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THE VAS: A NEW NON-CONTACT SENSOR FOR MEASURING SURFACE VIBRATION

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1. INTRODUCTION

Experimental investigations of sound radiation from vibrating solid surfaces often require measurements to be made of the surface vibration field. The most commonly used transducers are accelerometers. They are usually selected because they are relatively cheap, they are rugged and they need no support/reference structure, because they operate on an inertial principle. However, a major disadvantage of accelerometers in respect to sound radiation studies is that they sample the vibration field only at discrete points. This can produce serious sampling errors in cases of spatially non-uniform structures such as stiffened body panels and modular sound insulation treatments of vehicles. Figure 1 shows the differences between acceleration spectra measured at three points on model of an aircraft fuselage structure [1]. It is clearly impossible to choose a 'representative' sample point.

A problem which arises even with spatially uniform structures is that point sampling suffers from spatial frequency (wavenumber) aliasing, which is the same phenomenon as that produced by undersampling a time history. This has serious consequences for the interpretation of the sampled data in terms of sound radiation from the surface. At any frequency, surface wavenumber vector components of which the magnitudes are greater than the acoustic wavenumber in a contiguous fluid radiate no sound energy. Aliasing can cause non-radiating components to be folded back into the radiation domain, thereby giving rise to over prediction of radiation. This effect has been observed in the results of studies of sound radiation of plates using the principle of vibroacoustic reciprocity [2].

Laser vibrometers are also used to measure surface vibration fields. They may be scanned to sample time histories, and hence auto- and cross-spectra on a dense mesh of points. However, they are extremely expensive and rather unsuitable for use in operational vehicles, especially since they require a 'static' mounting system.

Two-microphone intensity probes can, in principle, be used to estimate the normal surface velocities of structures but because they are working in the exponentially decaying near field, the results are not reliable [3].

For these reasons, attempts have been made by ISVR over the past decade to develop alternative means of measuring surface vibration, with the particular objective of providing volume velocity distribution data for combination with reciprocally measured transfer functions in order to establish the contributions of segments of vibrating surfaces to the sound pressure level at target points such as a car driver's ear. The first device to be developed was named the VVT (Volume Velocity Transducer). It comprises an anechoically terminated tube containing an electret microphone and is illustrated in Figure 2. With a tube measuring 70 mm square it has a useful frequency range from 40 to 2000 Hz. The mouth of the tube is placed about 15 mm from the surface of a vibrating structure and the microphone signal is proportional to the spatial integral of the instantaneous normal velocity of the local surface. The device automatically filters out components of surface

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vibration which have wavenumbers greater than $2\pi/L$, where L is the side length of the square sampling tube. The VVT has been successfully used to map the volume velocity distribution over the inner surface of the driver compartment of a light commercial vehicle and thence to rank the contributions of the various regions of the surface to noise at the driver's head position [4]. It has also been specifically developed for application to the estimation of noise radiated from industrial pipework. The results are currently confidential to the client.

The development of the Volume Acceleration Sensor (VAS) was motivated by a requirement on the part of a truck manufacturer for a device for measuring low frequency (0-400 Hz) vibration of the inner surfaces of a driver's cab. The VVT was not considered to be ideal for this purpose because of the large area segments appropriate to the task which would have required an unacceptably cumbersome model. Previous experience had also shown that the VVT was vulnerable to high levels of reverberant sound generated by surfaces other than that being monitored. This paper charts the development process and presents design and performance data for the new device.

2. THE FIRST PROTOTYPE

The aim was to develop a lightweight, easily manageable, sensor to measure instantaneous volume acceleration distributions over the inner surfaces of vehicles. The principle employed was based upon Euler's equation which relates fluid particle acceleration to the associated pressure gradient. This is, of course, the principle employed in the *p-p* intensity measurement probe. In order to provide an approximation to the spatial integral of the instantaneous pressure gradient close to a vibrating surface, it was decided to sample the sound pressure on two planes separated by a suitable distance by means of two parallel planar arrays of small pressure microphones. The signals from the microphones in each array were to be summed and the difference between the two sum signals output as a measure of the average pressure gradient across the space between the arrays.

