I-342 MASS AND DASHPOT REPRESENTATION OF NON-LINEAR PASSIVE MECHANICAL DAMPERS

仮想質量と仮想粘性減衰を用いた非線形機械式ダンパーの特性表示とTLDのモデル化への応用

Benito M. PACHECO and Yozo FUJINO, Members, JSCE
University of Tokyo

SUMMARY 非線形性機械式ダンパー（図１）の特性が加振実験、シミュレーションあるいは解析解により記述できるとしても、近似モデルを持つことはダンパーの予備的設計あるいは物理的現象の理解には有用と思われる。ここでは、非線形ダンパーの特性を仮想質量と仮想粘性減衰により表わし、それをベースに近似モデルを構築する方法を提案する。次に、本手法をTLD（同調液体ダンパー）の実験結果に適用し、線形TMDモデルの等価パラメータを決定した例を示す。

OBJECTIVES Many passive mechanical dampers (e.g. [1-3]) have amplitude-dependent, i.e., nonlinear, properties. The effectiveness of such dampers may depend on amplitude and frequency of vibration. Shaking-table tests, computer simulations, or analytical solutions for the simpler cases may provide details of nonlinear behavior; but compactly summarized properties as dampers are preferable for preliminary design.

The **first** objective here is to use the idea of frequency- and amplitude-dependent virtual mass, mv, and dashpot, cv, in the description of nonlinear dampers. A procedure to approximate these properties is suggested. Fig.1(a)-(d) are examples of damper that may be attached.

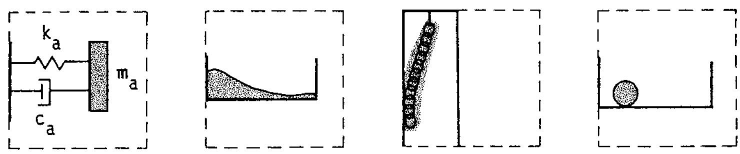
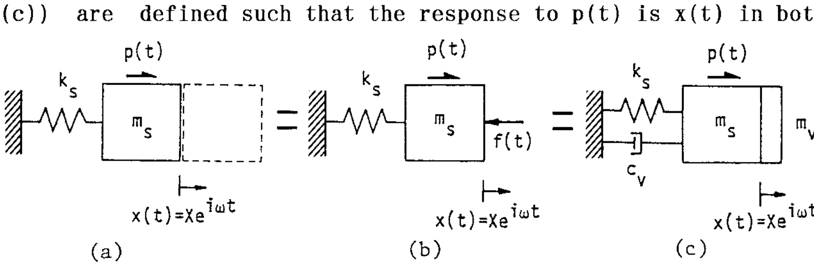


Fig.1 Examples of passive mechanical dampers

The **second** objective is to study the possibility of further summarizing these mv and cv information. One way is to use an analogy with a model for which the frequency dependence of mv and cv are set by a few parameters. For example, a nonlinear TLD (tuned liquid damper) may have a TMD (tuned mass damper) analogy (Fig.1(a)), meaning amplitude-dependent but frequency-independent effective mass, ma, dashpot, ca, and natural frequency, ωa. To avoid confusion, 'virtual' and 'effective' are to be used separately; 'effective' properties are to be independent of excitation frequency.

DEFINITION AND CALIBRATION OF VIRTUAL MASS AND DASHPOT For simplicity consider the SDOF structure without inherent damping in Fig.2(a). The steady-state displacement at the structure-damper interface is **harmonic**: x(t) = X exp(iωt). Virtual mass, mv, and dashpot, cv, (Fig.2(c)) are defined such that the response to p(t) is x(t) in both Figs.2(a) and 2(c). These mv and cv can be related to the interface force f(t) (2(b)). For example, **assuming** that f(t) is of the form:

$$f = m_v \ddot{x} + c_v \dot{x} \quad (1)$$



then (also see [2]): *Fig.2 Virtual mass and dashpot in harmonic displacement*

$$m_v = \int_0^T f(t)\,\ddot{x}(t)\,dt \,/\, \pi\omega^3 X^2 = m_v(\omega,X); \quad c_v = \int_0^T f(t)\,\dot{x}(t)\,dt \,/\, \pi\omega X^2 = c_v(\omega,X) \quad (2),(3)$$

where the integration is over one cycle of x(t); T = 2π/ω. If the damper is **linear**, Eq.(1) is true; and Eqs.(2) and (3) are **exact**. If the damper is **nonlinear**, Eq.(1) is **approximate**, since only the fundamental Fourier component of f(t) would be in the form of the right hand side of Eq.(1). Only that fundamental harmonic contributes in the integrals of Eqs.(2) and (3), while the final effect of higher harmonics on x(t) is assumed to be secondary.

