Proceedings of Meetings on Acoustics

Volume 18, 2012 http://acousticalsociety.org/

164th Meeting of the Acoustical Society of America
Kansas City, Missouri
22 - 26 October 2012
Session 4aEA: Engineering Acoustics

4aEA8. Sound radiation of rectangular plates containing tapered indentations of power-law profile

Elizabeth P. Bowyer and Victor V. Krylov*

***Corresponding author's address: Aeronautical and Automotive Engineering, Loughborough University, Ashby Road, Loughborough, LE11 3TU, Leicestershire, United Kingdom, V.V.Krylov@lboro.ac.uk**

In this paper, the results of the experimental investigations into the sound radiation of vibrating rectangular plates containing tapered indentations of power-law profile are reported. Such tapered indentations materialise two-dimensional acoustic black holes for flexural waves that result in absorption of a large proportion of the incident flexural wave energy and, therefore, cause efficient damping of plate's flexural vibrations. A multi-indentation plate was compared to a plain reference plate of the same dimensions, and the radiated sound power was determined in accordance with ISO 3744. It was demonstrated that not only do such multiple indentations provide substantial reduction in damping of flexural vibrations within the plate, but also cause a substantial reduction in the radiated sound power. This paper also considers the effect of distribution of the plate's vibrational response on the amplitudes of the radiated sound. It is shown that, despite an increase in the amplitudes of displacements at the indentations' tips, the overall reduction in vibration level over the plate is large enough to result in substantial reduction in the radiated sound power.

Published by the Acoustical Society of America through the American Institute of Physics

Received 12 Oct 2012; published 2 Jan 2013

1. Introduction

Sound can be generated by a variety of different mechanisms. This paper deals with one of such mechanisms, namely with sound radiation resulting from structural vibration, i.e. 'structure borne sound'. More specifically, radiation of sound by flexural vibrations of rectangular plates will be considered. The amplitudes of flexural vibrations of a plate are directly linked to the amplitude of sound radiated from the same plate. Therefore, if the radiated sound is unwanted (noise), a reduction in its level can be obtained via 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 [1-3]. However, this method of damping is not very efficient, and it requires covering of entire surfaces of vibrating structures with rather thick layers of absorbing materials, which is undesirable as it substantially increases masses of the structures.

Over the last decade, a new method of damping flexural vibrations using the so-called 'acoustic black hole effect' to reduce edge reflections has been developed and investigated [4-6]. The acoustic black hole effect is based on peculiarities of flexural wave propagation in plates of variable thickness. Namely, if the local thickness of a plate changes with distance according to a power-law and a power-law exponent is equal or larger than two, then the flexural wave propagating towards the sharp edge slows down very substantially near the edge. If to attach even a small amount of absorbing material to the surface at the sharp edge, the wave energy dissipation is greatly amplified, and only a small fraction of the incident energy is reflected, which constitutes the acoustic black hole effect. It has been demonstrated both theoretically [4, 5] and experimentally [6] that this method is very efficient for damping structural vibrations. As was mentioned above, the traditional methods of vibration damping in plate-like structures involve the use of significant quantities of viscoelastic absorbing materials on plate surfaces, which adds significant mass to the plates. The key advantage of the acoustic black hole effect is a significant reduction in added masses of absorbing materials required, as only sharp edges of tapered plate (wedge) should have small pieces of absorbing materials applied. Recent developments in this area considered structures with both one-dimensional acoustic black holes (wedges of power-law profile attached to plate edges) [7, 8] and two-dimensional acoustic black holes (circular indentations of power-law profile drilled inside plates) [9-15].

The present paper describes the results of the first experimental investigation of sound radiation from vibrating plates containing two-dimensional acoustic black holes (circular 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 an array of six circular 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.

2. Experimental set up and procedure

A plate containing an array of six indentations of power-law profile (with the power-law exponent m = 4) was used for experimental measurements in this investigation, Figure 1. The plate had dimensions of 300 x 400 mm, with the indentations' diameter of 110 mm and central holes' diameter of 14 mm. The plate was made from 5 mm thick steel. A small amount of visco-elastic damping layer was applied to the centres of the indentations where stated. The results were compared to the results obtained for a plain reference plate having the same dimensions and thickness and made of the same material.

