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MEASURING THE POWER FLOW OF NOISE IN BEAMS AND FLUID FILLED PIPES

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SUMMARY

This paper describes a series of experiments in a programme to develop techniques for measuring the spectrum of power flow around networks of fluid filled pipes.

INTRODUCTION

The acoustic pressure distribution in operating hydraulic systems may not be easily measured. This led to the investigation of the use of accelerometers to measure the pattern of radial pipe-wall motion. The signals would then be used to quantify the flexural and acoustic waves. Two different methods were adopted for this, i.e. wave-number and cross-spectrum analysis. Both involved the measurement of frequency response functions in the first instance. Initially the two methods were compared by examining power transmitted in a flexural wave along a thin steel beam with a rectangular section. This experiment was extended to find out whether the methods were sensitive enough to confirm that the total power flowing into a junction of beams is equal to that flowing out. The methods, extended to measuring power flow in both the acoustic and flexural wave, were first tested on a laboratory test rig and further explored on the hydraulic test facility at NEL.

THEORETICAL BACKGROUND

List of Symbols

E	Young's modulus for the pipe wall material
t	Pipe wall thickness
d	Mean diameter of the pipe
C_p	Speed of the acoustic wave in the pipe
C_f	Free field wave speed
ρ_f	Density of the fluid in the pipe
K	Bulk modulus of the fluid
m'	Mass per unit length of the pipe or beam
B	Flexural rigidity of the pipe or beam
ω	Angular frequency
k	Wavenumber
Δx	Small change in x

$ImG\{x,(x+\Delta x),f\}$ represents the imaginary part of the cross-spectrum of signals from sensors located at x and $(x+\Delta x)$

The use of wavenumber spectra to measure power flow relies on determining the amplitudes of each wave type present and applying the appropriate physical law relating each wave-type to power flow. If the amplitude of the waves at a given frequency in either direction along a beam or pipe are A and B say, then the nett power flow is given by

$P(x,f) = g(f)(B^2-A^2)$ where $g(f)$ represents the physical law relating power flow to wave amplitude for a particular wave-type.

For the acoustic wave at low frequencies well below the ring frequency

$$g(f) = \frac{2\pi}{\rho_f C_p}\left(\frac{Et}{d}\right)^{2}$$

This expression can be obtained by considering the radial deflection of the strained pipe wall to be a measure of the pressure in the pipe and is confirmed by making a low frequency approximation of results obtained by Fuller and Fahy [1] for what at these frequencies can be reasonably described as an acoustic wave.

The Kortweg correction can be applied to obtain the speed of the acoustic wave in the pipe which is the free fluid speed modified by the compliance of the pipe walls. That is

$$C_p = C_f\left(1 + \frac{Kd}{Et}\right)^{-\frac{1}{2}}$$

Similarly for the flexural wave an expression may be developed to relate power flow to displacement

$$g(f) = \frac{m'}{\omega^2}\left(\frac{B\omega^2}{m'}\right)^{\frac{1}{4}}$$

This is a general expression applicable to thin beams, but also applies to fluid filled pipes at low frequencies where fluid can be considered as a simple mass loading of a beam. This expression can be derived by considering that the kinetic energy in a progressive wave travels at the group velocity, which for a flexural wave is twice the phase velocity.

The power flow in the various types of wave may have a spectrum of components. The amplitude of these components was determined with wavenumber analysis.

To accomplish wave-number analysis, at steps in frequency, the wave-number components are determined by a Fourier transform of the displacement profile at that frequency. The sampled displacement profile may be determined with an array of accelerometers by measuring the amplitude and phase of the motion at each position relative to a reference position. Frequency response functions measured between the reference accelerometer and accelerometers along the array and obtained with a digital analyser provided the amplitude and phase information. Wavenumber spectra, determined at the discrete frequency intervals, defined by the resolution of the analyser, can be represented by a waterfall plot as shown in Figure 1.

If it is possible to isolate the signal due to one type of progressive wave then a straight-forward mathematical analysis shows that power flow can be determined from cross-spectra between two closely spaced sensors such that

$$P(x,f) = \frac{2g(f)}{\sin k\Delta x}\, I_m G\left\{\dot{x},(x+\Delta x),f\right\}$$

where, again g(f) represents the relationship between wave amplitude and power flow for a particular type of wave. A factor of two appears because power spectra are traditionally represented by rms values.

Verheij [3] has shown how a cross power spectrum may be used for measuring the power flow in the flexural and other wave-types, but by a different approach.

