easily identified. As for the electrical input impedance measurements, this is plotted as a function of frequency in Fig. 3b, the values of ω_1 and ω_2 being calculated from the resonance peaks in the linear frequency spectrum. Once these frequency values were identified, it was straightforward to calculate the dynamic stiffness according to the standard and the proposed approach by using Eq. (1) and Eq. (7), respectively. Results for the dynamic stiffness and relative errors of the tested materials are summarized in Table 2.



(a) (b)

Figure 3 – (a)Transfer function response obtained following the ISO 9052-1; and (b) electrical input impedance measured following the proposed approach.

Table 2 – Dynamic stiffness of the analysed specimens.

# ID	$s_{\text{ISO 9052-1}}$ (MN/m³)	$s_{\text{proposed approach}}$ (MN/m³)	Relative error (%)
MAT1	127	121	4.6
MAT2	508	515	1.4

While the above preliminary results showed the proposed approach to be a valid methodology to obtain the dynamic stiffness of resilient materials using cost-effective laboratory equipment, some important remarks are worth discussing. The dependence on dynamic stiffness of pre-static load is of minor importance in the case under study, the differences between values measured with a static load of 2 kPa and those measured with a very low preload being of the order of 10 % to 20 % according to the ISO 9052-1 [3]. It should be also noted that those tested materials whose airflow resistivity values range between 10-100 kNs/m^4 would require a porosity correction to account for additional stiffness phenomena. In this regard, the above approach could serve to indirectly obtain the airflow resistivity of porous materials as well as to provide additional data regarding the mechanical system to which the actuator is coupled.

5. CONCLUSIONS

Dynamic stiffness is an important parameter for the study of resilient materials from the civil engineering point of view both for the design of floating floors or analogous structural systems. The proposed approach is based on the measurement of the input electrical impedance of an electrodynamic actuator excited by a random noise signal when coupled to a loading slab-resilient material system. In doing so, the resonance frequencies of the coupled system can be identified in the impedance spectrum, and the dynamic stiffness calculated in a straightforward manner using fundamental dynamics theory. Results were compared with those obtained following the procedure described in the standard ISO 9052-1 showing a good agreement for the tested materials, thus encouraging further research to explore the potential of this approach for material characterization purposes.

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