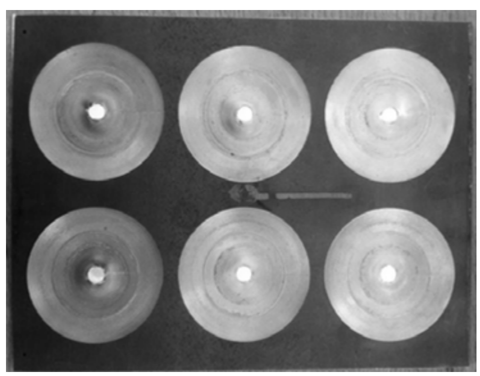


Figure 1: Plate containing six circular indentations of power-law profile.

The initial measurements were carried out 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.

The sound radiation experiments were conducted in the anechoic chamber of Loughborough University. The plates were suspended vertically from the test rig. The tests were carried out in accordance with ISO 3744, the engineering standard for the calculation of radiated sound power. The microphone positions given in ISO 3744 are shown in Figure 2. 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 preamplifier were connected to the RT Pro Phonon analyser, and the measured sound pressure was obtained. This was then converted to sound power.

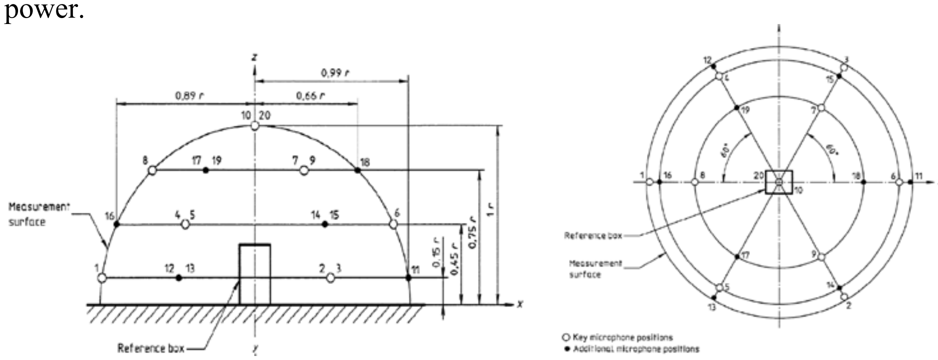


Figure 2: Microphone positions in relation to the sample (ISO 3744).

The sound radiation experiments reported here were conducted without a baffle. This resulted in the short-circuiting effect at low frequencies (dipole-type radiation), which was reduced as the frequency increased. As the plates were subjected to the same experimental conditions for comparative measurements, no frequency correction was applied. A schematic of the experimental set up is shown in Figure 3.

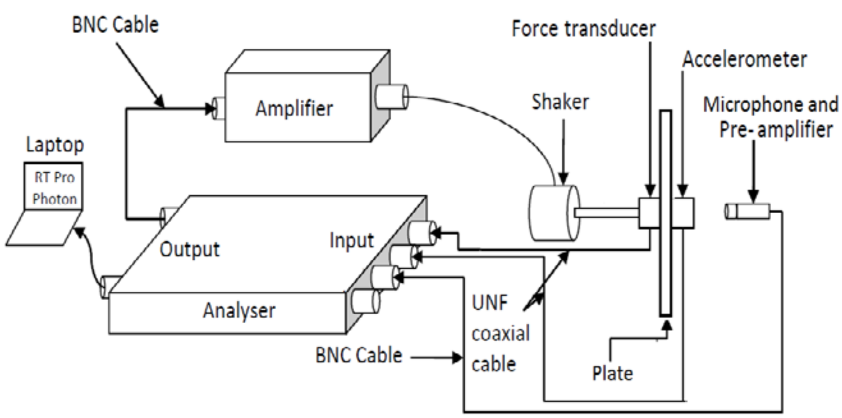


Figure 3: Schematic of sound radiation set up.