Extensive mathematical modelling of the theoretical performance of the proposed system was undertaken. Particular attention was paid to prediction of the performance in highly reverberant enclosures excited by panel vibration [5]. Microphones placed on a square grid of 50 mm pitch and an array area of 200×200 mm^2 was found to be optimum for the design frequency range and for vibration fields in 1 mm thick steel panels. The theoretical results indicated that excellent performance could be obtained provided that microphones at corresponding locations in the two arrays were very precisely matched for sensitivity. Phase match was predicted to be not so critical, but still important.

A prototype system was constructed in which two planar arrays each of sixteen cheap, 6 mm diameter, electret microphones were mounted upon a wire frame which separated the arrays by a distance of 30 mm (Figure 3). Experimental tests made on a 1 mm thick aluminium panel in a reverberation room confirmed the theoretical predictions and demonstrated excellent rejection of extraneous reverberant sound. However, the wire frame was bulky and vulnerable to damage, the microphones were also vulnerable, and the maze of microphone leads made the device heavy and impractical for consideration as a potential commercial development.

3. THE SECOND PROTOTYPE

It was realised that a more compact, structurally integrated model was needed. It was decided to investigate the possibility of introducing an impedance layer between the microphone arrays in order to increase the pressure gradient produced by a vibrating surface in close proximity without acoustically isolating the upper microphone array. Theoretical and experimental studies showed that a pure resistive layer converted the device into a sensor of volume *velocity* and greatly reduced its sensitivity. However, an *inertial* impedance layer having a normalised differential specific impedance of between one and two appeared to answer the demand. The obvious practical implementation took the form of a perforated plate.

The effect of the pressure difference enhancement was to allow the array separation distance to be reduced to 12 mm and the microphones and their cables to be embedded in a 12 mm thick, transparent, perforated plate structure, thereby solving the problem of structural fragility and microphone vulnerability in one fell swoop. The transparency of the plate aids location during measurement. Extensive theoretical and experimental studies of various configurations of holes led to a design which appropriately balanced the influence of the transmission through the holes and diffraction around the edge of the plate.

Thirty two microphones were selected from a larger batch as being acceptably phase matched, and variable attenuators installed in the associated electronic equipment allowed pair sensitivities to be very precisely matched. A special purpose microphone calibration system was constructed for this purpose. The assembled system is shown in Figure 4.

A performance test was made on a 1 mm thick vibrating panel by an independent laboratory in Germany. A comparison between the estimates of volume acceleration based upon a 100 point measurement made with a laser velocimeter and that indicated by the single VAS output signal is shown in Figure 5.

4. THE FINAL PRODUCT

The problem of pair sensitivity matching was then solved by replacing the corresponding microphone pairs by sixteen 6 mm diameter electret *pressure difference* microphones supplied by Knowles Electronics. These are embedded within the plate and communicate with the external air via holes on each side. Microphones were selected for good phase match from a larger batch by mounting them in a special purpose calibration plate on each side of which were placed a pair of phase matched B&K intensity microphones. The plate was insonified by a loudspeaker placed at a distance of about 40 mm. Variable attenuators were adjusted to achieve equal sensitivity among all the microphones. The associated amplifier incorporates a 4 Hz high pass filter to eliminate any adverse effects of 'hand shake' The final design is shown in Figures 6 and 7. **Readers should take careful note that the VAS does not correctly measure particle acceleration in *free field*. It is designed to operate only in close proximity to a vibrating surface**

5. CALIBRATION

There is no unique calibration for a spatial sampling device such as the VAS. The performance will depend to some extent upon the form of field sensed. For this reason, a BEM model of the VAS has been developed and studies are continuing into theoretical performance when sensing a range of acceleration distributions. The model is also being used to try to further improve the perforation configuration.