EXPERIMENTAL RESULTS

The methods for measuring power flow were first verified for a single wave type, the flexural, with a steel rectangular beam, 5m long, 16mm wide and 10mm deep. Power was injected at one end with a shaker and absorbed at the other by a free layer damping. Figure 2 shows the good agreement of power flow obtained with wavenumber spectra and that with cross spectra. Later, this rig was extended by joining on two dissimilar beams at the end of the first beam (Figure 3). Power, in this case, injected into an end of the first beam, is distributed at the joint between the added beams and absorbed at the ends remote from the shaker by free layer damping. Figure 4 shows the excellent agreement between the power flowing into the junction with the total power leaving the junction. The graph shows results using wavenumber analysis. Equally good agreement was obtained with cross spectrum measurements. This experiment was the first step in establishing the feasibility of using the methods for energy accounting in networks of beams or pipes.

The methods for measuring power flow with both flexural and acoustic waves present, were first tested on an oil filled pipe. The pipe was 40mm mean diameter and had a 2.5mm wall thickness. It was 5 metres long and the measurement array had 20 accelerometers with a 0.2m spacing.

A wavenumber waterfall plot for this pipe is shown in Figure 1. The dispersion law for the flexural wave is recognised from the parabola traced out by peaks in the wavenumber spectra. Inside this is the linear dispersion curve of the acoustic wave. The double sided nature of these curves is indicative of the two way flow of energy in both types of wave. The clarity of presentation of wavenumber peaks in Figures 1 is a feature of the Maximum Entropy Method for spectral estimation, which was used to obtain these waterfall plots. Although other similar spectral estimation techniques [3] do provide more accurate amplitude estimation, a least squares curve fit was used which, in addition to accurate amplitude assessment, provided an estimate of the error in the power flow. The dispersion laws required to apply a curve fit were determined from average results provided by the Maximum Entropy Method.

The difference in amplitudes between the positive and negative peaks of the wavenumber spectra enabled power flow to be determined in both types of wave. In order to use cross spectra the signal due to the acoustic wave needs to be separated from that due to the flexural wave. By summing the signals from opposed pairs of accelerometers the acoustic wave is isolated from the flexural wave. Likewise the flexural wave is obtained by differencing signals.

The hydraulic pump test facility at NEL was kindly made available for the confirmation of the techniques. The test rig had an internal gear pump delivering to a 70 metre straight run of steel pipe. A flexible hose in a return loop to the pump absorbed energy in the acoustic wave. A number of closely spaced pressure transducers was available to provide an alternative means of measuring power flow with which to check measurements made with cross spectra and wavenumber spectra. Measurements of power flow in the flexural wave were also made, but the main interest was in the acoustic wave which was the main component of the power flow, although low in signal strength. The extent to which the acoustic wave is buried in the signal due to the flexural wave is shown in Figure 5. It can be seen in this figure that by applying the appropriate correction to the imaginary part of the cross spectrum of summed signals that the power flow agrees well, if not precisely, with power flow derived from pressure measurements. For comparison the same correction was applied to the difference signal to demonstrate how much greater was the signal due to the flexural wave. An alternative approach to the summation of signals across the pipe is to carry out the summation in the frequency domain having first made the extra measurements of frequency response function between the two opposed pairs of accelerometers. These two approaches to the cross spectrum measurement of power flow together with that determined from wavenumber spectra are compared with that obtained from pressure measurements in Figure 6. The pressure measurements provided an accurate estimation of power flow and a good basis for comparison. The various methods agreed well but lacked precision in detail pointing to the need for further refinement of the techniques.

CONCLUSIONS

1. Confidence was established in the use of both wavenumber spectra and cross-spectra for the measurement of power flow.

2. Added confidence in the techniques was gained for measuring power flow in networks of beams or pipes by demonstrating that the power flowing into a joint is equal to the total power flowing away.

3. The methods were extended successfully to measure both the acoustic and flexural wave in pipes.

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[2] J. W. Verheij 'Cross Spectral Density Method for Measuring Structure Borne Power Flow on Beams and Pipes', Journal of Sound and Vibration (1980) 70(1), 133 - 139

[3] S. M. Kay and S. L. Marple 'Spectral Analysis - A Modern Perspective' Proceedings of the IEEE, Vol. 69, No. 11 November 1981

