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Experimental study of sound radiation by plates containing circular indentations of power-law profile

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ABSTRACT

In this paper, the results of the first experimental investigation into sound radiation of rectangular plates containing tapered indentations of power-law profile are reported. Such tapered indentations materialise two-dimensional acoustic black holes for flexural waves in plates that result in absorption of a large proportion of the incident wave energy. A multi-indentation plate was compared to a plain reference plate of the same dimensions, and the radiated sound power was determined according to ISO 3744. It was demonstrated that not only do such multiple indentations provide substantial reduction in the damping of flexural vibrations within the plates, but also cause a substantial reduction in the radiated sound power. As the amplitudes of the flexural vibrations of a plate are directly linked to the amplitudes of radiated sound from the same plate, this paper also considers the effect of redistribution of the amplitude of the plate's response due to the presence of acoustic black holes on the amplitudes of the radiated sound. The results show that, in spite of some increase in the amplitudes of the displacements at the centres of black holes (circular indentations), the overall reduction of vibration response over the plate is large enough to cause a substantial reduction in the resulting sound radiation from plates containing indentations of power-law profile.

1. Introduction

Demands for noise reduction, especially within the transport industry, are continuously increasing, which stimulates researchers to explore new and more efficient ways of noise suppression at source. Amongst the variety of different mechanisms of noise generation, the radiation of sound as a result of structural vibration, i.e. 'structure-borne sound', is probably one of the most practically important mechanisms. This paper deals with sound radiation by flexural vibrations of rectangular plates that are designed specifically to reduce the structure-borne sound via certain modifications to the geometry of the plates.

As it is well known, the amplitudes of flexural vibrations of a plate are directly linked to the amplitude of sound radiated from the same plate [1–4], which means that the required reduction in the level of radiated sound can be obtained via efficient damping of structural vibrations of the plate. Passive damping of structural vibrations is traditionally achieved by adding layers of highly absorbing materials to the structure in order to increase energy dissipation of propagating (mostly flexural) waves [5–7]. Another well-known approach to suppression of resonant vibrations of different structures is to reduce reflections of structural waves from their free edges [5,8].

Over the last decade, a new method of damping flexural vibrations using the so-called 'acoustic black hole effect' to efficiently reduce edge reflections has been developed and investigated [9–11]. This method has been applied to plates containing one- and two-dimensional recesses of power-law profile (wedges and circular indentations respectively) that had to be covered by narrow strips of absorbing layers near sharp edges.

In the case of one-dimensional geometry, the equation describing a power-law profile is given by $h(x) = \varepsilon \cdot x^m$, where $h(x)$ is the local thickness of the plate, and ε and m are positive constants. Ideally, if the power-law exponent, m is equal or larger than two, the flexural wave never reaches the sharp edge and therefore never reflects back either [12]. However, this never happens in reality because real wedges always have edge truncations that do not permit the reflection coefficients to be reduced substantially. The addition of a thin strip of absorbing material to the edge of a wedge of power-law profile [9–11] changes this situation dramatically and reduces the reflection coefficient down to 1–3%, which constitutes the 'acoustic black hole effect'. It has been established theoretically [9,10] and confirmed experimentally [11] that

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this method of damping structural vibrations is very efficient even in the presence of noticeable edge truncations. This has been demonstrated also by numerical calculations combined with experimental testing for rectangular plates with attached power-law-shaped wedges [13].

Two-dimensional acoustic black holes, i.e. circular indentations of power law profile, have been considered as well both theoretically and experimentally [14–17]. The practical advantage of two-dimensional acoustic black holes (indentations) over one-dimensional ones (wedges) is that they are placed inside plates. Therefore, they do not have exposed sharp edges that represent health hazard and make it difficult to use the plates with sharp edges as parts of machines and constructions. It has been demonstrated that two-dimensional acoustic black holes are also very efficient for damping structural vibrations.

Note that traditional methods of vibration damping in plate-like structures involve the use of significant quantities of viscoelastic absorbing material on plate surfaces, which is not very efficient and adds significant mass to the plates. The key advantage of the acoustic black hole effect is a significant reduction in added mass of the absorbing material required, as only the edge of a tapered wedge or the centre of a circular power-law profiled indentation have small pieces of absorbing material applied.