The VAS has been tested on vibrating surfaces having very different vibration distributions. One was that of a low frequency loudspeaker having a very stiff 'piston' radiator measuring 140 mm × 200 mm. The other was a 3.5 mm thick aluminium plate measuring 900 mm × 620 mm driven by a single electromagnetic shaker. The fundamental mode resonance frequency is 43 Hz and the asymptotic modal density is 0.05 modes/Hz. Transfer functions were measured between the inputs and accelerations sampled at ten points on the loudspeaker 'piston' and twenty five points on the area of the plate covered by the VAS. The real and imaginary parts of the TF's were averaged and compared with that from the VAS signal. Results for a stand-off distance of 17 mm are shown in Figure 8 and 9. The sensitivity was very similar for both vibration fields and the calibration curve is reasonably flat over the range 40 to 400 Hz which meets the design target. The average sensitivity for a stand-off distance of 17 mm is 25 mV/ms^{-2} in terms of surface-average acceleration, or 625 mV/m^3s^{-2} in terms of volume acceleration.

The variation of VAS sensitivity as a function of stand-off distance was also measured. A typical result is shown in Figure 10. The step variation was very similar, within ± 0.2 dB, for the plate test. The VAS/amplifier combination remained linear up to an acceleration of at least 2.0 $m\ s^{-2}/Hz$. The instrument noise referred to input corresponded to an acceleration of $10^{-3}\ m\ s^{-2}/Hz$. The dynamic range is therefore at least 60 dB.

Finally, the influence of extraneous reverberant sound on the VAS output was measured by exciting a room by a loudspeaker driven by broad band random noise and placing the VAS at a stand-off distance of 20 mm from the 400 mm thick concrete floor of the room. The VAS signal was equivalent to a displacement of 7×10^{-8}m/Pa over the range 70–500 Hz. With the VAS displaced laterally in its own plane so that it was just clear of the loudspeaker piston, the response was at least 20 dB below that when placed at a distance of 17 mm over the piston. These values indicate a remarkably high degree of immunity to noise generated by surfaces other than that being monitored.

6. CONCLUSION

A rugged and easily manipulated device for measuring surface volume acceleration over the frequency range 40-400 Hz has been developed. It exhibits satisfactory sensitivity, linearity, dynamic range and immunity from the influence of extraneous reverberant noise. In principle, all its dimensions could be halved to double its frequency range.

ACKNOWLEDGEMENTS

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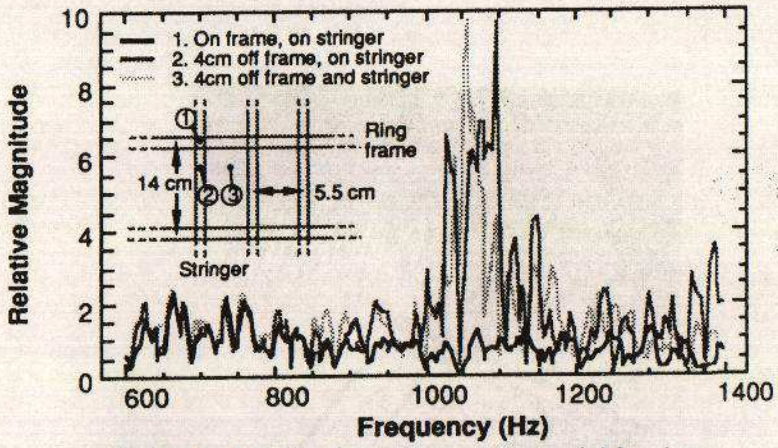

Figure 1 Acceleration spectra on a model fuselage

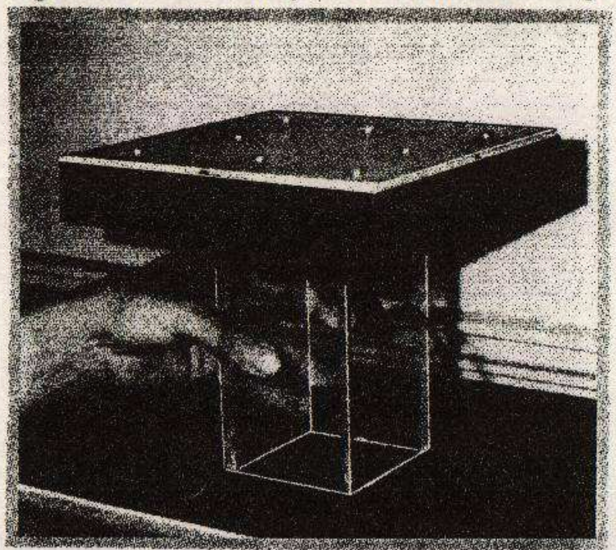

Figure 2 The Volume Velocity Transducer (VVT)