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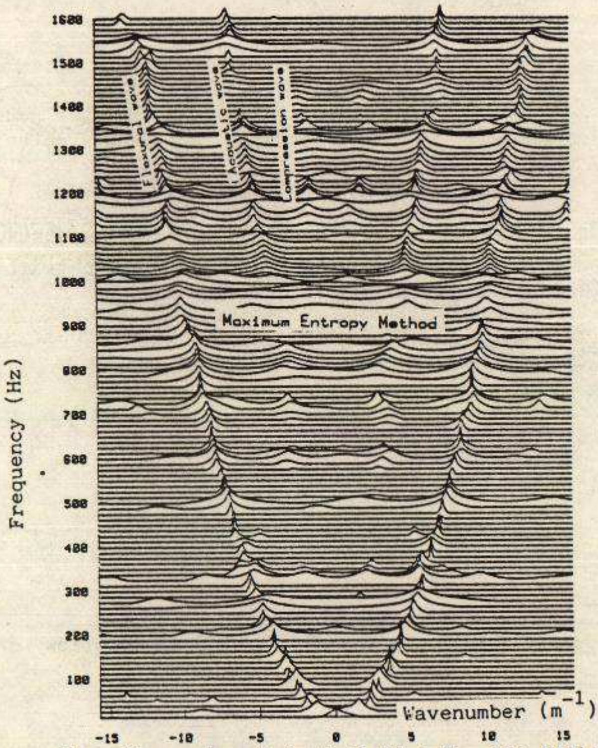

