



A sensorless method for measuring the point mobility of mechanical structures

R. Boulandet ^{a,*}, M. Michau ^{a,b}, P. Herzog ^b, P. Micheau ^a, A. Berry ^a

^a Groupe d'Acoustique de l'Université de Sherbrooke, Université de Sherbrooke, Sherbrooke, Canada J1K 2R1

^b Laboratoire de Mécanique et d'Acoustique, UPR CNRS 7051, 13453, Marseille cedex 13, France

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ABSTRACT

This paper presents a convenient and cost-effective experimental tool for measuring the mobility characteristics of a mechanical structure. The objective is to demonstrate that the point mobility measurement can be performed using only an electrodynamic inertial exciter. Unlike previous work based on voice coil actuators, no load cell or accelerometer is needed. Instead, it is theoretically shown that the mobility characteristics of the structure can be estimated from variations in the electrical input impedance of the actuator fixed onto it, provided that the electromechanical parameters of the actuator are known. The proof of concept is made experimentally using a cheap commercially available actuator on a simply supported plate, leading to a good dynamic range from 100 Hz to 1 kHz. The methodology to assess the basic parameters of the actuator is also given. Measured data are compared to a standard shaker testing and the strengths and weaknesses of the sensorless mobility measuring device are discussed. It is believed that this sensorless mobility measuring device can be a convenient experimental tool to determine the dynamic characteristics of a wide range of mechanical structures.

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1. Introduction

The concepts of mechanical impedance and mobility are part of the design process and analysis in structural dynamics. Developed from electromechanical and electroacoustic analogies in the 1920s [1–4], they define the relationship between force and velocity at given locations of a structure. The point mobility characteristics of a mechanical structure, which is based on a collocated measurement of force and velocity, has broad and practical applications in: (1) modal testing to determine the natural frequencies, modal damping and mode shape of structures [5], (2) materials testing to determine certain specific properties of materials such as the loss factor and the modulus of elasticity [6], (3) structural monitoring in order to investigate non-uniformities, structural defects or tolerance deviation that can be detected by comparing the mobility function of a standard with a recently manufactured item [7]. It is also used in system modelling since mobility measurement performed at many locations on a structure can be used as verification of mathematical models, or the response of subsystems or cascaded substructures may be measured and the properties of the assembled system be predicted before final assembly [8], similar to the study of complex electrical circuits. In smart structures and vibration isolation, furthermore, it allows the dynamic interaction between electromechanical transducers and structure to be involved

* Corresponding author.

E-mail address: romain.boulandet@gmail.com (R. Boulandet).

in the development process [9]; vibration isolator, proof-mass actuator and machinery mounting can then be optimized to minimize structural vibration or sound transmission [11,12].

The measurement of mechanical impedance and mobility in general requires three devices: an actuator, a force sensor and a vibration sensor [6,8,13]. In impact testing, the structure under test is excited by a sharp and clean force input of small time duration, generally by using an impact hammer equipped with a load cell, and the vibration response is typically sensed by using an accelerometer. In shaker testing, a vibrating-rod actuator is required to mechanically excite the structure according to the amplified input signal. In both cases mechanical energy is supplied to the structure with a known frequency content, allowing the mobility function to be calculated from the force applied and the vibration response. Achieving collocated sensing is a challenging task and imperfect collocation may result in significant errors in the measured mobility function [14]. An alternative approach for the direct measurement of the driving point mobility of a structure has recently been proposed by Sands et al. [15]. In this method, an electrodynamic inertial actuator combined with two accelerometers is attached to the structure directly so that the assembly can be used as a mobility measuring device. The two sensors are actually placed strategically on the actuator frame and proof mass, allowing the mass-loading effect of the device on the structure to be removed. The feasibility of the method was validated in [15] on a cantilever beam. Although this approach overcomes some practical limitations encountered in impact testing and shaker testing, such as allowing better control over the frequency, amplitude and duration of the force excitation applied to the structure while compensating the mass-loading effect of the actuator on the structure, it requires developing a specific device. On the other hand, several authors have studied how to use electromechanical transducers as both sensor and actuator simultaneously, a technique which is commonly referred to as *self-sensing actuation* in the literature. The idea of self-sensing actuation was developed in the early nineties by Hagood et al. [16] and Dosch et al. [17] concurrently, where the piezoceramic elements were used as sensors and actuators simultaneously to reduce implementation, cost and complexity, by achieving truly collocated control. The principle was later implemented to achieve active control of noise and vibration [18–21], to implement self-sensing vibration damping using electrodynamic shaker actuators [22], for active acoustic attenuation [23] and for biomedical applications using an electromagnetic actuator [24]. More recently, the principle has been applied to an electrodynamic inertial exciter for active vibration control of a simply supported plate [9] and for active structural acoustic control of an aircraft panel [10]. In particular, it was shown in Ref. [10] that the vibration of the structure at the actuator base can be estimated from the actuator impedances and the current and voltage at the transducer's terminals, paving the way for the development of a *sensorless* mobility measuring device. The approach of estimating the mechanical impedance and mobility of a structure from the electrical impedance of an electromechanical transducer attached onto it is not new. In the mid 1990s, studies on the coupling of the electrical impedance of piezoceramic materials and the mechanical impedance of structure at the location of the piezo patch were reported by Liang et al. [25]. In the early 2000s, Ling et al. developed a technique for measuring the mechanical impedance of structures using the sensing capability of a piezoceramic inertial actuator [26]. Experimental results for monitoring structural integrity of a clamped–clamped beam can be found in [27], showing that some structural defects can be detected by examining the changes of the electrical impedance of the actuator. In the footsteps of Ref. [26], Doutres et al. [28] developed a methodology for determining the loss factor and Young's modulus of a porous sample from the measurement of the electrical impedance of an electrodynamic loudspeaker used to apply static and dynamic stress on it. Bois et al. [29] also proposed a method for detecting and characterizing a delamination process in a composite structure using embedded piezoelectric transducers, which allows to determine the modal parameters from electromechanical impedance measurements.

This paper intends to simplify the mobility measuring device proposed by Sands et al. [15] by jointly using the self-sensing capabilities of the inertial exciter, as suggested in Ref. [10]. The proposed sensorless mobility measuring device (SMMD) therefore enables the dynamic properties of mechanical structures to be evaluated quickly and inexpensively. The remainder of the paper is organized as follows. Section 2 provides a dynamic model of the electrodynamic actuator as a two-port network, including its transduction functions that are used in the analytical derivation of the mobility function of the structure. In Section 3, we present the methodology used to experimentally evaluate the electromechanical parameters of the actuator needed to determine the transduction functions of the actuator. The proof of concept is provided in Section 4 on the basis of a simply supported plate and experimental results are compared to standard shaker testing. The strengths and weaknesses of the SMMD are discussed in Section 5, including the possible reasons for the observed limitations on the current prototype.

2. The electrodynamic sensoriactuator

This section provides the theoretical basis about the operation and characteristics of the electrodynamic inertial exciter, and explains how it can be employed for self-sensing actuation. A lumped parameter model is used in the following assuming $\exp(j\omega t)$ harmonic dependence and linear behavior. Otherwise, some of the model parameters would need to be considered as time-varying nonlinear functions of the input variables [30].

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