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Measurement of volume velocity of a small sound source

Anders Lindberg *, Goran Pavić

Laboratoire Vibrations Acoustique, Institut National des Sciences Appliquées de Lyon, 20 Avenue Albert Einstein, 69 621 Villeurbanne Cedex, France

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ABSTRACT

Two methods for measuring volume velocity of a back-enclosed driver, that make no assumptions about the shape or the vibration distribution of the driver's diaphragm, are investigated: a compression chamber and a blocked pipe. Both methods were implemented on an off-the-shelf driver using a microphone installed in the driver's cavity. The relationship between the pressure inside of the driver's cavity and the volume velocity of the driver's diaphragm was established by measurement. The two methods produced similar results.

1. Introduction

An engineering implementation of a simple source can be a small back-enclosed driver, provided that its driving surface is small compared to the wavelength and vibrates in phase [1]. In such a case the pressure response does not depend on the details of the vibrating surface and can be expressed by a point transfer impedance Z. Such an impedance relates volume velocity amplitude $\widehat{Q}$ of the driver located at a source point $\mathbf{s}$ to sound pressure amplitude $\hat{p}$ at a field point $\mathbf{f}$

$$Z(\mathbf{f}|\mathbf{s}) = \hat{p}(\mathbf{f})/\widehat{Q}(\mathbf{s}). \tag{1}$$

All the quantities in Eq. (1) are complex functions of frequency, and hat [^] is used to denote amplitude [2]. The driver becomes increasingly inefficient when the frequency decreases, whereas at higher frequencies it develops pronounced directivity and thereby ceases to be a simple source [1]. In the mid-frequency range the transfer impedance can be measured, independently of the choice of driver, provided that the volume velocity of the source is known.

The need for a volume velocity source has been motivated by the demand for quantifying radiation by vibroacoustic sources. The principle of such a characterisation is to replace the complex vibroacoustic source by a simpler substitute source for use in noise synthesis. It is presumed that the radiation can be modelled by superposition of simple sources set in a rigid closed baffle of similar volume and shape as the original source. Such a characterisation critically depends on the knowledge of the source volume velocities.

One way of measuring volume velocity of a driver is to measure the velocity of the voice-coil, and multiply it with the projected surface of the driver's diaphragm in the direction parallel to its motion. The velocity of the voice-coil may be deduced by knowledge of the blocked electrical impedance and the motional impedance of the driver [1]. The measurement of motional impedance can thus be used for an estimation of volume velocity assuming that the diaphragm moves as a rigid body. This requires prior knowledge of the blocked electrical impedance which can be found by e.g. casting the driver's moving parts into an epoxy resin [3]. Thus a second driver is needed for the measurement of motional impedance. This makes the method sensitive to differences between the two drivers [3]. Furthermore the motional impedance depends on the ambient space. Therefore the approach is rather cumbersome, and the supply voltage is not proportional to volume velocity.

Several designs for implementing volume velocity sources have been reported [4–6]. Common to all of these designs are that an additional transducer producing a signal proportional to either velocity, acceleration or volume displacement is used. The relationship to volume velocity can then be either deduced by theory or measured.

Three different designs of volume velocity sources have been reviewed by Salava [4]. The first design is based on use of a supplementary porous acoustic resistor. The advantage of the design is that it can be assembled quickly, but the disadvantage is that for accurate measurements careful calibration of the resistor is necessary and the resistor may not be linear in regards to the volume

* Corresponding author.
E-mail address: anders.lindberg@insa-lyon.fr (A. Lindberg).

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velocity [4]. The second design uses a microphone which provides a signal proportional to volume displacement. The disadvantage of the design is that in order to obtain a signal directly proportional to volume velocity a derivative circuit is required [4]. The third design is to equip a rigid piston, driven by an electrodynamical transducer, with a measuring voice-coil [4]. The advantage of the design is that the output signal is proportional to the velocity of the voice-coil, but the disadvantage is that it assumes mechanical rigidity of the moving parts which is not met in practice [4].

A more recent design described by Salava [5] uses two coupled drivers put together face-to-face: one acting as an exciter, and the other as a sensor. The exciting driver is in a rigid enclosure, and given that there is no supply voltage in the measuring and radiating driver's voice-coil the output voltage is proportional to its velocity. Another design is to equip the diaphragm with an accelerometer [5]. The relationship between the volume velocity and the transducer's signal is however not known, and experimental calibration is carried out in a free-space. The disadvantage of such a calibration is that it requires access to an anechoic room.