Figure 1. Wavenumber Waterfall Plot for Oil-Filled Pipe

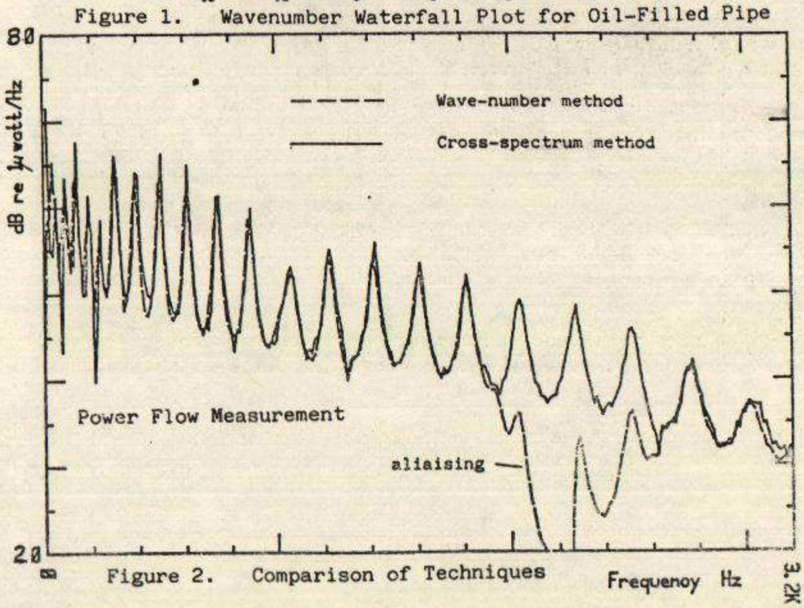

Figure 2. Comparison of Techniques

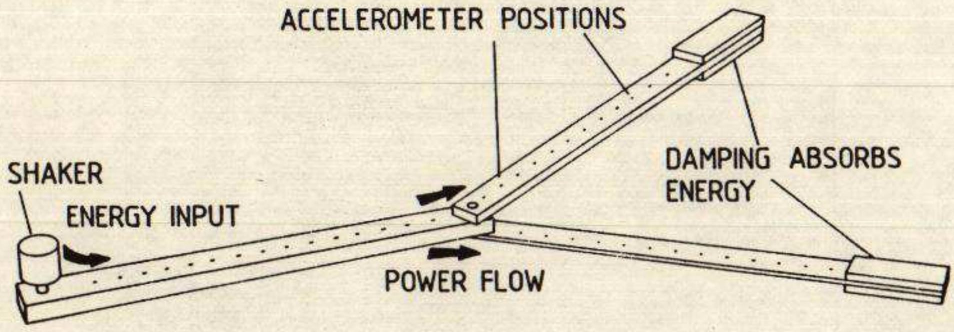

Figure 3. Beam Experimental Rig

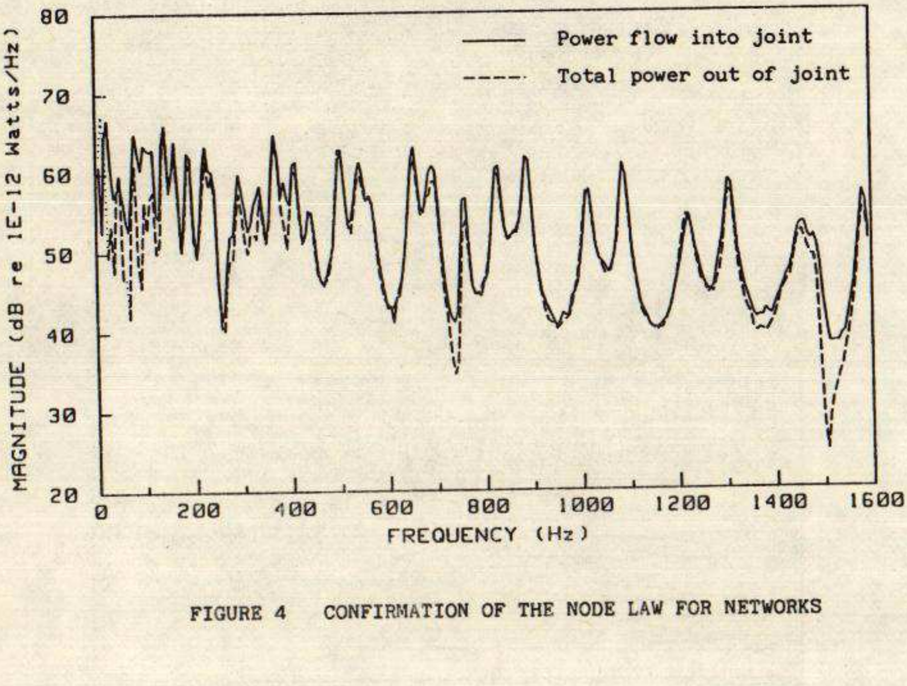

FIGURE 4 CONFIRMATION OF THE NODE LAW FOR NETWORKS

