Applied Acoustics 101 (2016) 39–46

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

A noncontact method for determining surface density of nonporous materials with the limp-wall mass law

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ARTICLE INFO

Article history:
Received 13 November 2014
Received in revised form 27 July 2015
Accepted 3 August 2015

Keywords:
Surface density
Air-coupled ultrasound
Limp-wall mass law
Material characterization
Through-transmission
Mass per unit area

ABSTRACT

A new noncontact technique for determining the surface density or mass per unit area of nonporous, homogeneous membranes and foils of sub-wavelength thicknesses is introduced. Surface densities are determined through application of the limp-wall mass law and through-transmission ultrasonic measurements of bulk waves. The ultrasonic measurements are performed with commercially-available, broadband air-coupled ultrasonic transducers. Surface densities of aluminum foil, brass shim, and plastic sheets are typically found to be within 3% of their accepted values.

1. Introduction

For many years, the limp-wall mass law has been used by engineers to aid in low-frequency noise suppression in their architectural partition design or vehicle noise control in passenger cabins. The engineer typically must choose the material that reduces the most noise at certain (usually audible) frequencies. The choice is constrained by space, weight and cost limitations, leading to an optimization problem that can be solved by selecting from a list of materials with known physical and acoustical properties.

However, the use of the limp-wall mass law can be reversed where the objective is no longer to reduce the acoustic energy transmitted through a slab, wall, or blanket, but to determine certain material properties associated with the flat, sheet-like material by measuring the loss of acoustic energy as it transmits through the material. In this situation, the key material parameter that can be found is the surface density, also known as the mass per unit area or grammage. If the bulk density of the material is known, then the thickness of the material can be indirectly determined since the thickness is equal to the surface density divided by the bulk density. Thus, the surface density can be an important parameter when performing quality control inspections of the manufacturing of metallic foils, plastic films or paper products.

A simple method for determining the surface density of a material involves weighing a sample of the material which has been cut to specific dimensions. This 'cut and weigh' approach is common in the textile [1,2] and foil [3] industries, where in the latter case, the surface density is combined with the bulk density to determine the thickness of the foil. While there are other methods to determine surface density such as X-ray absorption [4] and ellipsometry [5], the present paper will focus on a new ultrasonic approach developed from the limp-wall mass law.

The limp-wall mass law is described in many acoustics texts [6,7] and treats the membrane or sheet-like material as a perfectly limp mass [8] with its inertial effects determining the specific impedance and thus the acoustic transmission loss, also known as the limp-wall mass-law transmission loss [9]. The model only applies to nonporous materials since it assumes the particle velocities are equivalent within the material and on either side of the material.

Determining the acoustic energy loss through materials, both porous and nonporous, has traditionally been accomplished with impedance tube measurements [10] or through measurements in large, sound-proof reverberation rooms [11]. Each techniques has certain advantages and disadvantages, however, neither can be applied to in-process, real time quality control inspections of production processes.

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http://dx.doi.org/10.1016/j.apacoust.2015.08.001

In contrast, air-coupled ultrasound is not constrained to off-line inspections of specially prepared samples of the material (impedance tube) nor requires a reverberation room. In recent years, the transduction efficiency of commercially available transducers has reached a useful level under normal atmospheric conditions, i.e., without the need for pressurized or pure gases. Because it is a non-contact technique that requires only air as a couplant, it is well-suited for inspecting relatively fragile materials such as thin membranes that can be damaged by conventional ultrasonic inspection techniques like direct contact or immersion, or from which a back wall reflection cannot be detected. It may be possible use air-coupled ultrasound for in-line process inspections much earlier in the production chain of events for manufacturing of relatively high volume, low cost products such as foils, films and paper [12].

The paper proceeds with a description of the theoretical development of the limp-wall mass law. This development does not follow the traditional approach used in many acoustics texts, but instead begins with the modeling of the complete ultrasonic measurement process with the Thompson–Gray Measurement Model [13]. It is shown how this general model can be simplified to the limp-wall mass law when certain assumptions are made which will eventually lead to an estimation of the surface density of the material. A discussion of the range of applicability of these assumptions follows. A description of the experimental measurement technique highlights the important characteristics of the technique: the use of long wavelengths when compared to the material's thickness which removes the need to detect back wall reflections or establish resonance within the material, the broadband nature of the measurements, and the need for two-sided access to the material. Estimates of surface densities for metallic and non-metallic films and foils are shown along with a brief discussion of these results, followed by concluding remarks.

2. Theoretical modeling

The new measurement technique used to determine the surface density relies on the acquisition of two through-transmission bulk waves in the time domain where the material is aligned orthogonally to the propagation of the ultrasound. One waveform is captured with the membrane present between the transducers and the other with the membrane absent (see Fig. 1). The surface of the material is assumed to be flat and smooth with no wrinkles or creases. The frequency response of each of the time wave forms can be modeled with the Thompson–Gray Measurement Model [13] which models the entire ultrasonic measurement process as a series linear time-shift invariant systems that represent individual components of the measurement process such as transducer diffraction, material attenuation, phase propagation, reflection/transmission processes, and equipment efficiencies [14]. Modeling the material's transfer function, which is one of many components in the entire measurement process, can be accomplished with the classic fluid-layer model found in numerous acoustic texts. Under certain assumptions, the fluid-layer model can be simplified to the limp-wall mass law from which the surface density of the membrane can be determined.