The use of the scanning laser vibrometer Polytec OFV 056 was kindly provided by the Universite du Maine (Le Mans, France). This allowed for accurate visual representation of the mode shapes and displacement amplitudes at any given frequency in the test range. The response was recorded by a combined accelerometer and force transducer (PCB Type 208 B02) that was attached to the opposite surface to that being scanned, using 'glue'. The laser vibrometer recorded the point accelerance of the plate along with the amplitude of deflection over the entire plate surface. A frequency range of 0-6 kHz was investigated.

3. Results and discussion

3.1 Sound radiation of a steel plate containing six circular indentations of power-law profile

This section considers sound radiation from the plate containing six indentations of power-law profile (with and without a damping layer) and from a plain reference plate. The sound power level (in dB) and the radiated sound power (in Watts) were calculated. It has been shown in the earlier publication that the addition of a thin visco-elastic layer to the indentation' tip, when a central hole is present, considerably increases the damping performance of the indentation of power-law profile [11]. It was therefore expected that the addition of such a damping layer to the indentation tip will also reduce the sound radiated from the vibrating plate.

Figure 4 shows a comparison of the radiated sound power level (in dB) for a plate containing six indentations of power-law profile with and without a damping layer. It can be seen that, as with the reduction in the vibration response, there is also a reduction in the levels of sound power radiated by the plate when a damping layer is attached to the centres of indentations, showing that the vibration energy is not released as sound but converted to heat, as expected, through the pieces of damping layer. At low frequencies, below 1.2 kHz, the damping layer provides no increased level of sound reduction. A maximum reduction in sound power level of 8 dB occurs at 1.7 kHz.

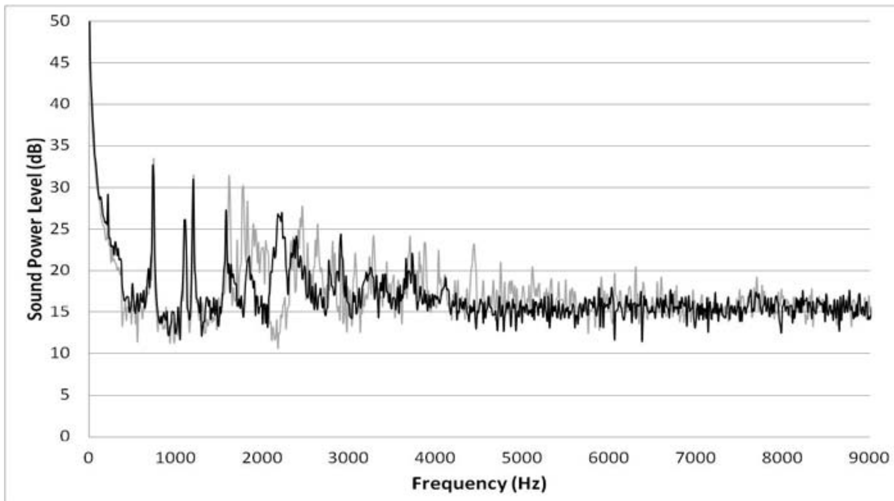


Figure 4: Sound power level comparison for a plate containing six indentations of power-law profile with (black line) and without (grey line) a damping layer.

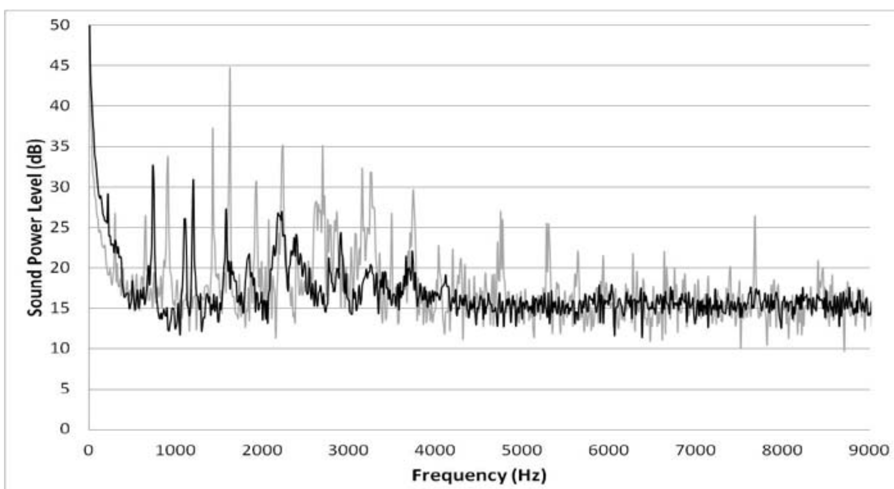


Figure 5: Sound power level comparison for a plate containing six indentations of power-law profile with a damping layer (black line) compared to a reference plate (grey line).

