A SIMPLE TRANSDUCER OF SURFACE VIBRATIONAL VOLUME VELOCITY

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1. INTRODUCTION

In the study of the radiation of sound from vibrating surfaces, it is often desirable to be able to measure the distribution of normal velocity over a surface. This is traditionally carried out using accelerometer measurements at points on the surface with a spacing determined by the acoustic wavelength of the highest frequency of interest: $d < \pi / k_a(\mathrm{max})$, where d is the spacing between points and $k_a(\mathrm{max}) = 2\pi f(\mathrm{max}) / c_o$ is the acoustic wavenumber of the highest frequency of interest. Many practical vibrating surfaces, such as a cover on part of an engine, contain stiffeners and edges which can give rise to vibrational patterns containing high wavenumber components. Such short-wavelength vibration components do not radiate sound very efficiently so attempts to characterise the radiation of sound from such a surface using point sampling techniques can give rise to gross errors due to spatial aliasing. This problem can be minimised if the total volume velocity, averaged over an area of $d \times d$ is measured instead, as the high wavenumber vibration components are then largely averaged out. If the surface to be characterised is reasonably flat and electrically conducting, this spatially averaged volume velocity can be measured using a capacitance probe (see [1]); however an alternative method is required for other surfaces. This paper contains a description of a prototype of a simple volume velocity transducer which can be used to measure the instantaneous spatial integral of normal velocity of many different types of surface including hot, dirty or fragile structures.

2. INVESTIGATION OF SPATIAL ALIASING

To investigate the spatial aliasing errors associated with point vibration measurements, a computer simulation of a vibrating plate has been set up. The vibration of the plate, which is assumed to be simply-supported in an infinite baffle, consists of the summation of the first 50 modes of vibration in the two planes of the plate (2500 modes in all). All of the modes have the same amplitude, but random phase. The radiation of sound to a point in the far field at 45° to the plate axis is then calculated using an analytical solution of the Rayleigh integral equation (see [2]), over a range of frequencies up to just below $f(\mathrm{max})$. The plate is then divided into small areas ($d \times d$) and the radiation calculated using the velocity at a point in the centre of each area in a numerical approximation to the Rayleigh integral. Finally the velocity is integrated over each area and the radiation re-calculated. The differences between the two far-field pressure approximations and the 'exact' analytic solution are then evaluated. The mean and standard deviation of the error (in dB), calculated from an ensemble of 50 different random vibration fields are shown in figures 1 and 2. It can be seen that the point sample approximation gives rise to much higher errors than the spatial integral approximation and that the mean of these errors is always positive indicating an over-estimation of the radiated sound field. The small errors in the spatial integral result are probably due to the geometric approximation of assuming that the integrated velocity acts at a point in the centre of the area; this error is of course common to both methods. The error from using either approximation tends to zero as the spacing (*d*) tends to zero.

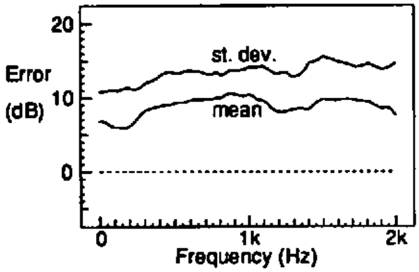

Figure 1. Mean and Standard Deviation of Error in Far-Field Pressure: 1m × 0.7m Plate; d = 0.05m: Point Sample Approximation.

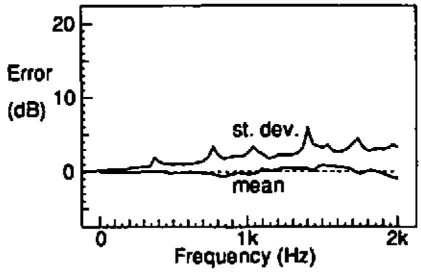

Figure 2. Mean and Standard Deviation of Error in Far-Field Pressure: 1m × 0.7m Plate; d = 0.05m: Area Integral Approximation.

The vibrating plate simulation represents an extreme situation with the high wavenumber vibration components having equal magnitude to the low wavenumber components. For most practical structures, the high wavenumber components will be present in smaller quantities than in the simulation, and the errors correspondingly lower. Experiments on real structures are planned, and it is hoped that some of the results of these will be presented at the conference.