From discretized records of f(t) and x(t), the integrals of Eqs.(2) and (3) can be evaluated numerically. For example, using the experimental f(t) and x(t) data for the tuned liquid damper of Fig.4 of Ref.1, virtual mass and dashpot were calculated and plotted as **points** in Fig.3 for two amplitudes of tank oscillation, namely X=0.1cm (Fig.3(a)) and X=1.0cm (Fig.3(b)). Note that the fundamental sloshing frequency of this TLD at very small amplitude is 0.458Hz; and the total liquid mass is 5.93kg.

APPLICATION TO EFFECTIVE-TMD ANALOGY OF TLD For TMD with natural circular frequency ωa, mass ma, and damping ratio $\xi a = ca/2ma\omega a$, the virtual mass and dashpot are simple functions of frequency ratio $\Omega a = \omega/\omega a$ and ξa (also see [3]):

$$m_v = m_a\alpha = m_a \frac{(1-\Omega_a^2) + (2\xi_a\Omega_a)^2}{(1-\Omega_a^2)^2 + (2\xi_a\Omega_a)^2} \; ; \qquad c_v = c_a\beta = c_a \frac{\Omega_a^4}{(1-\Omega_a^2)^2 + (2\xi_a\Omega_a)^2} \qquad (4),(5)$$

These equations give the **curves** in Fig.3, using the parameters fa= $\omega a/2\pi$= 0.468Hz, ma= 5.0kg, and ξa=0.02 for X= 0.1cm (Fig.3(a)). For X= 1.0cm, fa= 0.504Hz, ma= 5.8kg, and ξa= 0.08. For each amplitude X, the parameters fa, ma and ξa have been **calibrated** such that good overall fit is achieved for both mv and cv data. The curves reasonably **fit** the experimental points for the smaller amplitude (Fig.3(a)). For the larger X (Fig.3(b)), the fit is not so good for mv at high frequencies, but reasonable for cv.

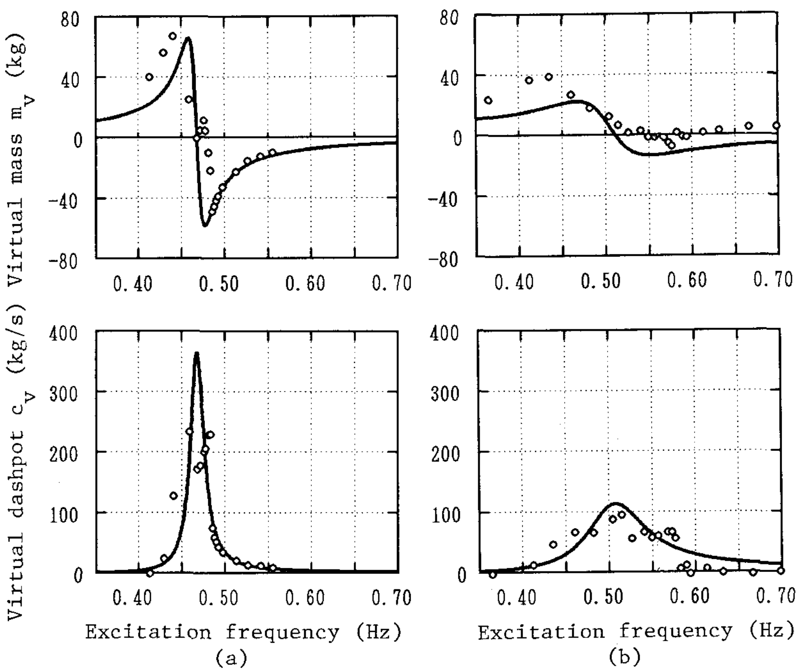


Fig.3 Virtual mass and dashpot of example TLD. (a) X=0.1cm. (b) X=1.0cm.

The nonlinearity of TLD is shown in the dependence of effective-TMD parameters fa, ma and ξa on X. In this example, larger X caused higher fa, ma (approaching total liquid mass) and ξa.

REMARKS mv and cv properties of nonlinear damper can be used iteratively in calculating the harmonic response even of multi-degree-of-freedom structure. Simple mechanical analogy, when obtainable, simplifies the interpolation and extrapolation of mv and cv on the basis of a reduced number of parameters. Such an analogy also provides a simplified physical model for an otherwise complicated damper.

ACKNOWLEDGEMENT The authors are grateful to Messrs. A. Sulekh, L.M. Sun and P. Chaiseri, Univ. of Tokyo graduate students, for the processing of TLD data.

REFERENCES

[1] Y. Fujino et al., JSCE J. Struct. Eng., 35A, 561-574, 1989 (in Japanese).
[2] W. H. Reed, Proc. Wind Effects Bldg. Struct., U. Toronto Press, 284-321, 1968.
[3] F. E. Reed, Shock and Vibration Handbook, Harris and Crede (ed.), 2e, Ch. 6, 1976.