The results for a plate containing six profiled circular indentations with additional damping layers, compared to a reference plate, are shown in Figure 5. Again, below 1 kHz there is little to no reduction in the sound power level, as was the case with the reduction in vibration response. Between 1 – 3 kHz, the sound power level response is reduced from the reference plate's response by 10 – 18 dB, with the maximum reduction in the sound radiation occurring at 1.6 kHz. Above 3 kHz, almost all peak responses in sound radiation are flattened.

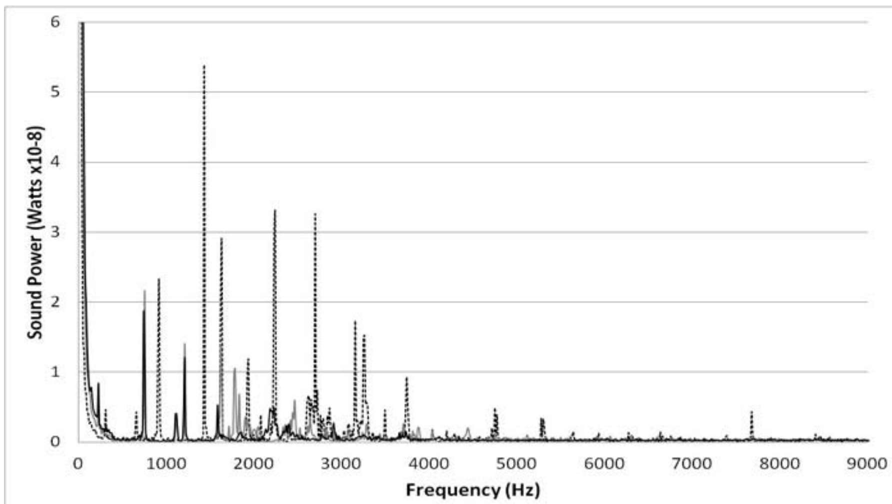


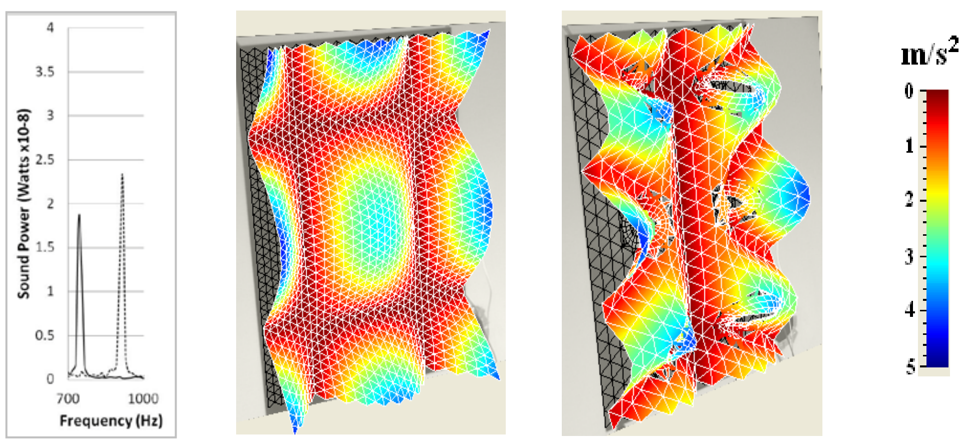
Figure 6: Radiated sound power in watts for a plate containing six indentations of power-law profile with (black line) and without (grey line) a damping layer, compared to a plain reference plate (dashed line).

