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STRUCTURAL AND FLUID POWER TRANSMISSION MEASUREMENT IN EMPTY AND FLUID FILLED PIPES

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1. INTRODUCTION

Measuring vibrational power transmission within pipeworks is of prime interest for identifying noise sources and transmission paths. An external circumferential piezoelectric transducer is introduced which detects the radial wall motion of fluid filled pipes. The transducer consists of a piezoelectric wire [1] and is wrapped an integral number of turns around the circumference of a pipe. The transducer is therefore only sensitive to the axisymmetric n = 0 waves, which involves a net extension. The sensitivity of the piezoelectric transducer to the axisymmetric wave types of a fluid filled pipe has been studied [2].

This paper discusses the use of the piezoelectric transducer in measuring structural and fluid borne power transmission within fluid filled pipes in the low frequency range (i.e. below the ring frequency of the pipe). Only the axisymmetric (n = 0) wave types are considered here.

2. POWER TRANSMISSION EXPRESSIONS

The first step of this investigation was to devise ways, using the piezoelectric transducer, of predicting the longitudinal power transmission within a straight section of piping. This was achieved using a range of measuring point configuration on the surface of a pipe, made possible with the piezoelectric wire. Indeed, when the piezoelectric transducer is used in conjunction with axial accelerometers, three novel ways for predicting the power transmitted within pipes with or without fluid were found.

These were then formulated in terms of theoretical power transmission expression for the structure borne and fluid borne wave types. These expressions allow estimates to be made of the transmitted power in the frequency domain and may be used to locate the prominant transmission paths in pipe installations.

3. EQUATIONS OF MOTION FOR A FLUID FILLED PIPE

With reference to a semi-infinite cylindrical shell the displacements in the axial and radial directions are u and w respectively. σ_x, σ_θ refer to axial and circumferential stress. The fluid pressure inside the shell is p.

The following equations are simplified forms of Kennard's equations [3].

$$\rho \ddot{u} + \frac{E}{1 - \nu^2}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\nu}{a}\frac{\partial w}{\partial x}\right) = 0 \qquad (1)$$

and

$$\frac{E}{1 - \nu^2}\left(\frac{w}{a} + \nu\frac{\partial u}{\partial x}\right) + \rho a \dot{w} = \frac{pa}{h} \qquad (2)$$

These are the two coupled shell equations for the n = 0 axisymmetric motion. E, ν are the shell material Young's modulus and Poisson's ratio; w/a, $\partial u/\partial x$ represent the circumferential and axial strain. These equations are valid for thin walled shells and exclude the effects of rotary kinetic energy and transverse shear.

The time average axial power transmission in the shell wall and fluid field are given by :-

(i) Structural power $= \frac{1}{T}\int A_s\, \sigma_x\, \dot{u}_s\, dt$ (3)

where $\dot{u}_s$ is the axial shell wall velocity and A_s is the cross sectional area of the shell.

(ii) Fluid power $= \frac{1}{T}\int A_f\, p\, \dot{u}_f\, dt$ (4)

where $\dot{u}_f$ is the axial fluid particle velocity and A_f is the cross sectional area of the fluid region. The axial fluid particle velocity can be obtained from the momentum relation,

$$\dot{u}_f = -\frac{1}{i\rho_f\omega}\frac{\partial p}{\partial x} \qquad (5)$$

where ρ_f and ω are the fluid density and frequency of vibration respectively.

Equations (1 - 5) can be used to determine both the structure and fluid borne power transmission within a pipe.

4. STRUCTURE BORNE POWER TRANSMISSION

(i) The power transmission in an empty pipe can be determined using an axial accelerometer and a PVDF transducer. Figure 1 shows the transducer configuration used for this measurement. Here the accelerometer is positioned as close as possible to the piezoeletric wire. The excitation is applied axially to the shell wall only.

It can be shown that the normalised time average output power transmission, $< P_{out} >$ using this technique is given by;

$$\frac{< P_{out} >}{G_{ff}} = \frac{EA_s}{va\omega} \text{ Im } \{G_{wa}\} \qquad (6)$$

where G_{wa} represents the cross-spectral density between the radial wall displacement w, and a, the axial acceleration. All output power discussed here will be normalised w.r.t the spectral density G_{ff} of the input force. This method enables the power transmission to be measured at a single point without using any finite - difference approximations.