3. THE VOLUME VELOCITY TRANSDUCER

3.1 Principle of Operation.

The prototype volume velocity transducer consists of a miniature electret microphone mounted in the wall of a short pipe, one end of which is anechoically terminated and the other open. When the open pipe-end is brought close to a vibrating surface, an acoustic wave propagates along the pipe towards the microphone in response to the velocity of the surface. If the microphone is mounted a sufficient distance from the open pipe-end, only plane-waves, generated by the *average* velocity of the surface will reach the microphone; the output from the microphone is then a measure of the instantaneous normal volume velocity of the surface, integrated over the area beneath the pipe-end (figure 3).

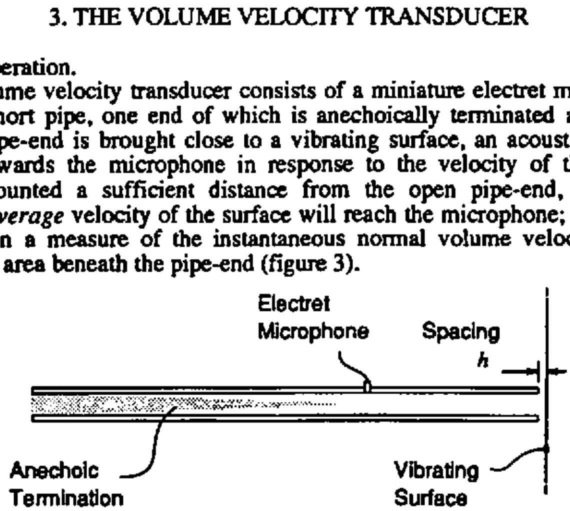

Figure 3. Operation of Transducer.

VOLUME VELOCITY TRANSDUCER

3.2 Calibration of Transducer.
The method used to calibrate the prototype transducer relies on the principle of acoustic reciprocity, according to which the transfer function between an acoustic volume velocity source and an acoustic receiver is independent of a reversal of the positions of source and receiver. The transfer function between the volume velocity of the surface and the pressure at the microphone is thus the same as that between the volume velocity of a source placed at the microphone position and the resultant pressure on the surface (figure 4).

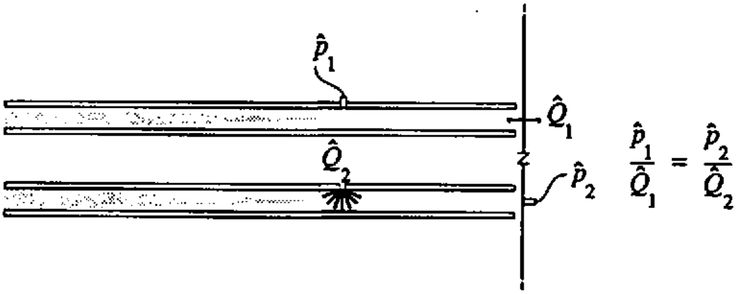

Figure 4. Acoustic Reciprocity Applied to Transducer.

To calibrate the transducer, the microphone is mounted in a rigid baffle and a small pipe, to which is attached an electroacoustic driver, is mounted in the tube (figure 5).

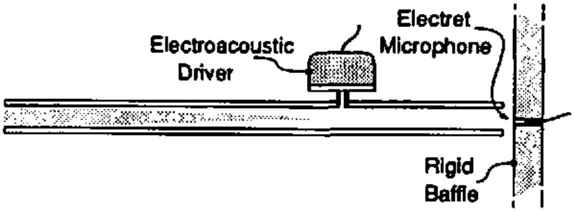

Figure 5. Reciprocal Calibration of Transducer.

The sensitivity to the size of the gap (h) between the surface and the pipe-end and the spatial selectivity of the transducer can then be investigated by moving the pipe-end relative to the microphone.

3.3 Calibration of Electroacoustic Driver.
The reciprocal transducer calibration procedure relies on a knowledge of the volume velocity of the electroacoustic driver. Because the driver used is not a perfect velocity source, it must be calibrated under loading conditions as similar as possible to those under which it will be used. Calibration can be carried out in the pipe by sealing the pipe-end to the rigid baffle (in figure 5); by reciprocity, assuming the anechoic termination to be perfect, the volume velocity output of the driver is then given by

$$\hat{Q} = \frac{S}{\rho_o c_o}\hat{p}e^{ikl} \quad ,$$

where S is the cross-sectional area of the pipe, p is the pressure measured on the baffle, k is the acoustic wavenumber, l is the distance from the driver to the baffle and $\rho_o c_o$ is the characteristic impedance of the propagating medium.