Figure 6 shows a comparison of the radiated sound power (in Watts) for a plate containing six indentations of power-law profile with and without (grey line) a damping layer, compared to a plain reference plate. After 1.2 kHz the radiated sound power (in Watts) for the six indentation plate with damping layers has been reduced to a level where almost all peaks seen in the reference plate have been removed. The effect of the addition of a damping layer can be seen, but it is less obvious than that seen in the sound power level plots. A maximum reduction of 5.1×10^{-8} Watts is seen at 1.4 kHz.

From the above results, it can therefore be concluded that making six indentations of power-law profile (with a damping layer) in a plate is an effective method of reducing the sound radiation of a steel plate in the medium frequency range (~1-4 kHz). It is well known that sound radiation by higher order plate modes (at higher frequencies) is less efficient. So this method, although efficient at damping higher frequency vibrations, is not expected to greatly reduce higher frequency sound radiation, which is low anyway. This is clearly seen in Figure 6 above 5 kHz.

3.2 Comparison of the sound power response to the vibrational response of the plate

This section considers the amplitudes of the plate's vibrational response in comparison to the amplitudes of the associated sound radiation. A frequency range of 0-5 kHz was used for this investigation. There are two reasons for this choice; the first is that above this value the accuracy of the scanning laser vibrometer is reduced due to the high angles of reflection around the centre of the indentations. The second is that the difference in response in sound power is little to non above the upper frequency range value. This is due to the well-known fact that plates radiate inefficiently at higher order vibration modes, i.e. at higher frequencies. Three resonances were selected for comparison from this frequency range; a low frequency resonance where there is little to no difference in the sound power of the two samples, one in the centre, with a substantial difference in responses, and a resonance towards the upper limit of the frequency range. The two samples considered were the reference plate and the plate containing six indentations of power-law profile with attached damping layers.

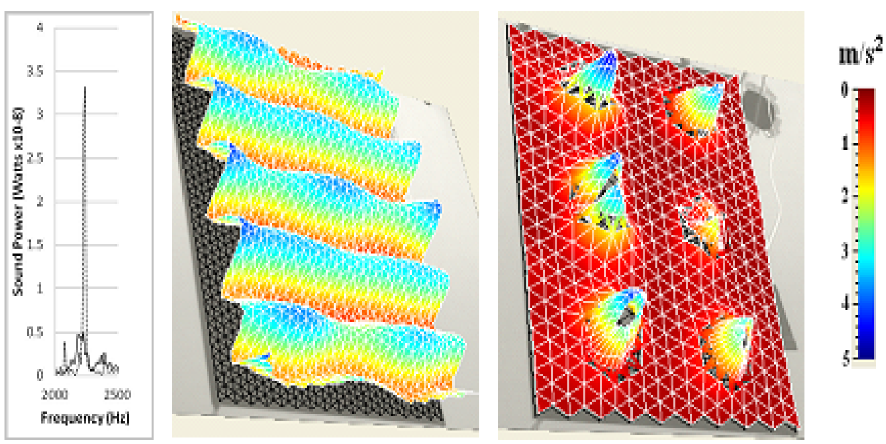


(a) (b) (c) (d)

Figure 7: Results for the resonant peak at 900 Hz: (a) Sound power in Watts for a reference plate (dashed line) compared to the plate containing six indentations with damping layer, (b) Modal response of the reference plate, (c) Modal response of the plate containing six indentations with damping layers, (d) Amplitude of response; key.

The first resonance considered was that at 900 Hz. Although there is a peak shift in the response, there is a minimal difference between the amplitude of the resonance in sound power and accelerance. Figure 7 shows the results for the sound power (in Watts) for the reference plate compared to the plate containing six indentations with damping layers and the modal response of the reference plate and the plate containing six indentations with damping layers. A defined mode shape can be seen with little to no difference in the amplitude of the response. This corresponds to the limited reduction in sound power that can be seen in Figure 7(a). The effect of the indentations has served to slightly alter the mode shape seen at this frequency.