(ii) The power transmission in the shell wall can be determied using two axial acelerometers $\{a_1, a_2\}$and one PVDF transducer $\{w\}$ as shown in Figure 2. This configuration can be used for measuring the structural power transmission within a pipe containing fluid. Again, the excitation is applied axially to the shell wall only.

The normalised time average output power transmission is given by:-

$$\frac{< P_{out} >}{G_{ff}} = \frac{EA_s}{\omega^3(1-v^2)\Delta} \text{ Im } \{G_{a1a2}\} + \frac{EvA_s}{2(1-v^2)a\omega} \text{ Im } \{G_{wa1} + G_{wa2}\} \qquad (7)$$

where Δ is the spacing between the two accelerometers $\{a_1, a_2\}$ and A_s is the area of cross-section of the shell wall. Here it is assumed that the spacing Δ is less than one half the wavelength of the shell wave.

In a practical situation bending waves associated with the n = 1 mode will be present in the pipe. These can be eliminated using accelerometers, located at diametrically opposing sides of the pipe.

5. FLUID BORNE POWER TRANSMISSION

(i) The power transmission in the fluid can be determined using three axial accelerometers $\{a_1, a_2, a_3\}$ and two PVDF transducers $\{w_1, w_2\}$ as shown in Figure 3. In this case the excitation is applied axially to the contained fluid only.

The normalised time average output power transmission is given by :-

$$\frac{< P_{out} >}{G_{ff}} = \frac{A_f}{\rho_f}\left[\frac{K^2}{\omega\Delta} \text{Im } \{G_{w1w2}\} + \frac{A^2}{\omega^5\Delta^3} \text{ Im } \{G_{a1a2} - G_{a1a3} + G_{a2a3}\}\right]$$
$$- \frac{A_f}{\rho_f}\left[\frac{KA}{\omega^3\Delta^2} \text{ Im } \{G_{w1a2} - G_{w1a3} + G_{w2a1} - G_{w2a2}\}\right] \qquad (8)$$

where $K = \dfrac{Eh(1 - \Omega^2)}{a^2(1 - \nu^2)}$ and $A = \dfrac{\nu Eh}{a}$. A_f and ρ_f are respectively the area of cross-section of the fluid and the density of the fluid. Here it is assumed that the spacing Δ is less than one half the wavelength of the fluid wave within the pipe.

Figure 4 shows the arrangement in which only the first term in equation (3) is used, i.e. when only the two PVDF transducers are used to measure power transmission.

6. EXPERIMENT

Experimental investigations were undertaken on a vertical perspex pipe containing fluid in order to verify the theoretical predictions.

For structure borne power measurements the pipe was excited axially on the empty shell using the top vertical shaker. Graph 1 shows a plot of transmitted (or output) longitudinal power and input longitudinal power for an empty pipe versus frequency of excitation. The power was calculated using equation (6) and it can be seen that there is good agreement between the input and transmitted power.

The pipe was then filled with water. An air gap of one centimetre was left between the fluid surface and the top honeycomb cap.

The fluid filled pipe was then axially excited on the shell from the top as had been done with the empty shell. Graph 2 shows a plot of transmitted longitudinal power and input longitudinal power versus frequency of excitation. Here equation (7) was used calculate the output power transmitted and again it can be seen that there is good agreement between the input and transmitted power.

Finally the fluid filled pipe was axially excited on the fluid from the top. Here a wooden piston was fitted to the honeycomb cap and postioned so as to make contact with the water at the top of the pipe. A concentric ring of neoprene rubber, 6mm - 6mm thickness, was then used to isolate the honeycomb cap from the pipe wall. The rubber also prevented water inside the pipe from leaking. Finally a straw tube was inserted inside the piston to prevent bubbles from forming at the top.

Graphs 3 and 4 show plots of the transmitted longitudinal power and input longitudinal power versus frequency of excitation. It can be seen on both these plots that there is good agreement between the input and transmitted power up to about 1kHz. After this frequency, the transmitted longitudinal power diverges from the input power. The difference is probably due to the finite-difference spacing Δ of 20 cm, which at this frequency exceeds the limit of being less than one half the wavelength for the fluid wave. It is also seen in graph 4 that below 100Hz results are better using only two PVDF transducers for a 'soft' walled pipe.

7. CONCLUSIONS

(1) A technique for measuring axial power in an empty tube has been tested successfully.

(2) The structural power in the shell of an empty and full pipe has been measured.

(3) The power in the fluid of a pipe with soft walls has been measured successfully.

8. REFERENCES

[1,2] A R BRISCOE & R J PINNINGTON, 'Externally applied sensor for axisymmetric waves in a fluid filled pipe' (1993). To be published in Journal of Sound and Vibration.

