PIEZOFILM SENSORS FOR THE DETECTION OF PROPAGATING ACOUSTIC PRESSURE IN PIPES

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INTRODUCTION

There are a number of situations in industry in which one may wish to measure the acoustic pressures in a piping system, but for which standard microphone methods are expensive or difficult to implement. These include cases of high fluid temperature, pressure or velocity, and material handling systems in which there are particulates or debris in the flow.

As an alternative, some researchers have investigated the possibility of using structural sensors attached to the piping, which is coupled to the interior acoustic field, to estimate the pressure [1,2]. This method has shown reasonable promise for axisymmetric waves well below the ring frequency of the piping.

This study describes the theory of the method, and the results of some experimentation performed at the University of Toronto using piezofilm ring sensors attached to a rubber tube, with air as the contained fluid. Some approximations which can be made for low frequencies are described, and some practical limitations of the method presented.

THEORY

The dispersion characteristics of free waves in infinitely long thin walled cylinders of finite shell impedance, including the effect of contained fluid, has been investigated by Fuller and Fahy [3], among others. The *in vacuo* shell dynamics are described by appropriate coupled equations of motion, and the pressure field in the pipe is assumed to take on the form of an acoustic wave equation in cylindrical coordinates. The wave dynamics of the shell and the fluid are then coupled through the boundary condition which ensures that the radial velocity of the shell and fluid at the pipe wall are equal.

Assuming travelling shell and pressure waves only, we may write:

$$u = \sum_s U_s \, e^{i(k_s^x - \omega t + \frac{\pi}{2})}$$

$$w = \sum_s W_s \, e^{i(k_s^x - \omega t)}$$

$$p = \sum_s P_s \, e^{i(k_s^x - \omega t)} \, J_0(k_s^r r)$$

where u, w are the axial and radial displacements of the pipe wall (torsional motion is uncoupled for axisymmetric waves and can be neglected), p is the acoustic pressure, and k_s^x, k_s^r are the axial and radial wavenumbers, respectively, related to the free wavenumber, k, through the Helmholtz equation by $k_s^r = \sqrt{k^2 - (k_s^x)^2}$.

Substitution of these forms into the equations of motion and coupling p, w through the boundary condition yields the characteristic equation of propagation, from which the axial wavenumber can be solved:

$$L = -\Omega^2 + 1 + \beta^2 \left[(k_s^x a)^4 + \frac{2+\nu}{2(1-\nu)} \right] + \frac{\Omega^2 \rho_f a J_0(k_s^r a)}{\rho_s h (k_s^r a) J_1(k_s^r a)} - \frac{\nu^2 (k_s^x a)^2}{-\Omega^2 + (k_s^x a)^2} = 0$$

The terms in L represent, in sequence, the pipe mass, membrane stiffness and bending stiffness (entire term in square brackets), the fluid loading term, and longitudinal effects coupled through Poisson's ratio. As the fluid loading term is non-linear, it may be expanded in a power series to linearize the equation to any desired degree of accuracy. At low frequencies, the solutions for k_s^x may be shown to include two real roots, one with energy predominantly in the fluid and characterized by relatively large radial motion, the other primarily a longitudinal shell mode. There are also two complex conjugate roots, representing solutions for a bending near field on the pipe wall, and an infinite number of imaginary roots representing evanescent acoustic modes.

Once the type of propagating mode is determined (i.e. an acoustic wave in the fluid will primarily excite the first mode while a structural excitation will excite the longitudinal shell mode, and shell discontinuities will excite the complex near field bending modes in that vicinity), the boundary condition can be used to solve for the pressure corresponding to a given radial displacement:

$$p = \frac{\omega^2 \rho_f a J_0(k_s^r a)}{(k_s^r a) J_1(k_s^r a)} \, w$$

Here the radial wavenumber corresponds to the propagating axial wavenumber, or a series can be used if more than one type of propagating wave exists at the cross section where w is measured.

EXPERIMENTS

Experiments have been performed to test the method, using a rubber tube down which acoustic energy is introduced via a 150W loudspeaker, coupled by a lined contraction to minimize the loading effect back on the woofer as the excitation frequency is varied. Piezofilm strips are bonded around the circumference to measure the axisymmetric ring strain, which is proportional to the radial displacement, w. These sensors also serve to filter out higher order circumferential motions. The corresponding acoustic pressure p calculated from the above equations are compared to the pressure measured inside the tube wall using a microphone probe. Figure 1 illustrates the experimental apparatus.

The experiments and theory are slightly different than described above, in that sensor pairs are used, and the average pressure between them calculated, while the actual pressure between the two is measured. This has the added advantage that the propagating part of the pressure can be separated out in a manner similar to an intensity measurement, but the theory is somewhat more complex, and is described elsewhere [1].

