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Acoustic characterization of a nonlinear vibroacoustic absorber at low frequencies and high sound levels

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ABSTRACT

A nonlinear vibroacoustic absorber (Nonlinear Energy Sink: NES), involving a clamped thin membrane made in Latex, is assessed in the acoustic domain. This NES is here considered as an one-port acoustic system, analyzed at low frequencies and for increasing excitation levels. This dynamic and frequency range requires a suitable experimental technique, which is presented first. It involves a specific impedance tube able to deal with samples of sufficient size, and reaching high sound levels with a guaranteed linear response thank's to a specific acoustic source. The identification method presented here requires a single pressure measurement, and is calibrated from a set of known acoustic loads. The NES reflection coefficient is then estimated at increasing source levels, showing its strong level dependency. This is presented as a mean to understand energy dissipation. The results of the experimental tests are first compared to a nonlinear viscoelastic model of the membrane absorber. In a second step, a family of one degree of freedom models, treated as equivalent Helmholtz resonators is identified from the measurements, allowing a parametric description of the NES behavior over a wide range of levels.

1. Introduction

Nonlinear vibroacoustic absorbers are passive devices dedicated to noise reduction at low frequencies. Such devices consist in a thin structure submitted to large deformations, which exhibits non linear resonances used to absorb sound energy. Such a structure is a thin viscoelastic membrane in Ref. [1], whereas in Ref. [2] the diaphragm of a loudspeaker without motor assembly is used. This kind of device takes advantage of a phenomenon called “Targeted Energy Transfer” or “Energy Pumping”, due to the coupling of the nonlinear resonance of the absorber with the acoustic field that has to be reduced. It is described in detail in Ref. [3] in terms of resonance capture and nonlinear modes showing an irreversible energy transfer from the acoustic medium toward the absorber, the energy being thus dissipated within the absorber. In the literature, such a device is often designated as a “Nonlinear Energy Sink” (NES). Nonlinear vibroacoustic absorbers have shown their ability to reduce sound especially at low frequencies and high enough sound field levels. They may thus overcome some limitations of classical devices such as porous materials, Helmholtz resonators, perforated plates [1,2,4–6].

In these early papers, the nonlinear behavior of the vibroacoustic absorbers was modelled, using nonlinear plate equations of the Von-Kármán type for the thin structure, coupled with the acoustic medium through an impedance boundary condition. In addition to these models, experiments were based on vibration measurements focused on the mechanical NES behavior. Conversely, the present paper focuses on the NES considered as an acoustic device with desirable absorbing properties. Dealing

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with low frequencies, it uses an approach common to the characterization of other kinds of absorbers, *i.e.* a cylindrical tube connecting a sound source to the NES. At the considered frequencies, plane waves may safely be assumed into the tube, so the NES may be considered as a single port acoustic device.

A review about linear impedance measurements can be found in Ref. [7]. The most employed method is the Two Microphone Method (TMM). It was initially developed by Seybert and Ross [8] and expanded by Chung and Blaser using transfer functions [9,10]. Abom and Boden [11] later reviewed different implementations of this method, the most usual being standardized as ISO 10354-2. Basically, it involves two microphones placed between the sample and the source, their relative calibration requiring them to be switched. The microphones spacing must be adapted to the targeted frequency band, which becomes problematic when dealing with wide frequency ranges. An improvement of the calibration method, using three loads, was later proposed by Gibiat and Laloë [12]. Recently, Boonen et al. [13] proposed a method to deal with high impedance magnitudes over a wide frequency range: the calibration is then again performed by measuring several different acoustic loads instead of switching the microphones.

In our study, the absorber is essentially nonlinear and its absorbing properties have to be dug out at low frequencies, under controlled high excitation levels. No standard equipment is available to deal with this need, so we built an impedance tube (thereafter named “Short Kundt’s Tube”, *i.e.* SKT) able to reach very high levels at low frequencies (typically several hundreds of Pascals between 10 and 200 Hz). The measurement of the acoustic characteristics of the absorber device are obtained through an original method inspired from the indirect source characterization methods proposed in Refs. [14–16]. A single microphone is needed, as the source is first characterized using different known acoustic loads. An “equivalent impedance” and the apparent reflection coefficient of the NES are then deduced from this single pressure measurement.

The SKT is named “short” because it is shorter than should be a Kundt’s tube according to ISO 10354-2. A single microphone method can use a tube as short as possible with respect to the plane waves approximation. Such a short device is easy to move and occupies a small area. With this setup we expect to reduce errors due to thermal gradient and instabilities along the tube, and we expect to reject the source resonances above the measurement range, as shown in this article.

The structure of this paper is as follows. Section 2 presents the experimental set-up and the identification method allowing to estimate the reflection coefficient of a device under study (DUT). Section 3 applies this method to the estimation of the reflection coefficient of a sample nonlinear absorber, and its measurements are then compared to an analytic model previously published (Section 3.3) and to a set of equivalent resonators (Section 3.4).

In this paper, all quantities, unless otherwise stated, will be considered in the frequency domain, assuming a $e^{+j\omega t}$ temporal dependence.

2. Measurement method

2.1. Basic principle

Fig. 1(a) presents the acoustical scheme of the set-up. It is made of a sound source (controlled by a voltage U) and a sample (or DUT), connected through a tubular section of minimal length (hence the name “Short” Kundt’s Tube). The source must be linear over the full dynamic range, and therefore features several driver units (only two are shown in Fig. 1(a)). The left hand side of the tube is closed next to the source, and the DUT is mounted on the right hand side. A high pressure microphone is positioned on the axis of the tube (P), in the measurement plane separating the source from the DUT which is taken as the origin for the x-axis. The grayed part between 0 and x_m is a part of the tube which is always in place. The grayed part above x_m represents the mobile part of the DUT. The actual shape of the device is shown Figs. 2 and 11.

The DUT is characterized by an equivalent impedance Z_T, which is defined as the ratio of the fundamental components of the spectra of the pressure and the volume velocity, both considered over the tube section in the measurement plane. Plane waves are assumed along the cylindrical part of the system, at sufficient distances from the source and the DUT: the measurement plane is distant at least of the magnitude of one tube diameter from the loudspeaker connectors, and one membrane diameter from the sample membrane. Tests were made with a 0.8 m long extension of the tube between the DUT and the microphone, and no significant difference was noticed between the results. The local pressure P measured by the microphone is thus considered as a good estimate of the pressure averaged over the measurement section. The local volume velocity is not measured, but is indirectly obtained through the setup calibration. When the DUT is nonlinear, Z_T corresponds to a linear approximation of the relationship between the pressure and volume velocity. In this case, Z_T is an indicator depending on the DUT, obviously, and depending also of the conditions of the experiment (*i.e.* U and the source frequency content).

The source is considered as linear and time-invariant, so it can be represented using the Norton equivalence by the electro-acoustic scheme shown in Fig. 1(b). It is characterized by its impedance Z_S and its volume velocity Q_a. Equivalently, it may be characterized by Z_s and the transfer function H_{ae} between the acoustic volume velocity Q_a and the control voltage U, defined as $Q_a = H_{ae}\ U$. The equivalent impedance Z loading the volume velocity source is therefore:

$$Z = \frac{Z_T Z_s}{Z_T + Z_s}. \tag{1}$$

Considering the transfer function H_m between the control voltage U of the source and the acoustic pressure P at the microphone, Eq. (1) reduces to: