MEASUREMENT OF THE LONGITUDINAL WAVE PROPAGATION PROPERTIES OF REINFORCED FLEXIBLE HOSE

LONGMORE D K., STAMMERS C W and TUC B.

UNIVERSITY OF BATH

Introduction

Noise in hydraulic systems has in recent years been acknowledged to be a serious problem. The lower harmonics of the pressure fluctuation produced by a pump can excite pronounced resonances of the fluid columns within a system, resulting in high airborne sound levels. A theoretical study of the dynamic pressures in a circuit requires a knowledge of the relevant characteristics of the various components. Pump, pipeline and valve characteristics can be measured [1,2]. The aim of the work outlined herein is to provide a convenient method of measuring the wave properties of reinforced flexible hoses, which commonly form part of a circuit.

It has been shown [3] that at the dominant frequencies generated by pumps, the pressure fluctuations along a straight hose are the result of two types of wave travelling in each direction and these involve predominantly axial motion of the fluid and hose wall. For sinusoidal excitation at frequency ω, the complex amplitude of the axial fluid motion, the axial wall motion and the pressure at a distance x along a hose can be written :

$$U = K_1e^{-\gamma_1 x} + K_2e^{\gamma_1 x} + K_3e^{-\gamma_2 x} + K_4e^{\gamma_2 x} \quad (1)$$

$$W = N_1(K_1e^{-\gamma_1 x} + K_2e^{\gamma_1 x}) + N_2\ (K_3e^{-\gamma_2 x} + K_4e^{\gamma_2 x}) \quad (2)$$

$$P = j\omega Z_1\ (K_1e^{-\gamma_1 x} - K_2e^{\gamma_1 x}) + j\omega Z_2\ (K_3e^{-\gamma_2 x} - K_4e^{\gamma_2 x}) \quad (3)$$

The properties of a fluid filled hose which influence the pressure fluctuations in a circuit of which it forms part can thus be specified by two propagation constants, γ_1,γ_2; two modal ratios, N_1,N_2; and two characteristic impedances, Z_1,Z_2, defined here in relation to fluid velocity rather than flow. The propagation constants tend to be proportional to frequency, variations from proportionality being due to frequency dependance of elastic moduli and the effect of fluid viscosity. It is therefore convenient to put

$$\gamma_i = M_i\omega = (F_i + jG_i)\omega \qquad i = 1,2 \quad (4)$$

Test method

Factors taken into account when choosing a convenient method of measuring the forementioned wave properties were the difficulties involved in generating closely controlled pressure fluctuations superimposed on a realistic mean pressure, the difficulty of measuring the pressure or flow of the fluid within a hose, and the need for definite end conditions. Wave velocities are very much greater than typical mean fluid velocities and hence flow was not considered to be necessary.

The test configuration is shown in Fig. 1. One end of the test hose is connected to a ball valve which is mounted on a large concrete block; the hose end fitting is also clamped to give additional rigidity. The other end is vibrated axially by an electrodynamic shaker. Here a close fitting plug ensures that

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the end of the fluid column coincides with the junction between the hose and its end fitting. Controlled temperatures are achieved by blowing warm air through a surrounding enclosure. The required mean pressure is obtained from a hand pump and the valve is then closed.

A swept sine resonance test is carried out, measuring the pressure at the fixed end with a piezoelectric transducer and the axial motion at points along the hose with small accelerometers. The mounted response of the accelerometers was found to be adequate for the frequency range used, but at higher frequencies direct mounting on the reinforcement is desirable rather than on the surface of the outer cover.

Analysis of results

If damping is not too large, the imaginary parts of N_1, N_2, Z_1 and Z_2 are small and do not have a significant effect on pressures in a circuit. The approximation is therefore made that these quantities are real and hence [4], putting ρ as the fluid density, that

$$Z_i = \frac{\rho}{G_i} \qquad i = 1,2 \qquad (5)$$

The fixed end of the test hose is terminated by a closed ended pipe formed by the end fitting, pressure transducer housing and valve. This will have an entry impedance (pressure/fluid velocity) Z_e which can be readily calculated [1]. In the tests, the length of this extra pipe was kept as short as possible, so that Z_e was very large. If, as an initial approximation, Z_e is taken to be infinite, then the ratio of pressure at the fixed end of the hose, P(O), to the displacement amplitude at the moving end, $W(\ell)$, is given for a hose length ℓ by

$$\frac{P(o)}{W(\ell)} = \frac{2j\omega Z_1(1-N_2)}{(N_1-N_2)}\left(\frac{1}{e^{-M_1\ell\omega}-e^{M_1\ell\omega}}\right)+\frac{2j\omega Z_2(1-N_1)}{(N_2-N_1)}\left(\frac{1}{e^{-M_2\ell\omega}-e^{M_2\ell\omega}}\right) \qquad (6)$$

While the response at mid span is given by

$$\frac{W(\tfrac{1}{2})}{W(\ell)} = \frac{N_1(1-N_2)}{(N_1-N_2)}\left(\frac{e^{-\frac{1}{2}M_1\ell\omega}-e^{\frac{1}{2}M_1\ell\omega}}{e^{-M_1\ell\omega}-e^{M_1\ell\omega}}\right)+\frac{N_2(1-N_1)}{(N_2-N_1)}\left(\frac{e^{-\frac{1}{2}M_2\ell\omega}-e^{\frac{1}{2}M_2\ell\omega}}{e^{-M_2\ell\omega}-e^{M_2\ell\omega}}\right) \qquad (7)$$