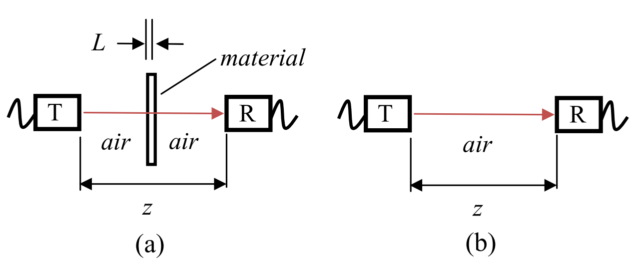

Fig. 1. Through-transmission measurements required for determining the surface density of a thin, sheet-like material of thickness, L. The first is taken with the material present in the wave field (a), and the second with the material absent (b).

2.1. Thompson–Gray Measurement Model

When the Thompson–Gray Measurement Model is applied to the measurement process shown in Fig. 1, the absolute magnitude of the response, $|\boldsymbol{TT}_{mat}(\omega)|$, measured with the material present can be expressed as a function of circular frequency, $\omega = 2\pi f$, leading to:

$$|\boldsymbol{TT}_{mat}(\omega)| = \beta(\omega)|\boldsymbol{C}(z-L,\omega)|exp[-\alpha_1(z-L)-\alpha_2 L]|\boldsymbol{T}(\omega,L)| \quad (1)$$

where $\beta(\omega)$ is the system efficiency factor, $|\boldsymbol{C}(z-L,\omega)|$ is the absolute magnitude of the transducer beam diffraction coefficient, z is the distance between the transducers, L is the thickness of the material, α_1 and α_2 are the attenuation coefficients of air and the material, and $|\boldsymbol{T}(\omega,L)|$ is the absolute magnitude of the transfer function of the material [15].

In a similar manner, the absolute magnitude of the reference signal, $|\boldsymbol{TT}_{ref}(\omega)|$, measured with the material absent can be expressed as:

$$|\boldsymbol{TT}_{ref}(\omega)| = \beta(\omega)|\boldsymbol{C}(z,\omega)|exp(-\alpha_1 z) \quad (2)$$

where $|\boldsymbol{C}(z,\omega)|$ is the diffraction coefficient for the reference signal. Both system efficiency factors will be the same assuming no changes have been made to the measurement process other than the removal of material in the second situation. If the reference signal response in Eq. (2) is divided into the 'material present' response in Eq. (1), then

$$\left|\frac{\boldsymbol{TT}_{mat}(\omega)}{\boldsymbol{TT}_{ref}(\omega)}\right| = \left|\frac{\boldsymbol{C}(z-L,\omega)}{\boldsymbol{C}(z,\omega)}\right| exp[-L(\alpha_2-\alpha_1)]|\boldsymbol{T}(\omega,L)| \quad (3)$$

The left hand side of Eq. (3) is generally referred to as the pressure amplitude transmission coefficient [16] and can be experimentally determined quite easily. However, in this most general form, it can be seen that the transmission coefficient may be dependent upon more than just the material transfer function, $\boldsymbol{T}(\omega,L)$. Diffraction coefficients might be required, depending on the material thickness, L, and wave speeds of the material and surrounding air. Additionally, the attenuation term may need to be evaluated since it is dependent not only on L but also on the air and material attenuation coefficients (α_1, α_2). Fortunately, these corrections are rarely needed when interrogating acoustically thin (thickness much less than a wavelength) nonporous membranes with air-coupled ultrasound. As will be shown later, the diffraction coefficient assumption will be experimentally verified. When both the diffraction and attenuation terms are assumed to approach unity, the right hand side of Eq. (3) can be approximated as:

$$\left|\frac{\boldsymbol{TT}_{mat}(\omega)}{\boldsymbol{TT}_{ref}(\omega)}\right| \cong |\boldsymbol{T}(\omega,L)| \quad (4)$$

As expected, the ratio of the absolute magnitude of the measured signals' frequency components approximates the absolute magnitude of the transfer function, $|\boldsymbol{T}(\omega,L)|$. If desired, the transfer function can be written in terms of the transmission loss, R_{TL}, which is oftentimes more convenient to measure experimentally and is defined as [6]:

$$R_{TL} = 10\log\left|\frac{1}{\tau}\right| \quad (5)$$

where τ is the sound-power transmission coefficient which is related to the transfer function, $\boldsymbol{T}(\omega,L)$, as $\tau = |\boldsymbol{T}(\omega,L)|^2$.