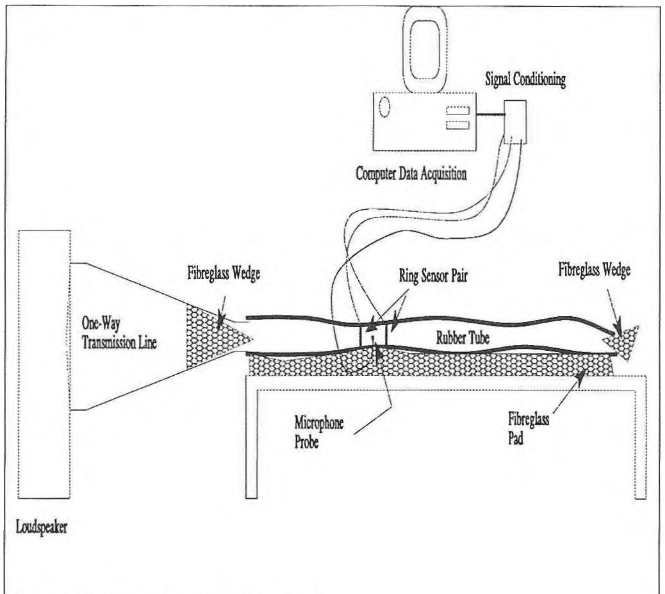

Figure 1: Experimental Apparatus

The experimental results indicate reasonably good agreement with theory for practical engineering purposes. At a number of frequencies below the ring frequency of the tube, the predicted pressure was on average within 6 dB of the measured pressure, and these differences remained highly constant through a range of signal amplitudes. Figure 2 illustrates the relative accuracy of the predicted pressure (re the measured pressure) at these frequencies, both unadjusted and corrected for the mean difference, which is approximately -3 dB, to account for such effects as imperfect bonding and imperfect shear transfer through the tube thickness. With the predicted accuracy so adjusted, the differences are within 3 dB, except at one frequency which corresponds to a full wavelength in the tube. That is, once a calculated or arbitrary figure for bonding losses is included, the sensors will provide a reasonably accurate estimate of the propagating pressure, provided that there are no significant standing waves at the frequency of interest, for which the above theory does not account.

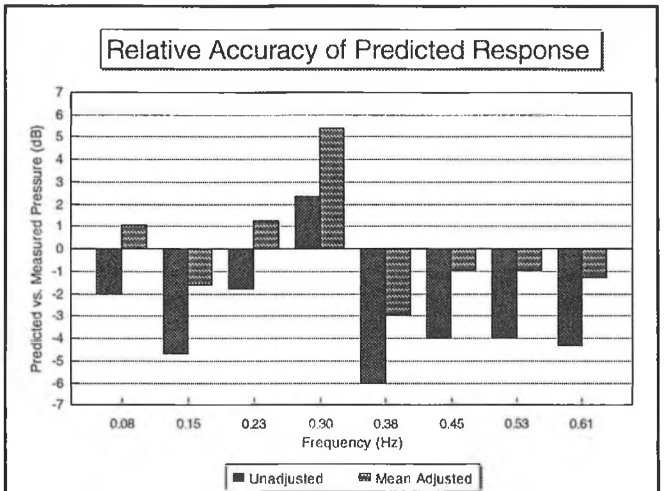

Figure 2

SIMPLIFICATIONS

For fluid borne excitation, if the forcing frequency is much smaller than the pipe ring frequency, then motion of the pipe wall is essentially controlled by its membrane stiffness. Provided that the sensor has negligible material properties in comparison with the pipe (which is **not** the case for the experiments described above, but will be the case in many industrial situations involving steel or hard plastic piping), then the pressure may be related to the displacement at the sensor location through the static membrane stiffness of the pipe [2]:

$$p = \frac{Eh}{a^2} w$$

Although this equation is useful only under the assumptions described above, it is much simpler to implement than the boundary condition equation described earlier. Also, for hard walled pipes, bonding losses are likely to be negligible when a stiff bonding adhesive such as epoxy or cyanoacrilate is used.

CONCLUSIONS

A method for estimating the internal acoustic pressure in piping systems using ring sensors attached to the pipe has been described. For arbitrary axisymmetric fluid borne waves, the internal pressure estimate is a function of the excitation frequency and wavenumber, which depends on mass and bending stiffness effects as well as the membrane stiffness. At frequencies well below the pipe ring frequency, the internal pressure estimate is a simple function of the membrane stiffness. Experimental results show that this method can be used to obtain reasonably good estimates when standing waves are not present, although imperfect bonding and shear transfer to the sensors should be considered. For long, hard walled pipes in particular, this method makes a simple and powerful alternative to in-pipe pressure transducers for acoustical measurements.

REFERENCES

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