Anthony and Elliott [6] have investigated two designs of known volume velocity sources. One of the designs is based on the previously mentioned method by Salava, and uses two identical drivers put together face-to-face. The volume velocity can be estimated by summing up individual contributions of smaller patches each considered to be in rigid motion. The calibration is based on measurement of multiple point velocity - voice-coil voltage transfer functions using laser velocimetry. The volume velocity was then expressed in terms of an effective area. The disadvantage of such a calibration is that the effective area is not straightforward to measure, and the method requires access to a Laser Doppler Vibrometer. The second design uses an internal microphone installed in the driver's back cavity of precisely known volume which had to be designed and manufactured. Here the volume velocity was deduced from the internal pressure assuming a compliance law theoretically valid for small cavities of rigid walls. The two designs were compared using a single-point velocity as a reference measurement of volume velocity.

In this study the latter technique using an internal microphone was applied on a small off-the-shelf driver. In this case the calibration between pressure and volume velocity was not modelled, as done in [6], but instead had to be measured in dependence of frequency due to the presence of internal damping material and the effect of cavity resonances. Such a calibration is advantageous because the features of the driver's back cavity do not have to be known and may vary with frequency. The disadvantage is the need to independently measure the volume velocity which has turned out not to be a trivial task.

Four different calibration methods were compared in [7]. The first calibration was based on laser velocimetry, as done in [6]. The technique was found difficult to apply on curved surfaces such as dome shaped diaphragms. Therefore the volume velocity was deduced from a single point velocity measurement in the centre of diaphragm. This requires rigidity of the diaphragm which is not met in practice. The second calibration was performed in a free-space, as done in [5], but using a large flat baffle to avoid radiation from the driver's enclosure. The accuracy of the measured data was found to suffer from baffle diffraction.

The inconveniences have prompted the authors to find alternative ways to calibrate the source. Two novel methods were thus conceived: a compression chamber technique and a blocked pipe technique. The key advantage of the two methods, which will be described in detail in this paper, is that no assumptions are made regarding the shape or the vibration distribution of the driver's diaphragm.

2. Method

The principle of measuring transfer impedance based on an internal microphone is discussed in Section 2.1. The transfer impedance is split into two transfer functions: a source function and a space function. A driver is characterised by its source function. In order to estimate the source function volume velocity has to be measured. The two methods for measuring the driver's volume velocity are discussed further on in Section 2.2.

2.1. Internal pressure technique

If the volume of air inside the back cavity of the driver is tightly closed, and if its back enclosure is small and rigid, then sound pressure p inside of the cavity is effectively proportional to volume velocity Q of the diaphragm when it compresses and expands the interior air, $p \propto Q$. The assumption of a tightly closed cavity may not be fully true: drivers are often equipped with either a small vent or a porous diaphragm for the compensation of changing ambient pressure. Such a compensation is however practically ineffective where sound pressure is concerned and needs not be accounted for.

Using an internal microphone, the transfer impedance, Eq. (1), can be rewritten in a form suitable for experimental work. The transfer impedance will be split into two independent transfer functions: a source function Ψ which relates internal pressure $\hat{p}(\mathbf{i})$ to volume velocity $\widehat{Q}(\mathbf{s})$ and a space function Ω which relates external pressure $\hat{p}(\mathbf{f})$ to internal pressure $\hat{p}(\mathbf{i})$

$$Z = \Psi\Omega, \quad \Psi = \hat{p}(\mathbf{i})/\widehat{Q}(\mathbf{s}), \quad \Omega = \hat{p}(\mathbf{f})/\hat{p}(\mathbf{i}). \tag{2}$$

Here $\mathbf{i}$ denotes the position of the internal reference microphone. A driver's diaphragm is characterised by its source function which is theoretically governed by compliance-like behaviour of the air inside of its back cavity. This transfer function depends on ambient factors such as temperature and will be discussed in detail in Section 2.2.1. This characterisation procedure is therefore approximate as it depends on the ambiance.

2.1.1. Modelling the source function by a polynomial

A compliance-like behaviour implies that the source function is inversely proportional to frequency. A measured source function Ψ may in practice not have such an ideal behaviour and can be perturbed by noise. A remedy is to fit the source function to a polynomial

$$j\omega\widetilde{\Psi} = \psi_0 + j\omega\psi_1 - \omega^2\psi_2 + \ldots, \tag{3}$$

of order N using a least squares fit were tilde [~] denotes a fitted estimate [8]. The angular frequency is denoted by ω and the imaginary unit is denoted by j. A model of the source function is required in order to interpolate the data, as will be discussed in conjunction with the blocked pipe method in Section 2.2. If the order N of the model is chosen too high, the polynomial over-fits the acquired data. A concern was therefore how to choose the order of the polynomial.

2.1.2. Interpreting the source function as a filter

The small volume inside the driver's back cavity may be represented as a filter [1]. Since the distance between the internal microphone and the diaphragm is small compared to the wavelength, $\|\mathbf{i} - \mathbf{s}\| \ll \lambda$, and assuming that the pressure inside of the cavity is spatially uniform at low frequencies the sound pressure at the driver's surface is $p(\mathbf{s}) \approx p(\mathbf{i})$. As the cavity has its own resonance frequencies the compliance-type behaviour will be valid at frequencies well below the first cavity resonance. At these