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Study on the Dynamic Characteristics of the Fluid Loaded Structure

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1. Introduction

Loose Parts Monitoring (LPM) systems have several objectives, some competing. They need to sense a transient vibration event, classify it as due to an impact, and estimate the strength or kinetic energy of the impact. The energy is an indication of the size or mass of the impacting part. The classification requirement is fairly standard; not to have too many false alarms, and not miss too many true impacts. This must be done in the general background of vibration noise. Telling more about the impact itself, such as its energy, the mass of the impacting part, requires that we understand very well the dynamics of the structure. Consequently, our work on this topic requires that we take a very fundamental look at the dynamics of the structure and the effects of fluid loading.

In this paper, we review the basic dynamics pertinent to dry and fluid loaded structures. This includes bending wave speed (phase and group), modal densities and the determination of drive point mobility (or impedance) in the structure. This information is important to extract information from the vibration signal relevant to the velocity, mass, and location of the impact due to a loose part.

2. Effect of fluid loading on structural dynamics

2.1 Dry Structure

The model plenum is chosen to be of convenient size for small scale laboratory measurements, and to have a thin wall so that fluid loading effects are important. The weight of this structure is M=2.9 kg and its wall thickness is h=0.6 mm. The material is steel; its longitudinal wave speed is c=5000 m/s, its density is ρ=8000 kg/m^3 and its total surface area is A=0.62 m^2. Treating the structure as a flat plate, the average modal separation when there is no fluid loading is [1]

$$\delta f = \frac{hc}{A\sqrt{3}} = 2.7Hz \qquad (1)$$

2.2 Fluid loaded structure

Fluid loading slows down the structural waves and increases the modal density (decreases δf) which has an important effect on the impedance of the structure. The bending phase speed for a dry plate is $c_b = 3\sqrt{f(Hz)h(mm)}$, graphed in Figure 1. The group speed can be represented in terms of the phase speed

$$c_g = c_b / \{1 - d(\ln c_b)/d(\ln \omega)\} \qquad (2)$$

For the dry plate, c_g=2 c_b, as graphed.

When the plate is water loaded, an amount of fluid of mass/unit area $\rho_f\lambda_b/2\pi$ "sticks to" the plate increasing its surface density, slowing down the bending waves and changing λ_b. [2] The effect of fluid loading is therefore implicit. If we note that in general, the phase speed with fluid loading will be $c_\varphi=(\omega D/\rho_s)^{1/4}$, where the bending rigidity $D=\rho c^2\kappa^2 h$. Combining these and expressing the condition as a polynomial in c_φ we get:

$$c_\varphi^5 \frac{\rho_f}{\omega\rho h} + c_\varphi^4 - c_b^4 = 0 \qquad (3)$$

which, although 5th order in c_φ, has only a single sign change in the coefficients and therefore only one real root. Using our plenum model parameters, the result of solving for c_φ in this relation as a function of ω is graphed in Figure 1. We see from Figure 1 that the bending waves are slowed considerably in this structure by the fluid loading. The corresponding group speed is determined from the phase speed c_φ by using Eqn. (2). The group speed for the fluid loaded structure is also graphed in Figure 1.

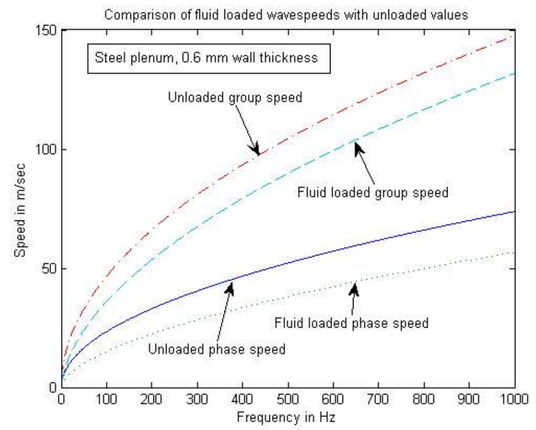

Figure 1. Theoretical phase and group speeds for bending waves in the model plenum structure "dry" and with fluid (water) loading.