[3] A W LEISSA, 'Vibrations of shells', NASA SP-288, Scientific and Technical Information Office, NASA, Washington DC (1973).

ACKNOWLEDGEMENT

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POWER TRANSMISSION MEASUREMENT IN PIPES

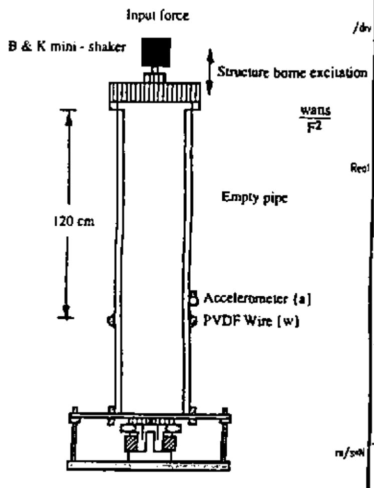
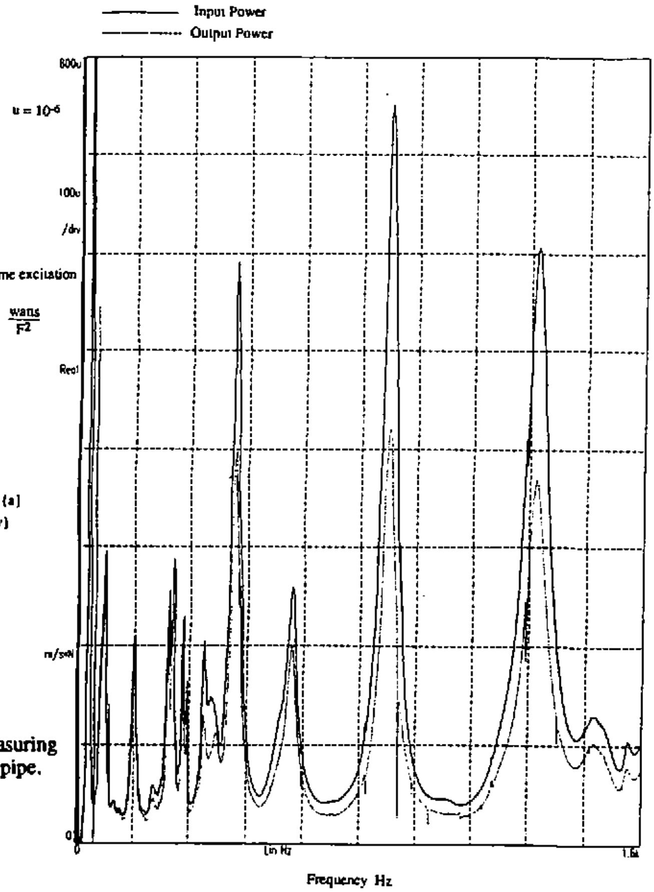


Figure 1.

Transducer configuration for measuring the structural power in an empty pipe.



Graph 1. Transmitted longitudinal power and input longitudinal power in an empty pipe.

POWER TRANSMISSION MEASUREMENT IN PIPES

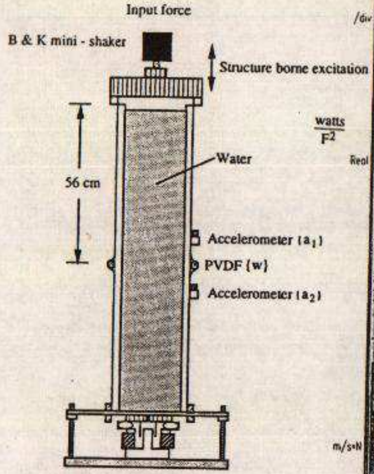
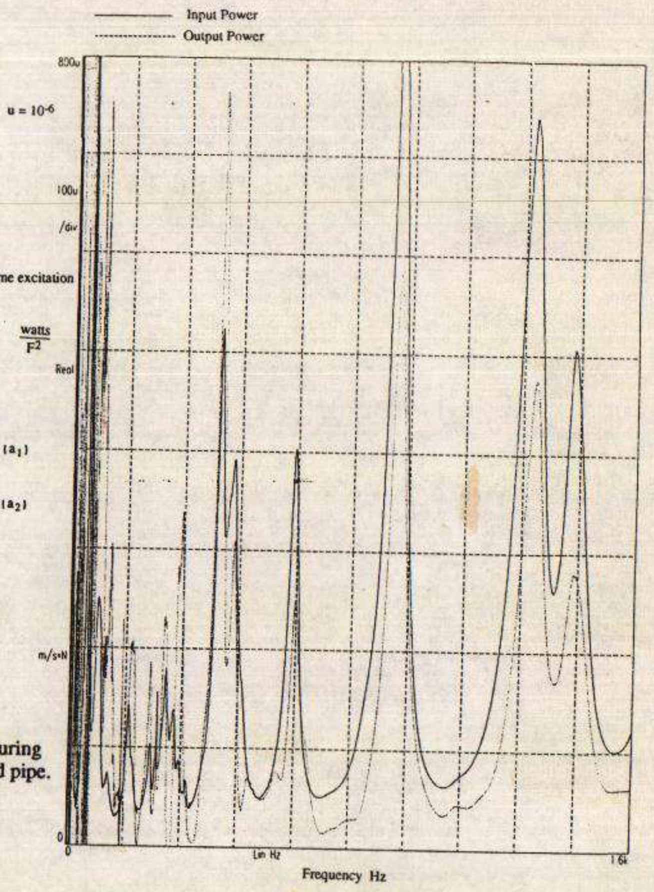