3.4 Spatial Selectivity.
In order to map the volume velocity of a surface, the transducer should employ of a square-section pipe to allow the entire surface to be divided up into areas of the same size as the pipe. Ideally, such a transducer would be sensitive only to vibration directly beneath the pipe-end but in practice some sensitivity to vibration outside this area is inevitable, leading to overlap and consequent over-estimation of total volume velocity. To overcome this problem the transducer should have a sensitivity at the edge of the area that is 6dB lower than it is in the centre; the estimation of the total volume velocity would be then be approximately correct. Figures 6 and 7 show the spatial selectivity of the 25mm diameter, circular-section prototype transducer along a radial line from the centre of the pipe, for gaps (h) of 3mm and 10mm, over a range of frequencies. The measurements are normalised to the sensitivity at the centre of the pipe.

Figure 6 shows that the sensitivity of the transducer to vibration at radial position 3, beneath the edge of the pipe-end, is close to the ideal -6dB over the entire range of frequencies when the gap is set to 3mm; the sensitivity is seen to fall fairly rapidly with increasing radial distance outside this, being approximately -15dB at twice the pipe radius. Figure 7 shows that the area over which the transducer is sensitive is larger than the pipe-end when the gap is set to 10mm, with approximately -6dB sensitivity at radial position 4 (approx. 3mm from outside edge of pipe); the sensitivity falls much less rapidly with increasing radial distance than with a 3mm gap, being approximately -7dB at twice the pipe radius.

In an attempt to improve the spatial selectivity of the transducer, a sleeve of cloth having a high flow resistance was attached to the end of the pipe such that it closed the gap between the pipe-end and the surface. Figures 8 and 9 show the spatial selectivity of the transducer for gaps of 3mm and 10mm with the sleeve in place. It can be seen from figures 8 and 9 that the presence of the cloth sleeve improves the spatial selectivity of the transducer, with an increase in rejection of vibration at a radial distance of twice the pipe radius of about 6dB compared to the un-sleeved case; with the gap set to 3mm, the selectivity of the transducer is close to ideal.

From these initial tests on the prototype transducer, it appears that by changing the size of the gap between the pipe-end and the surface, along with careful selection of sleeve material, the spatial selectivity of the transducer can be tailored to requirements. As the spatial selectivity of the transducer is essentially frequency independent, it is expected that this aspect of performance should scale in a non-dimensional manner; a pipe having twice the diameter should require twice the gap. Further experiments on pipes of different sizes and shapes are planned so that relationships between pipe-size, gap size, sleeve material and spatial selectivity can be proved.

3.5. Sensitivity to gap size.
Figure 10 shows the sensitivity of the prototype transducer to gap sizes of 3mm, 6mm and 10mm; the curves are normalised to the sensitivity with no gap. Figure 11 is as figure 10 but with the cloth sleeve in place. It can be seen from these figures that the transducer is less sensitive to the size of the gap when the sleeve is in place.

VOLUME VELOCITY TRANSDUCER

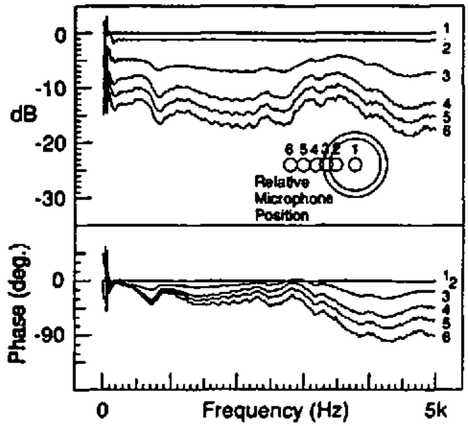

Figure 6. Spatial Selectivity of Transducer: h = 3mm.

