I-473 SEMI-EMPIRICAL INTERACTION MODEL FOR TUNED LIQUID DAMPER

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Introduction : In an effort to find a mechanical model to predict the response of the structure attached with Tuned Liquid Damper (TLD), the authors have proposed a model based on nonlinear shallow water wave theory (Ref.1). That model is valid up to moderately large amplitude of vibration where wave breaking starts to occur. Wave breaking itself is not yet modelled, however. The authors have subsequently conducted various shaking table experiments to investigate TLD's nonlinear properties at large amplitudes. The "Amplitude-dependent TMD-Analogy model", based on the concept of virtual mass and dashpot, implemented by Pacheco et.al. (Ref.2), is proposed.

Amplitude-Dependent TMD-Analogy Model : A linear (SDOF) system, attached with a TLD of amplitude-dependent effective mass, damping and stiffness, is employed as a TLD-Structure Interaction model (Fig.1). The structure has a modal mass m_s, damping ratio β_s and stiffness k_s. It is subjected to external sinusoidal force of amplitude P and frequency f. The effective mass m_a, damping ratio β_a and stiffness k_a (herein, expressed in terms of natural frequency f_a) of TLD were semi-empirically determined. Introducing the abbreviations $\mu = m_a/m_s$, $\Omega = f_a/f_s$ and $r = f/f_s$, the steady-state response amplitude of the main structure x_s is expressed as

$$x_s = \frac{P}{k_s}\sqrt{\frac{K^2+L^2}{M^2+N^2}} \qquad (1)$$

where $K = \Omega^2 - r^2$, $L = 2\beta_a r\Omega$,
$M = \Omega^2(1-r^2)-\mu\Omega^2 r^2 - r^2(1-r^2) - 4\beta_a\beta_s\Omega r^2$,
$N = 2\beta_a r\Omega(1-r^2-\mu r^2) + 2\beta_s r(\Omega^2-r^2)$

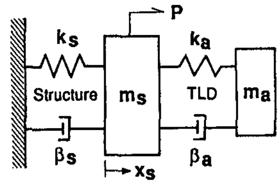

fig.1 TLD-Structure Interaction Model

The concept of virtual mass m_v and virtual damping ratio β_v is applied to find the trend of amplitude-dependent m_a and β_a from the shaking table experiment described in Ref.2. Fitting the experiment results with the simulation using eqs.(4) and (5) of Ref.2, it was found that there is a range of ma and βa that possibly yields good agreement. The range is shown as a shaded area in Figs.2(a) and (c).

To obtain the curve of amplitude-dependent m_a, β_a and f_a, TLD-structure interaction experiment similar to the one in Ref.1 were conducted. This time, the structure had a natural frequency f_s of 0.458 Hz. A 60 cm rectangular tank (2a = 60 cm) with water depth, h, of 3.0 cm was used as the TLD. The TLD, therefore, has fundamental frequency f_w of 0.458 Hz (in 60 cm direction); total mass m_w = 6.0 kg; mass ratio μ = 0.01. A sinusoidal external force of constant amplitude P was exerted in parallel with the 60 cm side. Excitation frequency was varied in the sweep. Different amplitudes of external force were tried in order to cover a wide range of vibration amplitude from relatively small to large where wave breaking occurs.

In determining the vibration amplitude - effective mass (A-m_a) curve, Housner's concept of an unmoving mass at the bottom of the liquid (Ref.3) is applied for very small A. We, therefore, make the A-m_a curve (Fig.2(a)) by starting at m_a/m_w = 0.943 which was computed using Housner's model. As the vibration amplitude A increases further, the trend obtained from the aforementioned shaking table test is followed. The value of ma/mw reaches 1.00 at A around 10 cm onward, which implies that practically the whole liquid in the tank is moving.

The curve for natural frequency of TLD f_a is determined next. For shallow liquid, as in the case of a TLD, f_a is strongly nonlinear in a "hardening" manner as explained by Hayama (Ref. 4). The nonlinearity of the liquid is dependent on a linearly computed natural frequency f_w and an amplitude of liquid sloshing which is mainly a function of the base vibration amplitude A, forcing frequency f and liquid depth ratio h/a. To obtain the relation between structure vibration and the natural frequency of the TLD (A-f_a), we consider only the liquid sloshing amplitude at the state when f/f_w = 1.00. This is because it is the external forcing frequency ratio which is expected to cause frequent large structure vibration. The A-f_a curve shown in Fig. 2(b) has the value of f_a/f_w = 1.00 at very small A and increases in a slow rate as A increases. Liquid at such small amplitude is assumed to be linear. The larger