Figure 2.

Transducer configuration for measuring the structural power in a fluid filled pipe.



Graph 2. Transmitted longitudinal power and input longitudinal power a fluid filled pipe.

POWER TRANSMISSION MEASUREMENT IN PIPES

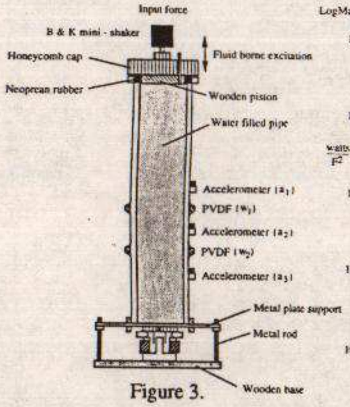
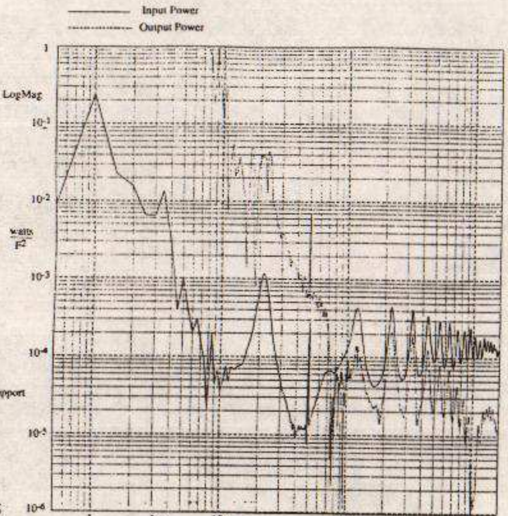


Figure 3.

5 - Transducer configuration for measuring the fluid power in a fluid filled pipe.



Graph 3. Transmitted longitudinal power and input longitudinal power a fluid filled pipe.

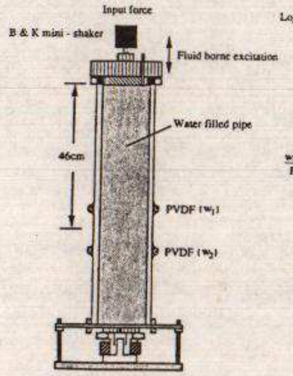
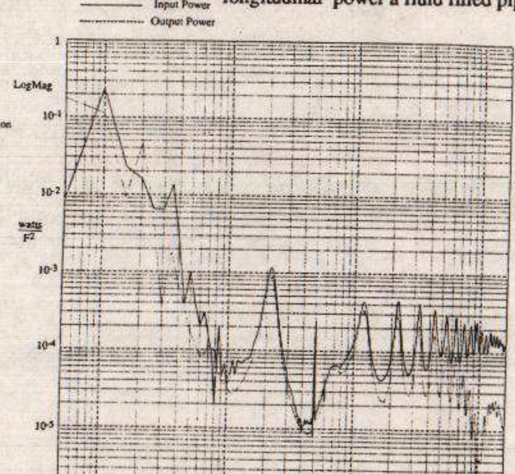


Figure 4.

2 - Transducer configuration for measuring the fluid power in a fluid filled pipe.



Graph 4. Transmitted longitudinal power and input longitudinal power a fluid filled pipe.