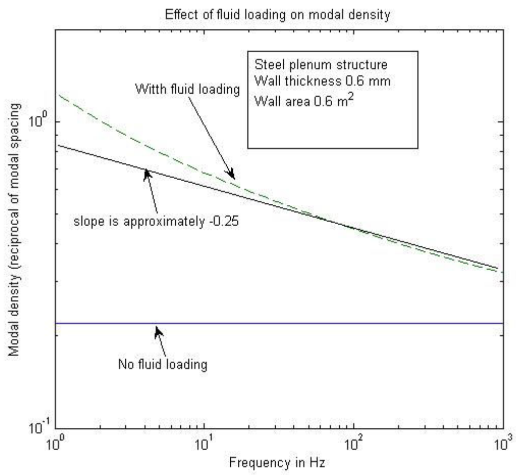

Figure 2. Effect of fluid loading on modal density for the model plenum structure

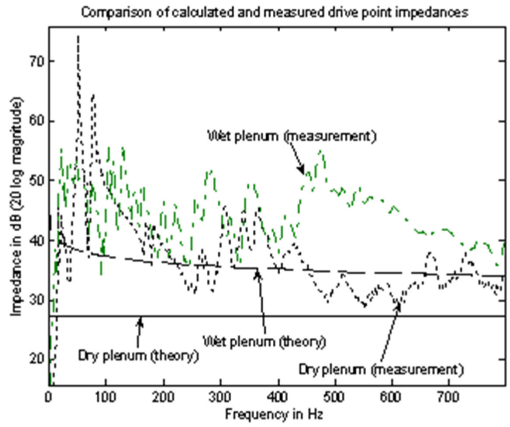

Figure 3 Comparison of calculated and measured drive point impedance

These changes in the phase and group speeds as a result of fluid loading have an effect on the modal spacing as presented in Eqn. (1). The general formula for modal spacing δf in a 2-dimensional structure is

$$\delta f = 1/n(f) = c_{\varphi} c_g / 2\pi f A \qquad (4)$$

The modal densities (reciprocal of the modal spacing) for the dry and fluid loaded model plenum structure are graphed in Figure 2. Over a significant part of the frequency range, we note that the modal density $n(f) \sim f^p$, where $p \approx -0.25 = -1/4$.

When the part comes into contact with the structure, the impedance of the part and the impedance of the structure determine the vibrations that will result. It turns out that the structural mobility (reciprocal of impedance) is determined by the modal density. The structural mobility is

$$< Y >= \frac{\pi < \psi^2 > n(\omega)}{2M}(1 - j\frac{2R}{\pi}) \qquad (5)$$

Where $R = \dfrac{2p}{p^2 - 1}$

When $p = -1/4$, $4p/\pi(p^2 - 1) = 0.34$ and

$$< Y >= \frac{\pi < \psi^2 > n(\omega)}{2M}(1 - j0.34) \qquad (6)$$

Only the real part of this expression is relevant for the drop impact tests for a dry structure, but when the structure is fluid loaded, the forces and motions will be modified by the mass loading.

2.3 Experimental Results

Figure 3 shows the comparison of calculated and measured drive point impedances. The impedance is affected by fluid loading in about the right ratio (10 dB) but the actual impedance is higher than the theory. That may be because the theory is for a flat plate but the plenum is cylindrical. And it also shows that the effect of the structural damping in the fluid loaded structure is greater than that in the dry structure.

3. Conclusion

Structural dynamics will determine the relation between the impact force and the resulting vibration. Therefore, detecting the impact events due to loose parts in a structure can be confused if we do not understand the characteristics of structural vibration. In this paper, we studied the importance of the fluid loading effects on the structural dynamics.

From the viewpoint of structural dynamics and the experiments, the effect of liquid loading on a structure is two-fold. First, it affects structural wave speeds, primarily through mass loading. Accordingly, it affects modal density and the impedance of the structure. Second, it increases the structural damping by viscosity (acoustic boundary layer) and sound radiation.

REFERENCES

[1] Richard H. Lyon, Machinery Noise and Diagnostics, MIT press, 1984.
[2] A. Dowling and J. E. Ffowcs Williams, Sound and Sources of Sound, Ellis Horwood Publishers, Chichester UK, 1983