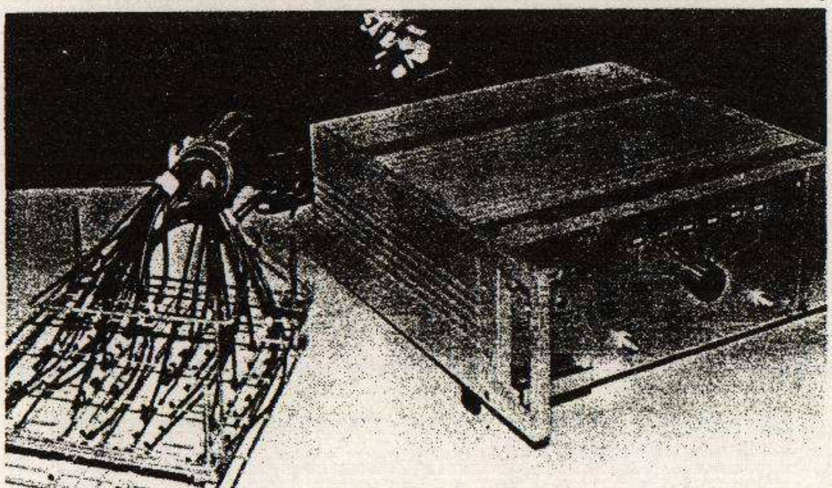

Figure 3 VAS1: the first prototype

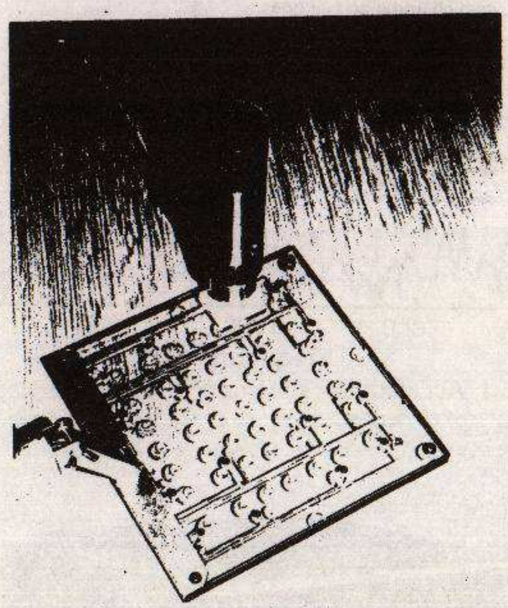

Figure 4 VAS2: the second prototype and calibrator

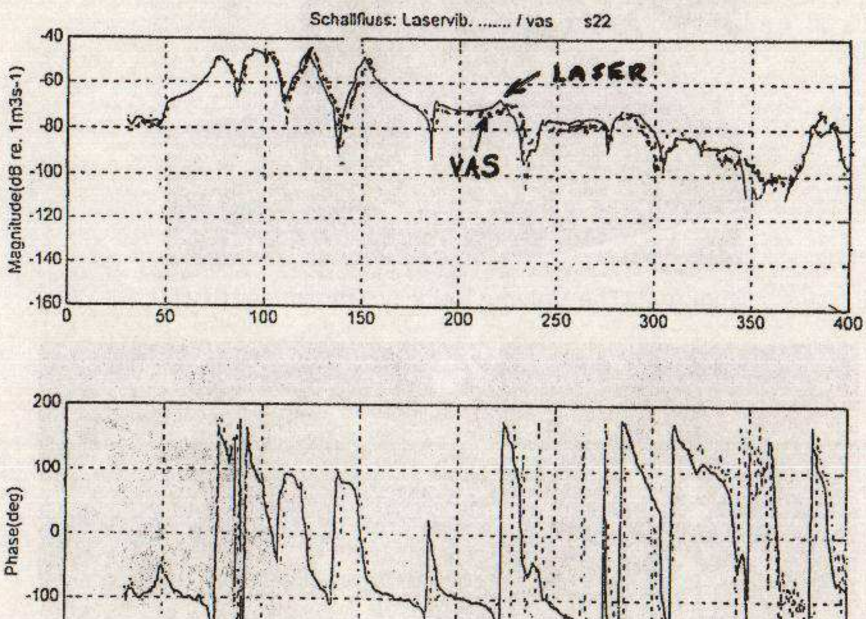

Figure 5 VAS2: Comparison of VAS and LDV estimates of volumetric acceleration