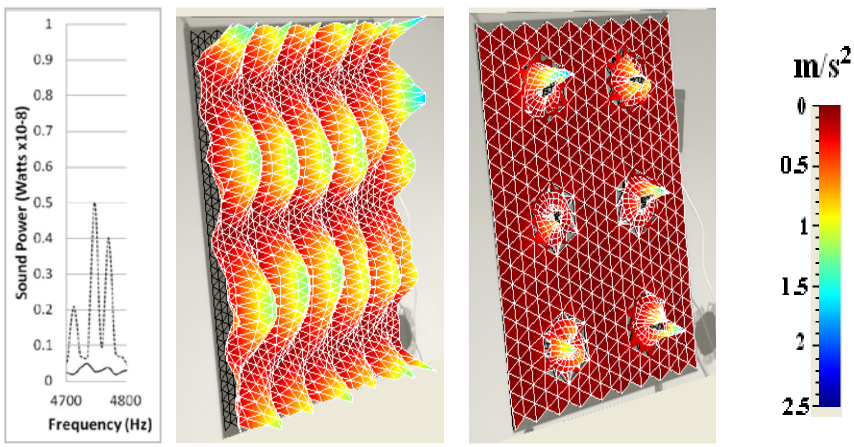
The second resonance considered was that seen at 2.2 kHz, where a reduction in sound power of 3×10^{-8} Watts and a reduction in accelerance of 9 dB from the reference plate can be seen. Figure 8 shows the results for the sound power (in Watts) for a reference plate compared to the plate containing six indentations with damping layers, and the modal response of the reference plate and the plate containing six indentations with damping layers. At this frequency, the mode shape seen in Figure 8(b) has been eliminated by the plate containing six indentations of power-law profile with a damping layer, Figure 8(c). This corresponds with the reduction in sound radiation seen in Figure 8(a).



(a) (b) (c) (d)

Figure 8: Results for the resonant peak at 2.2 kHz: (a) Sound power in Watts for a reference plate (dashed line) compared to the plate containing six indentations with damping layers, (b) Modal response of the reference plate, (c) Modal response of the plate containing six indentations with damping layers, (d) Amplitude of response; key.

There is however some sound radiation from the panel. This can be seen not only on the plot, but also in Figure 8(c), where some displacement over the constant thickness section can still be seen, this displacement increases in the indentations and then a large amplitude increase is seen at the final 2 cm at the tips (centres) of the indentations. Despite this tip deflection being equal in amplitude to that seen on the reference plate, the average reduction over the plate with six circular indentations is great enough to result in a considerable reduction in sound radiation when compared to the reference plate.



(a) (b) (c) (d)

Figure 9: Results for the resonant peak at 4.75 kHz: (a) Sound power in Watts for a reference plate (dashed line) compared to the plate containing six indentations with damping layers, (b) Modal response of the reference plate, (c) Modal response of the plate containing six indentations with damping layers, (d) Amplitude of response; key.

The final resonance considered was that seen at 4.75 kHz. Figure 9 shows the results for the sound power (in Watts) for a reference plate compared to the plate containing six indentations with damping layers, and the modal response of the reference plate and the plate containing six indentations with damping layers. It can clearly be seen, Figure 9(c), that other than a radius of 2 cm at the centre of the indentations the amplitude of the response over the entire plate is zero. The mode shape seen in Figure 9(b) had been eliminated in Figure 9(c). This 'active' area on the indentation plate, where a response is seen, corresponds to the area over which the damping layer was determined to be effective. The amplitude of the response in the 'active' area is approximately 1 m/s^2 greater than that seen on the reference plate. However, this does not affect the sound radiation of the plate, as seen in Figure 9(a). The trends described above are the same for all resonances observed during testing.

4. Conclusions

A plate containing the array of six indentations of power-law profile covered by small pieces of damping layers has shown a significant reduction in the level of sound radiation. In the medium frequency range, 1 – 3 kHz, the radiated sound power level response was reduced from the reference plate response by 10 – 18 dB.

As the frequency increases the amplitude of deflection over the constant thickness section of a plate containing circular indentations of power-law profile tends to zero. At lower frequencies, where no reduction in sound radiation or vibration response is seen, the plate behaves as a constant thickness plate, with a little difference from the plate without indentations.

In the frequency range where reductions in vibration response and sound radiation are seen the plate vibration pattern changes substantially, with a noticeable amplitude reduction outside the indentations. In the higher frequency range the only displacement on the plate is seen in the last 2 cm of the indentation tip (centre). This corresponds to the area of maximum effectiveness of the damping layer.