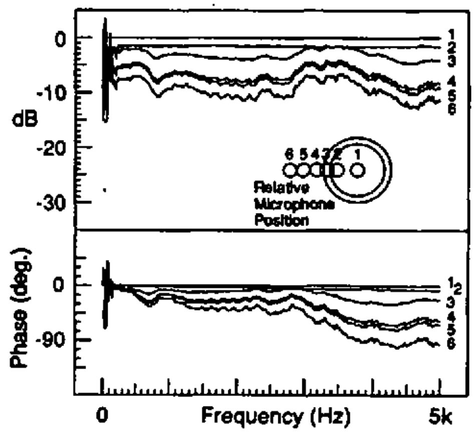

Figure 7. Spatial Selectivity of Transducer: h = 10mm

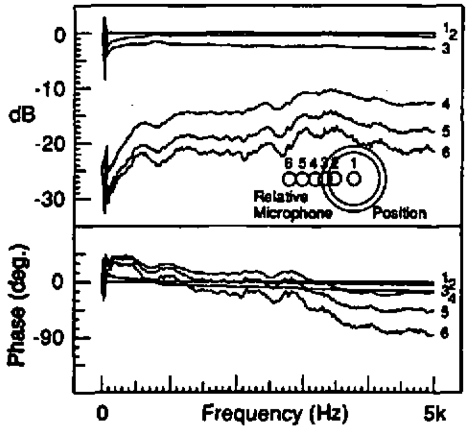

Figure 8. Spatial Selectivity of Transducer: h = 3mm with Sleeve.

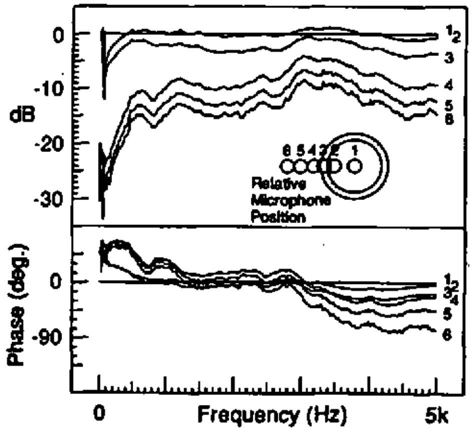

Figure 9. Spatial Selectivity of Transducer: h = 10mm with Sleeve.

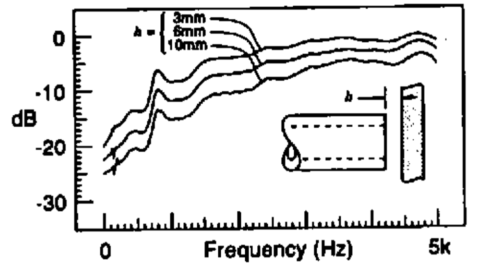

Figure 10. Sensitivity of Transducer to Gap Size (h).

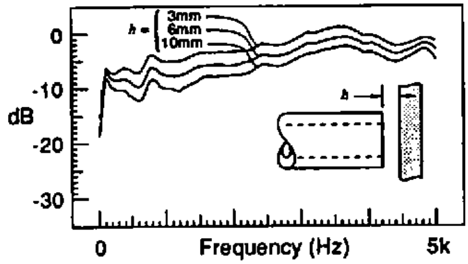

Figure 11. Sensitivity of Transducer with Sleeve to Gap Size (h).

4. TESTING OF PROTOTYPE TRANSDUCER

The prototype transducer was tested by measuring the spatial average volume velocity of a circular area (25mm diameter) of a 1mm thick aluminium plate driven by an electro-dynamic shaker. The measurement was then repeated using a miniature accelerometer which was moved to 21 positions within the area. The average of all of the accelerometer measurements was then compared to the calibrated transducer measurement. The transducer measurement was taken with a gap of 3mm and no sleeve. These two measurements, referenced to the voltage drive to the shaker, are shown in figure 12.

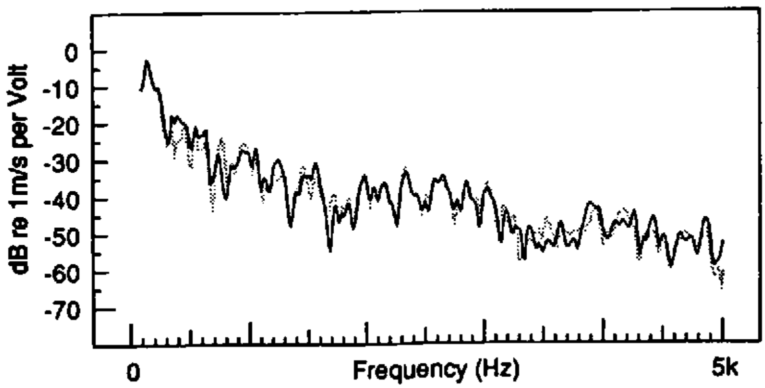

Figure 12. Spatial average velocity of a circular area of a vibrating plate, referenced to the voltage drive to the shaker, using: 21 accelerometer positions (grey line), and the volume velocity transducer (black line).

Neither of these measurements are correct as the transducer does not have perfect spatial selectivity and the accelerometer has a finite mass which will influence the velocity of the plate, but figure 11 shows that the two measurement techniques are at least comparable.