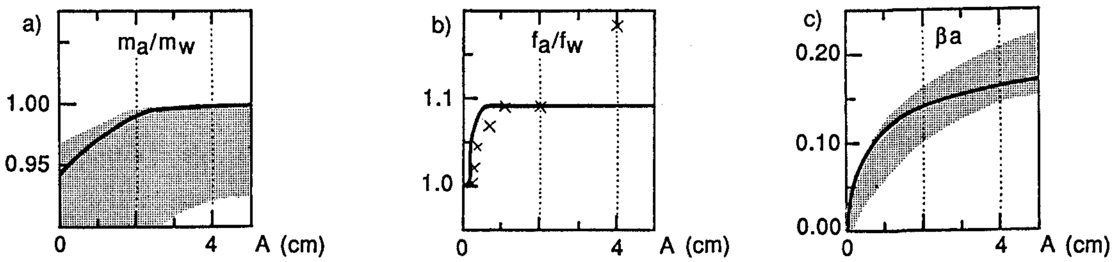

fig.2 Amplitude-dependent parameters

A leads to nonlinear behaviour, i.e., f_a increases together with A. The increasing trend in the A-f_a curve was obtained by considering numerical simulation results of wave at different base vibration amplitude by the same method as Ref. 1. The base amplitude was considered up to 0.4 cm where wave breaking starts to occur and the simulation is no longer valid.

There is no available theory for the natural frequency of liquid where wave breaking exists. We extend the A-f_a curve with consideration of the shaking table experiment, by using a constant f_a/f_w value of 1.09 for large amplitude A. The effective natural frequency preliminarily obtained from the shaking table test is shown as "x". The more precise value has to be investigated further.

Finally, the amplitude-dependent damping ratio (a-β_a) curve is derived by computing structure-vs-f/f_s curves (frequency response curves) using the model with amplitude-dependent parameters m_a and f_a , determined by the curves in Figs.2(a) and (b). A continuous and smooth A-β_a curve that lies within the aforementioned possible range and yields frequency response curves that are best fitted to the interaction experimental results, was chosen as shown in Fig.2(c). The frequency response curves obtained from the computation and the experiments are shown in Figs.3.(a)-(d).

Fig.3(a) shows the result for the case whose input external force causes the structure without TLD to vibrate at resonance ($f = f_s$) with amplitude Ao = 1.0 cm. No apparent breaking wave was observed. Fig.3(b) shows the result for the case of Ao = 5.0 cm. Mild wave breaking was observed. Beating of both structure response and liquid motion occurred at f/f_w = 0.95 to 1.08. It should be noted that the analysis only shows the response amplitude at steady-state. Figs.3(c) and (d) show the results when Ao = 10.0 cm and 20.0 cm respectively. Clear wave breaking was observed in both cases.

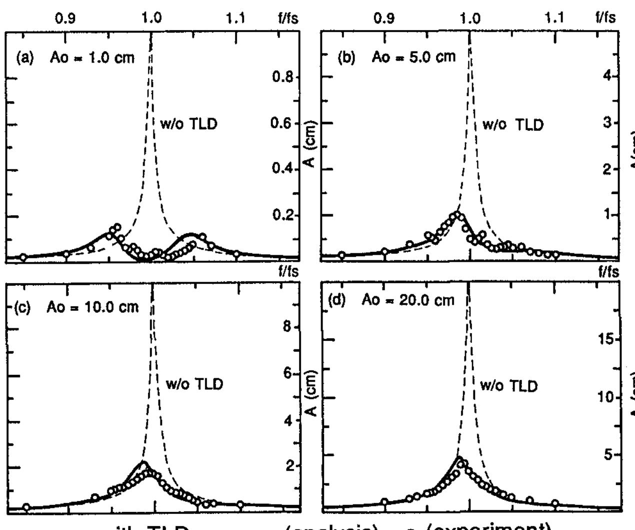

fig.3 Structure response -vs- f/fs

Concluding remarks : The amplitude-dependent properties of a 60 cm rectangular tank with depth ratio h/a of 0.10 were determined. The TMD-analogy model using these amplitude-dependent parameters can serve as a tool for TLD design. Nevertheless, as we know that the nonlinearity of shallow liquid mainly depends upon h/a, and frequency and amplitude of excitation, corresponding parameters as determined herein have to be obtained for other tanks of different size and depth ratio. A nondimensional form of the parameters should be investigated to enable the model to predict TLD performance for a range of tank size and water depth ratio.

Reference : 1) Fujino, Y. et. al., J. of Struct. Engg.,JSCE vol.35A, 1989. , 2) Pacheco, B.M. et. al., Proc. 44th JSCE Annual meeting, vol.1,1989., 3) Housner, G.W., BSSA, 1960., 4) Hayama, S. et. al., JSME(c), vol.49, No.437, 1983.