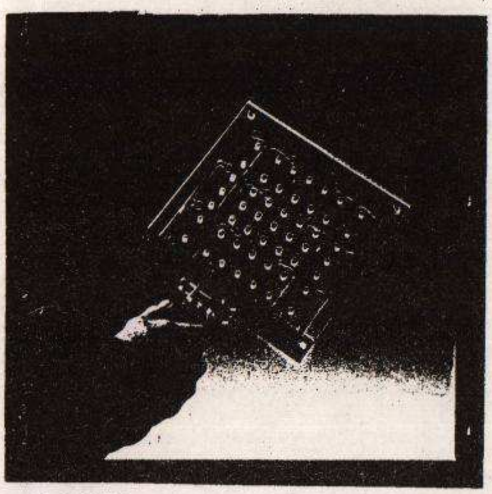

Figure 6 VAS3

Figure 7 Using the VAS

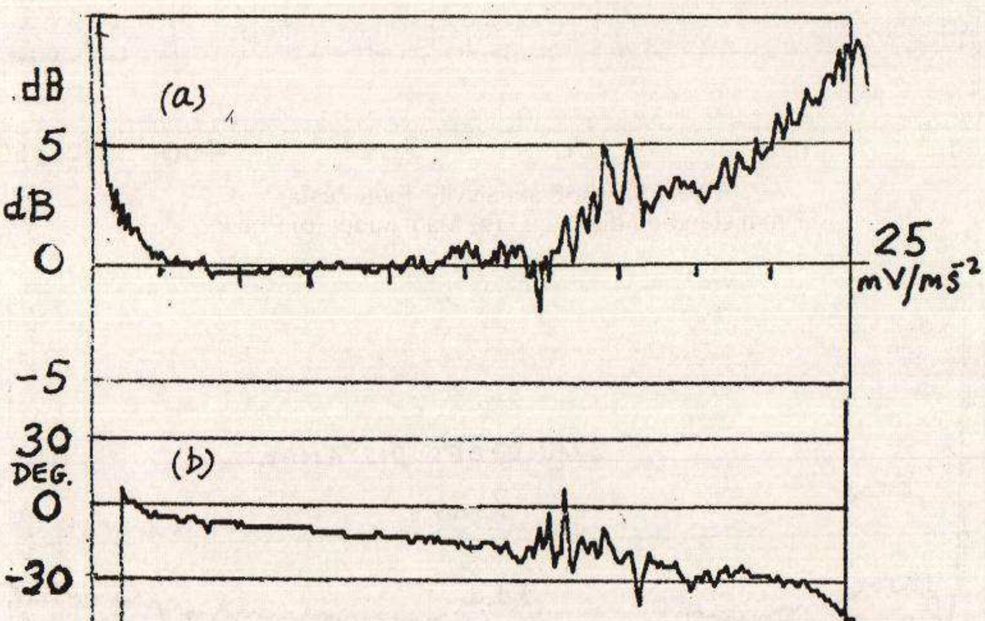

Figure 8 VAS3 sensitivity: Loudspeaker test.
17 mm stand-off distance. (a) Magnitude; (b) Phase.

