Proceedings of the Institute of Acoustics

AN EXPERIMENTAL INVESTIGATION INTO NOISE RADIATION FROM PAPER

M G Smith

University of Southampton, Institute of Sound and Vibration Research, Southampton, UK.

1. INTRODUCTION

This paper describes the results of an experimental investigation into noise radiation from paper. When a sheet of paper was excited sinusoidally three distinct regimes of response were found. At low amplitudes the paper behaved as a linear plate, at middle amplitudes sub and higher harmonics of the excitation frequency appeared in the response, but at high amplitudes of excitation the response of the paper became completely random.

Experiments were performed to find the radiation efficiency and other properties of this high amplitude random vibration. It was found that it was possible to relate the radiation efficiency to the correlation length of the paper vibration. It is also shown that paper vibrating as the result of an impact exhibits the same random vibration and radiation efficiency.

This research, which was completed in 1984, was funded by an SERC grant and was supervised by Professor E J Richards.

2. BACKGROUND

A preliminary investigation of noise sources in computer printers performed by E J Richards and G J Stimpson at ISVR indicated that noise radiation from paper was a significant contributor to the overall noise of the printer. When a sheet of paper is struck it is possible to separate out the noise of the impact and the sound of the paper 'ringing'. This paper describes the properties of the latter.

One possible description of paper ringing noise was given by Busch-Vishniac and Lyon [1] who used linear plate theory to describe the vibration of paper and the consequent radiation. The radiation efficiency that they used was based on work by Maidanik [2] for baffled plates, but this is far from the situation of free hanging paper in a computer printer.

3. EXPERIMENTAL TECHNIQUES

The principal experimental set-up for the study is shown in Figure 1. A sheet of paper was clamped at two edges, and was excited into vibration by a sinusoidal excitation applied either directly to the paper or indirectly through the frame. A non-contacting laser velocimeter was used to measure the vibration at some point on the paper. This device required only a tiny piece of retroreflective tape of negligible mass to be stuck to the paper.

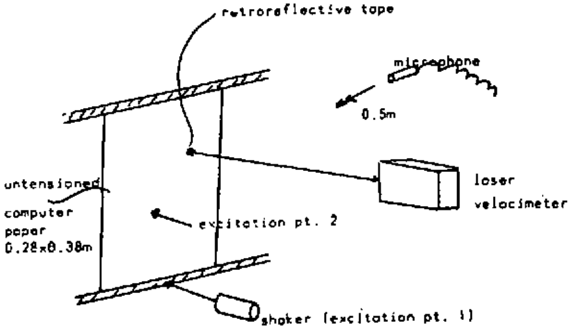

Figure 1. Experimental Setup

In order to derive a radiation efficiency for the vibration noise was measured with a microphone at points on the surface of a 0.5 metre radius sphere around the rig.

4. REGIMES OF VIBRATION RESPONSE

As the paper sheet was excited into vibration through the frame three distinct regimes of response were found. The excitation was sinusoidal except for low levels of higher harmonics.

4.1 Low Amplitudes

Where the amplitude of vibration of the sheet was much less than the thickness of the paper it was found that the sinusoidal excitation produced a sinusoidal response. It was possible to identify resonant modes of the paper, to find the mode shape by measuring the vibration amplitude at an array of points, and also to predict the frequency of the mode with a reasonable degree of accuracy from a knowledge of the bending stiffness of the paper.

Because paper is such a thin material its bending stiffness is low, bending wavelengths are short and resonant frequencies are low. The first resonant frequency of a sheet of computer paper 0.28 metre x 0.38 metre was 2 Hz, and the coincidence frequency at which the speed of bending waves equals the speed of sound in air was 450 kHz.

4.2 Mid Amplitudes

As the excitation level was increased, response of the paper sheet started to become non-linear. Figures 2a) to 2c) show the progression of the response spectrum at one point on the paper as the excitation level was increased by a factor of 8. First of all, higher harmonics of the excitation frequency are seen, then at higher amplitudes sub-harmonics of the excitation frequency appear.

In Figure 2c) the amplitude of the response was approximately equal to the thickness of the paper.

4.3 High Amplitudes

When the excitation level is increased again the response quite suddenly enters a third regime in which all frequencies are seen, and the vibration of the paper becomes completely broadband (Figure 2d)), although the excitation frequency, and its sub-harmonic, can still be seen.

For the remainder of this paper only this high amplitude response regime is considered.