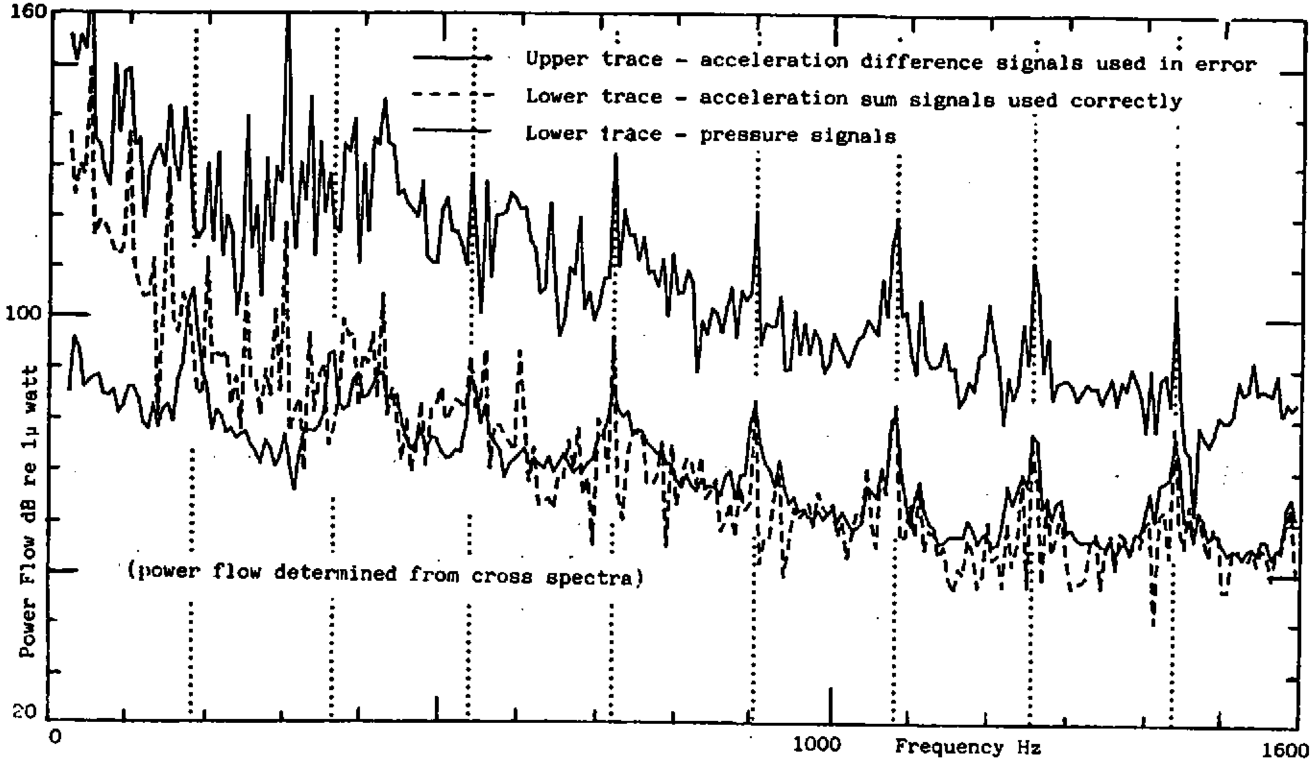

FIGURE 5 ILLUSTRATION OF THE EXTENT TO WHICH THE ACOUSTIC WAVE SIGNAL IS MASKED BY THE FLEXURAL WAVE

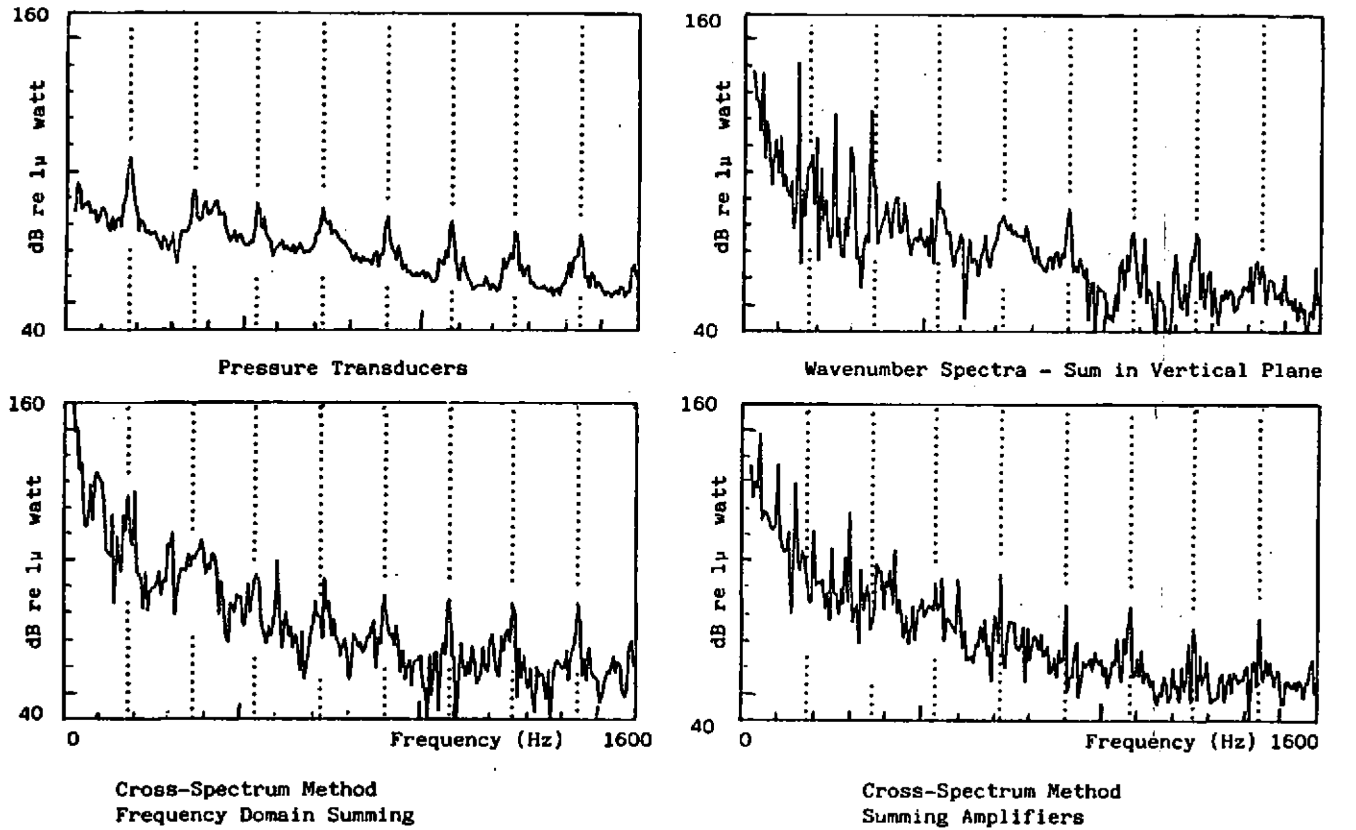

FIGURE 6 COMPARISON OF FOUR METHODS FOR THE MEASUREMENT OF POWER FLOW IN THE ACOUSTIC WAVE