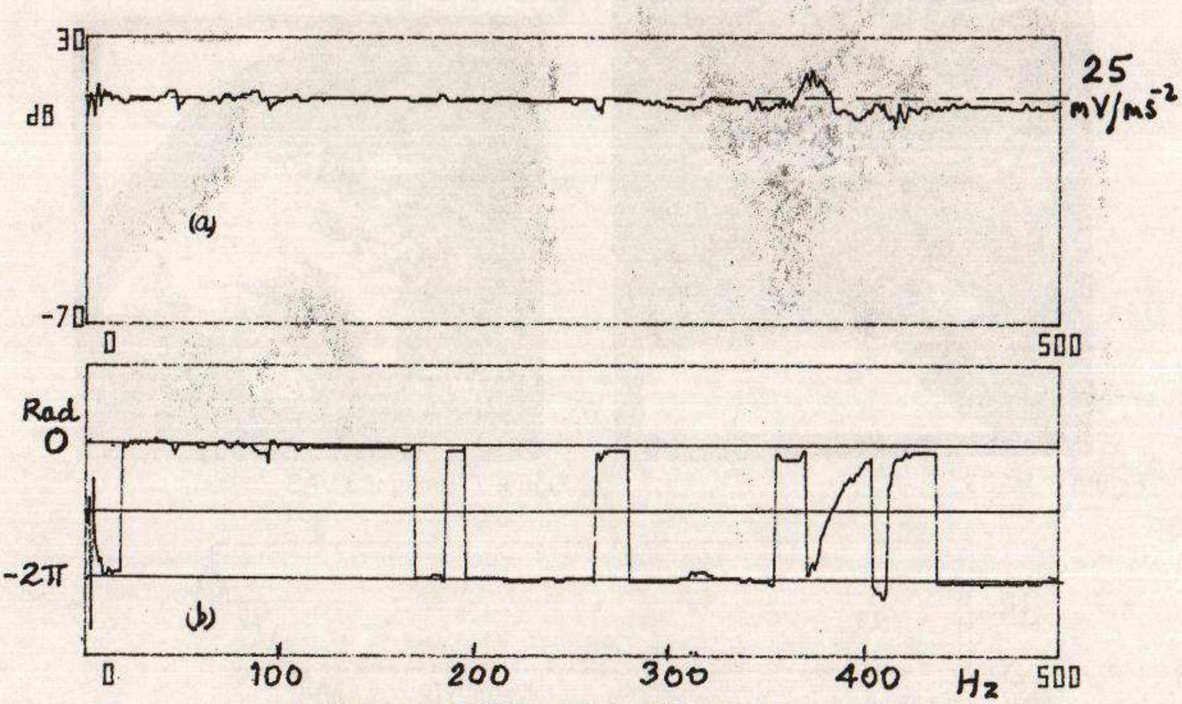

Figure 9 VAS3 sensitivity: Plate test.
17 mm stand-off distance. (a) Magnitude; (b) Phase.

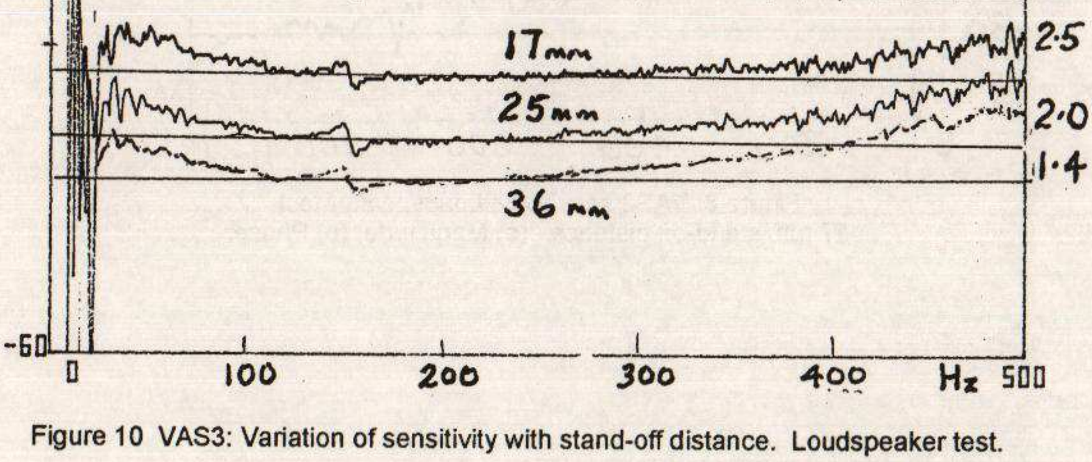

Figure 10 VAS3: Variation of sensitivity with stand-off distance. Loudspeaker test.