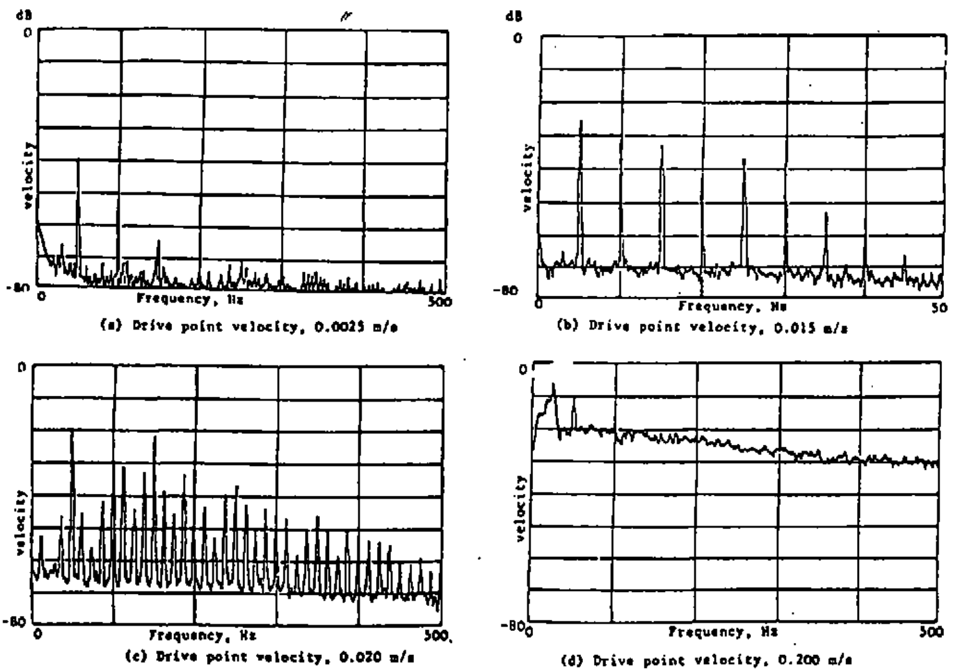

Figure 2. Paper Response at Different Excitation Levels

5. VIBRATION AND NOISE RADIATION AT HIGH LEVELS OF EXCITATION

In order to achieve higher levels of vibration the paper was excited directly, rather than through the framework.

By measuring the spatially averaged mean square velocity response spectrum, $\langle v^2 \rangle$, of the paper, and the spatially averaged sound pressure level on a hemisphere, $\langle p^2 \rangle$, the radiation efficiency, σ_{rad}, can be written:

$$\sigma_{rad} = \frac{2\pi R^2 \quad \langle p^2 \rangle}{(\rho c)^2 \; S \; \langle v^2 \rangle}$$

where R is the radius of the hemisphere, ρc is the characteristic impedance of air, and S is the area of paper.

A typical radiated noise spectrum is shown in Figure 3. The shape of the spectrum changes with drive point velocity, with high frequencies increasing more rapidly than low frequencies as the excitation level increases.

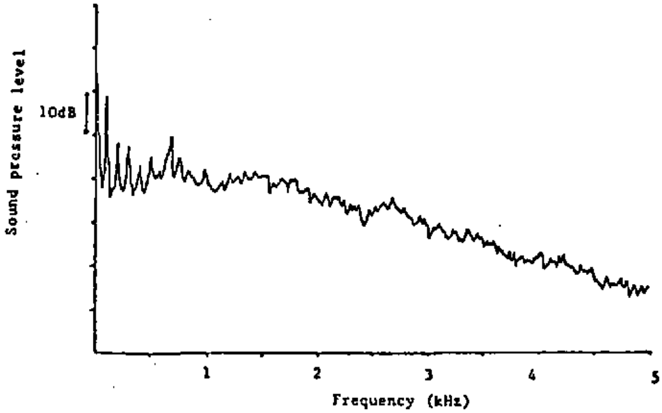

Figure 3 Noise spectrum of computer paper excited at 100 Hz, 0.5 m/s

Figure 4 shows the radiated noise level at 2750 Hz as a function of drive point velocity. The noise at this frequency increases by approximately 13 dB with each doubling of excitation level, furthermore the noise level in this frequency band is almost independent of the driving frequency.

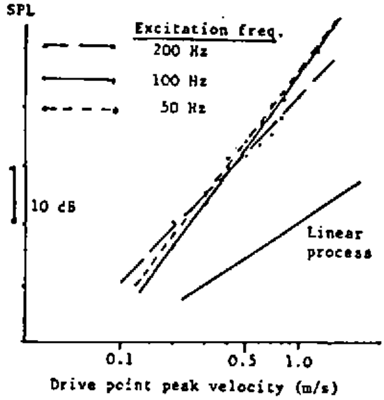

Fig. 4 Noise at 2750 Hz v drive point velocity

Figure 5 shows the narrow band radiation efficiency of the sheet of paper, plotted on a decibel scale, for two different driving point velocities. It has been shown above that between these two excitation levels, the radiated noise at 2750 Hz will have increased by 16 dB, and so to arrive at the same radiation efficiency the vibration must have increased by the same amount.