These ratios show the usual resonant response. If ω_1 and ω_2 are the frequencies of the relevant peaks, then G_1 and G_2 can be found from

$$G_i = \frac{\pi}{\omega_i \ell} \qquad i = 1,2 \qquad (8)$$

Near ω_1 the first terms will dominate the second and the diameters of the circular parts of the Kennedy and Pancu plots will be good approximations to their values. If the ratio of the diameter on the $P(o)/W(\ell)$ plot to that on the $W(\tfrac{1}{2})/W(\ell)$ plot is R_1 near ω_1, and R_2 near ω_2, then the following approximations will hold

$$N_i = -\frac{2\,\omega_i\,Z_i}{R_i}\left(\frac{1}{e^{-\phi_i}+e^{\phi_i}}\right) \qquad i = 1,2 \qquad (9)$$

where $\phi_i = \dfrac{\pi F_i}{2G_i}$

Higher modes can be used in the same way if measurements are made at $W(\ell/4)$ etc. A Kennedy and Pancu plot of the pressure ratio also reveals the values of F_1 and F_2. If ζ is the damping ratio measured in the usual way, it can be shown

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that for the nth mode associated with wave i the following approximate relationship holds

$$\frac{F_i}{G_i} = \left(\frac{1}{n\pi}\right) \tanh^{-1} (n\pi \ \zeta_{in}) \tag{10}$$

The most critical wave properties are G_1 and G_2. These, and consequently Z_1 and Z_2, can be obtained more accurately by allowing for the additional pipe length at the fixed end of the hose. The equations to be satisfied are, for $i=1,2$:

$$\left(\frac{N_2}{G_1}\right) \cot \ (G_1 \ell \omega_i) - \left(\frac{N_1}{G_2}\right) \cot \ (G_2 \ell \omega_i) = \left(\frac{j \ Z_e}{\rho}\right)^{(N_1 - N_2)} \tag{11}$$

When $i = 1$, the first term usually dominates the second, so this equation can be used to find an improved G_1 by using the previously obtained estimates for G_2, N_1 and N_2. Similarly, the equation in ω_2 can be used to refine G_2, provided ω_2 is not too close to $2\omega_1$.

Discussion

Theoretical approximations were checked by deriving theoretical response plots from typical wave properties. The numerical model of the test configuration did not involve the approximations implicit in equations 5,8,9,10 and 11. The wave properties obtained from measurements of these plots were then compared with those used to produce them. Close agreement was obtained for the propagation constants and characteristic impedances. The modal ratios were not quite so accurate, but since they tend to have less influence on predicted pressures in circuits, the agreement was considered acceptable. The accuracy of the modal ratios was reduced when a measured resonance was very close to a different mode of the other wave. In this situation the propagation constants could still be obtained satisfactorily by using the axial motion at appropriate positions along the hose to separate the modes.

Refinement of the modal ratios can be achieved by using the numerical model to calculate values of $\underline{P}(o)$ and $W(\ell/2)$ at the resonances of each wave; N_1 and N_2 are then varied in order to match these, using an iterative optimisation procedure.

In a practical application, the validity of wave properties obtained using the foregoing equations may be seen in Figs. 2 and 3, which show amplitude and phase of the pressure measured at hose entry in a circuit consisting of a pump, steel pipe, hose, further steel pipe and terminating valve, as the length of the second steel pipe is varied. Circles show experimentally measured values; the solid line shows predicted values using measured pump, valve and hose properties.

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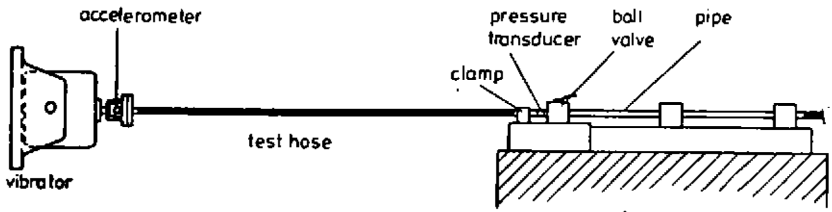
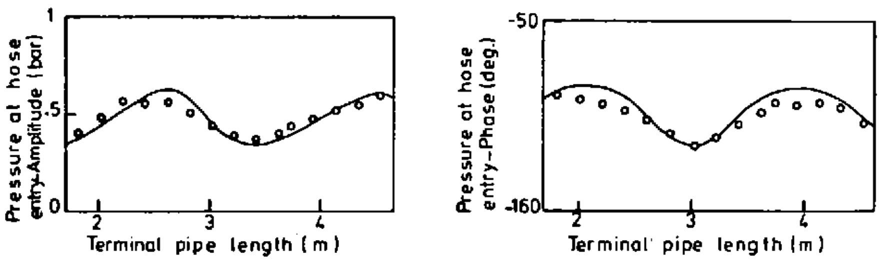


Fig. 1 Test configuration.



Figs. 2 and 3. Amplitude and phase of the pressure in a hydraulic circuit containing a double braid hose - comparison of measured and predicted values.