In the light of the above-mentioned advantages of acoustic black holes, it is important to consider sound radiation from structures containing such objects. Acoustic black holes damp flexural vibrations in plates over a broad frequency range, and therefore one would expect that sound radiation of the structure should also be reduced. However, it has also been shown that the amplitude of displacement at the wedge or indentation tip of power-law profile is noticeably increased. Therefore, it is essential to consider the implications of such increase in the amplitudes of the displacements at the indentation tips on the sound radiation. In particular, whether the overall reduction in the displacement amplitudes over the constant thickness section of the plate is large enough to result in substantial reductions in the overall vibration response and therefore in the resulting sound radiation from plates.

The present paper describes the results of the first experimental investigation of sound radiation from vibrating plates containing indentations of power-law profile. The results for the levels of sound radiation are expressed in terms of radiated sound power. Measurements are carried out for a rectangular steel plate containing multiple indentations of power-law profile, and the results are compared with the results for a plain reference plate of the same size. The results for radiated sound power are also considered in association with visual representations of the vibration displacements over the samples obtained using a scanning laser vibrometer. This helps to understand the observed sound reduction in the light of the amplitude variations of normal displacements over the plates. Part of the material described in this paper has been presented at the 164th ASA meeting (Kansas City, October 2012) and published in POMA [18].

2. Experimental set up and procedure

2.1. Experimental samples and their manufacturing

Two types of samples were used for this investigation: a plain reference plate and a plate containing six circular indentations of power-law profile (with $m = 4$), see Fig. 1. A CNC (Computer Numerically Controlled) milling machine operating at a cutter speed of 1200 rpm was used to produce circular fourth-power indentations into the plates. All experimental samples in the present work were manufactured from 5 mm thick hot drawn mild steel sheets; which are more resistant to mechanical stresses incurred in the manufacturing process than cold drawn steel sheets, thus resulting in fewer internal defects. Dimensions of the produced rectangular plates were 400 × 300 mm, and the indentation diameter was 110 mm with a central hole size of 14 mm. A piece of visco-elastic damping layer was applied to the flat surface on the back of the indentations where stated.

2.2. Experimental set up

Three sets of experiments were carried out in this investigation. The first tests followed the international standard ISO 3744 (see [19]) in order to determine and compare the levels of radiated sound power for the two styles of plates. These plates were then tested using a scanning laser vibrometer in order to compare the observed displacement amplitudes with the associated sound radiation. Finally, the amplitudes of response were considered at the indentation tip, again utilising the scanning laser vibrometer.

The sound radiation experiments were conducted in the anechoic chamber of Loughborough University in order to ensure that the free field conditions were met. The plates were suspended vertically from the test rig. The tests were carried out in accordance with ISO 3744, the international engineering standard for the calculation of radiated sound power [19]. The microphone positions prescribed in ISO 3744 are shown in Fig. 2. The geometrical distances of the microphone from the sample are given in Table 1. The excitation force was applied centrally on the plate via an electromagnetic shaker with force transducer (B&K Type 8200) attached to the plate using 'glue' and fed via a broadband signal amplifier. A microphone and a preamplifier were connected to the RT Pro Phonon analyser, and the sound pressure amplitude

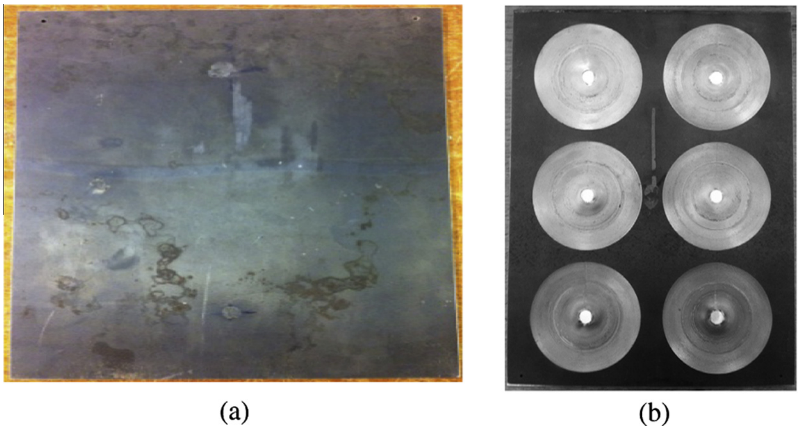
(a) (b)

Fig. 1. (a) Plain reference plate and (b) plate containing six indentations of power-law profile.