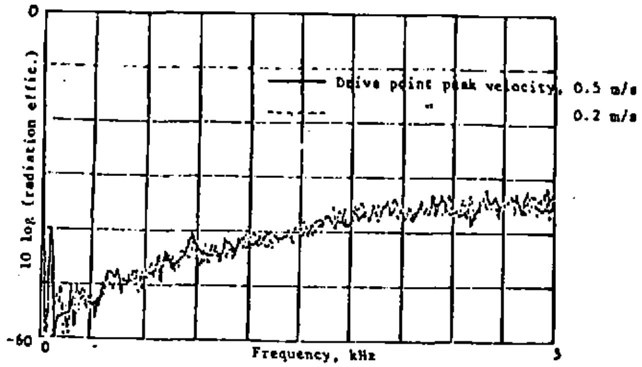

Fig. 5 Radiation efficiency of unbaffled paper at two drive point velocities

In printers the source of excitation is generally an impact, and so the noise radiation from paper struck at a point by a pendulum was also measured, being careful to exclude the sound of the initial impact from the analysis. The vibration level resulting from an impact shows exactly the same dependency on impact velocity as the continuous excitation, and an identical radiation efficiency was measured.

6. MEASUREMENT OF THE RADIATING SOURCE SIZE

By measuring the vibration response of the paper sheet at closely spaced points it was possible to obtain an indication of the area over which the paper was vibrating coherently. This was then compared with the radiation efficiency of known sources.

The coherence function was used as an indicator of correlation between two points. Figures 6a) to c) show how coherence falls with increasing separation.

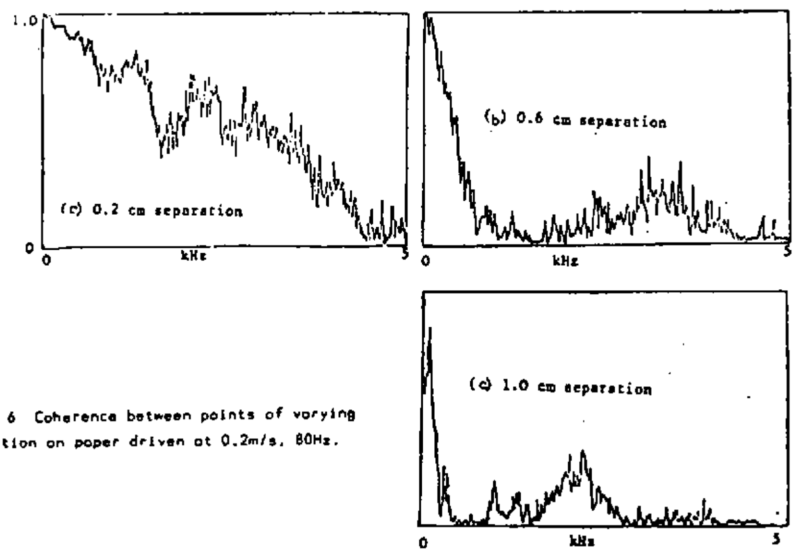

Figure 6 Coherence between points of varying separation on paper driven at 0.2m/s, 80Hz.

It was found that the vibration was correlated over a distance of approximately half the bending wavelength, and that an appropriated source radius was thus quarter of the bending wavelength.

For a plane distribution of uncorrelated dipole sources the radiation efficiency is given by:

$$\sigma_{dip} = 0.25/(kr)^4$$

and this is compared with the measured radiation efficiency in Figure 7.

The reason for the enhanced radiation efficiency of paper over a simple plate of equivalent properties thus appears to be the lack of correlation between neighbouring areas of the paper.

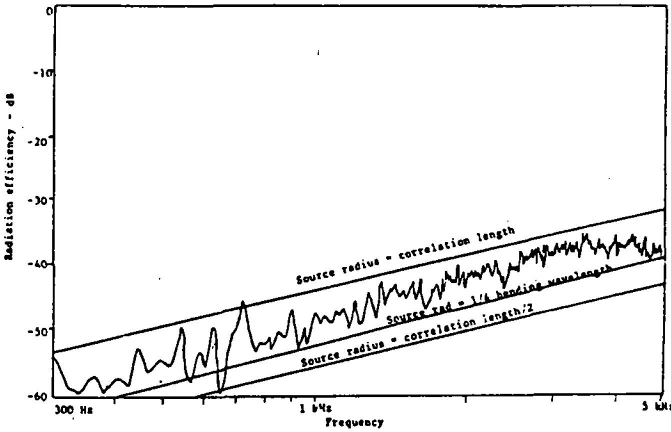

Figure 7. Measured radiation efficiency compared with dipole sources of various sizes

7. MECHANISMS

The main unexplained phenomenon arising from this work is the mechanism of energy transfer between frequencies. Figure 4 shows that the vibration and noise radiation is explicitly dependant on driving velocity (rather than drive point displacement). This was taken as an indication that local bending moments (which are also proportional to velocity) were involved in the process. For example the bending moments may be causing local buckling or "snap through" of the paper. No definitive experiment was found to confirm this mechanism.

8. CONCLUSION

When paper is forced into motion as occurs in computer printers the vibration can be highly non-linear resulting in an enhanced radiation efficiency.

The amount of noise radiated will apparently decrease as the bending stiffness of the paper is decreased.

9. REFERENCES

[1] I J BUSCH-VISHNIAC, R H LYON, 'Paper Noise in an Impact Line Printer', JASA, 70(6), December 1981.

[2] G MAIDANIK, 'Response of ribbed panels to reverberant acoustic fields', JASA, 34(6), June 1962.