Despite these tip deflections being equal in amplitude to that seen on the reference plate, the average reduction over the plate with six circular indentations is great enough to result in a considerable reduction in sound radiation when compared to a reference plate.

Acknowledgements

The research reported here has been partly supported by EPSRC grant EP/F009232/1. The authors are grateful to F. Gautier of Universite du Maine (Le Mans, France) for providing the opportunity to use their scanning laser vibrometer for some vibration measurements reported in this paper. The authors also would like to thank Mr M. Secail-Geraud for his assistance with the laser vibrometer in Le Mans.

References

[1] M. Heckl, L. Cremer, E. Ungar, "Structure borne sound", 2nd Edition, Springer-Verlag, Berlin (1988).
[2] D.J. Mead, "Passive vibration control", Wiley, Chichester (1998).
[3] D. Ross, E. Kerwin, E. Ungar, "Damping of plate flexural vibrations by means of viscoelastic laminae", In: Structural Damping (Ruzicka, J. E., ed), vol. 3, 44-87 (1959).
[4] V.V. Krylov, F.J.B.S. Tilman, "Acoustic black holes for flexural waves as effective vibration dampers", Journal of Sound and Vibration, 274, 605-619 (2004).
[5] V.V. Krylov, "New type of vibration dampers utilising the effect of acoustic 'black holes'", Acta Acustica united with Acustica, 90, 830-837 (2004).
[6] V.V. Krylov, R.E.T.B. Winward, "Experimental investigation of the acoustic black hole effect for flexural waves in tapered plates", Journal of Sound and Vibration, 300, 43-49 (2007).
[7] D.J. O'Boy, V.V. Krylov, V. Kralovic, "Damping of flexural vibrations in rectangular plates using the acoustic black hole effect", Journal of Sound and Vibration, 329, 4672–4688 (2010).
[8] E.P. Bowyer, D.J. O'Boy, V.V. Krylov, J.L. Horner, "Effect of geometrical and material imperfections on damping flexural vibrations in plates with attached wedges of power law profile", Applied Acoustics, 73, 514-523 (2012).
[9] V.V. Krylov, Propagation of plate bending waves in the vicinity of one- and two-dimensional acoustic 'black holes', Proceedings of the ECCOMAS International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2007), Rethymno, Crete, Greece, 13-16 June 2007, [CD-ROM].
[10] F. Gautier, J. Cuenca, V.V. Krylov, L. Simon, "Experimental investigation of the acoustic black hole effect for vibration damping in elliptical plates" (Abstract for the Conference "Acoustics 08", Paris, France, June 2008), Journal of the Acoustical Society of America, 123 (5), 3318 (2008).
[11] E.P. Bowyer, D.J. O'Boy, V.V. Krylov, F. Gautier, "Experimental investigation of damping flexural vibrations using two-dimensional acoustic 'black holes'", Proceedings of the International conference on Noise and Vibration Engineering (ISMA 2010), Leuven, Belgium, 20-22 September 2010 (Ed. P. Sas, B. Bergen), pp. 1181-1192.
[12] V.B. Georgiev, J. Cuenca, F. Gautier, L. Simon, V.V. Krylov, "Damping of structural vibrations in beams and elliptical plates using the acoustic black hole effect", Journal of Sound and Vibration, 330, 2497–2508 (2011).

[13] D.J. O'Boy, E.P. Bowyer, V.V. Krylov, "Damping of flexural vibrations in thin plates using one and two dimensional acoustic black hole effect", Proceedings of the 10th International Conference on Recent Advances in Structural Dynamics (RASD 2010), Southampton, UK, 12-14 July 2010, [CD-ROM].
[14] D.J. O'Boy, V.V. Krylov, "Damping of flexural vibrations in circular plates with tapered central holes", Journal of Sound and Vibration, 330, 2220–2236 (2011).
[15] D.J. O'Boy, E.P. Bowyer, V.V. Krylov, "Point mobility of a cylindrical plate incorporating a tapered hole of power-law profile", Journal of the Acoustical Society of America, 129, 3475–3482 (2011).