5. DISCUSSION

The volume velocity transducer, as described, could be developed into a very cheap and convenient tool for the measurement of the spatial average velocity of vibrating surfaces. A range of different pipe sizes and shapes could be used, depending upon the frequency range of interest, and because the plane-wave cut-off frequency of a square section tube is the same as the spatial sampling maximum frequency (f_{max}) stated in section 1, acoustic spatial aliasing errors in sound radiation estimations will automatically be eliminated if the correct pipe size is chosen. Because the transducer can be a non-contacting device (without the sleeve), it is possible to measure the vibration of very light structures, such as vehicle interior trim, or hot / dirty surfaces such as engine components. One property of the transducer which may be of considerable importance in some circumstances is its portability; even a fairly large tube, if constructed of lightweight material, could incorporate a handle and so be hand-held in operation.

One major problem with the transducer is the maintenance of the gap between the pipe-end and the surface. This is made easier with the sleeve in place, but figures 10 and 11 show that the sensitivity of the transducer changes by about 1dB per mm for practical gap sizes, so if the device is to be hand-held, some form of distance sensing device may be necessary.

Although the use of an anechoic termination at the end of the pipe is not required, in theory, for operation and calibration of the transducer (the reciprocal relationship still holds), in practice, a reflective termination will give rise to a very uneven calibration curve, which could cause signal-to-noise or dynamic range problems. Also, an anechoic termination *is* required for calibration of the driver using the technique described above. The prototype transducer described here has an anechoic termination which consists of a wedge of open-cell plastic foam inserted into the end of the tube. Such a termination is only effective at frequencies having an acoustic wavelength less than four times the length of the wedge. The prototype wedge is 300mm long, which gives a lower frequency limit of about 300Hz; a longer termination would make the transducer impractical to use unless it were coiled in a 'snail shell' type manner. A second prototype, having a diameter the same as that of the first, has been constructed which has a novel termination based on a paper by Dalmont et al [3]. This termination consists of a flange fixed to the end of the pipe to which is added a sheet of 'micro-porous' material with a small foam-filled gap inbetween (see figure 13). This termination is less effective at high frequencies than the foam wedge, but is effectively anechoic down to at least 20Hz (the low-frequency limit of the measurements taken) and takes up a lot less room. A combination of this termination and a short foam wedge has yielded acceptably reflection-free results over a wide range of frequencies.

A larger (50mm) square-section transducer, to be used in spatial sampling experiments (see section 2), is under construction at the time of writing. This transducer is to incorporate a termination similar to the second prototype but 'folded' around the pipe to further reduce physical size.

VOLUME VELOCITY TRANSDUCER

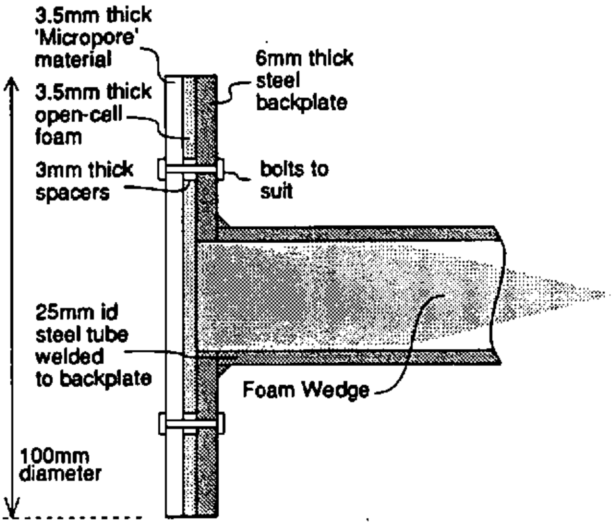

Figure 13. Details of New Anechoic Termination.

6. REFERENCES

[1] J. M. Mason, F. J. Fahy, "Development of a Reciprocity Technique for the Prediction of Propeller Noise Transmission Through Aircraft Fuselages", Noise Control Engineering Journal, 34 (2), pp 43-52, (1990).

[2] F. J. Fahy, "Sound and Structural Vibration: Radiation Transmission and Response", Academic Press Inc. (London) Ltd. ISBN 0-12-247670-9, pp 61-62, (1987).

[3] J. P. Dalmont, J. Kergomard, X. Meynial, "Réalisation d'une Terminaison Anéchoïque pour un Tuyau Sonore aux Basses Fréquences", C. R. Acad. Sci. Paris, t. 309, Serie II, pp 453-458, (1989).