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Tuned liquid dampers with porous media

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A B S T R A C T

A tuned liquid damper (TLD) filled with porous media is developed to promote an additional damping force for the conventional system. According to Darcy's law, the permeability of porous media and liquid viscosity form a damping force linearly proportional to fluid velocity. In this paper, an equivalent mechanical system considering the damping due to porous media in rectangular TLD is established. In contrast to the other operating TLDs with damping devices, the natural frequency and damping ratio of TLD in the present paper can be obtained without using empirical formulas. The dynamic characteristics and performances are also discussed.

1. Introduction

In the past decades, the vibrational control technologies for structures have been deeply studied in civil engineering (Housner et al., 1997). The tuned mass damper (TMD) is one of the most popular and effective dynamic vibration absorber (DVA). It is easy to build, so it has been widely adopted. However, TMD suffers some frequency-related limitations. For instance, it could be inappropriate for aging structures, because its mistuning could cause the reduction of performance. Besides, TMD has limited effort during earthquakes (Housner et al., 1997). Therefore, some modified TMD, such as active and semi-active TMD, had been developed (Chang and Soong, 1980; Hrovat et al., 1983). A tuned liquid damper (TLD), which is a tank filled with liquid (usually water) in a structure, is known as a much more economical DVA. In the early 1950s, it was originally designed for stabilizing vehicles and satellites in space (Graham and Rodriguez, 1952; Abramson, 1966). Afterwards, TLD was applied to structures from 1980s (Bauer, 1984; Modi and Welt, 1988) and soon became very attractive since it needed relatively low manufacture costs and almost no maintenance required. Nowadays, several high-rise buildings have adopted TLD systems (Wakahara et al., 1992; Tamura et al., 1995). The applications of TLD are also extended to different kinds of structures including bridges (Chen et al., 2008) and offshore structures (Jin et al., 2007; Ha and Cheong, 2016).

To understand the interaction between TLD and structures, the dynamic response of TLD was studied in advance. Graham and Rodriguez (1952) developed an equivalent mechanical system for liquid sloshing based on the linear wave theory. Then Housner (1957) revised the equivalent masses and their locations. Afterwards, this simple analytic model has been widely adopted in practice (Veletsos, 1984; Peek and Jennings, 1988; Dodge, 2000; Ibrahim et al., 2001; Ibrahim, 2005). Until recently, Li and Wang (2012) and Li et al. (2012) derived a numerical fitting method and exact solutions for the equivalent linear model of sloshing in a rectangular tank. On the other hand, the nonlinear wave problems became more and more important due to the large liquid motion (Chwang and Wang, 1984). Many numerical schemes have been developed to solve these sloshing problems such as finite difference method (FDM) (Liu and Lin, 2008), finite element method (FEM) (Okamoto and Kawahara, 1992), boundary element method (BEM) (Amano et al., 1993), method of fundamental solution (MFS) (Wu et al., 2016), and regularized boundary integral method (RBIM) (Chen et al., 2017). Overall, both analytic and numerical methods can offer the satisfactory predictions for the linear or nonlinear sloshing problems.

The traditional fresh-water TLD is well known to be inferior to TMD due to its insufficient damping. As a matter of fact, researchers have focused on increasing the damping effect of TLD to achieve an optimal control by additional devices, such as rough boundary (Fujino et al., 1988), wall baffles (Chang et al., 1998; Ju et al., 2004; Zahrai et al., 2012), vertical screens or baffles (Warnitchai and Pinkaew, 1998; Tait et al., 2005; Tait, 2008; Tait and Deng, 2010; Faltinsen and Timokha, 2011; Maravani and Hamed, 2011; Crowley and Porter, 2012; Nayak and Biswal, 2015; Kumar and Sinhamahapatra, 2016; Chen et al., 2018), horizontal screens (Jin et al., 2014), bars (You et al., 2007), or floating roof (Ruiz et al., 2016). In recent years, many researchers prefer slotted screens owing to their convenience in installation. The damping coefficient of a screen basically depends on its solidity ratio, location, number, and tank dimensions as well as the response of liquid. However, those parameters related to damping effect need to be determined by experiments; therefore it somehow increases the difficulty

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during the design stage. In addition, the change of natural frequency induced by additional damping device is always ignored. If the damping ratio has to be further increased by installing more screens or adjusting the screen solidity ratio, the natural frequency may be somewhat mistuned.

Instead of screens, the porous media provides another choice to increase the damping of TLD. This idea originated from the application of breakwater, which is developed to mitigate the response of ocean wave. Huang applied Biot's theory of poroelasticity (Biot, 1962) to consider both inertial force and viscous damping for the problems of breakwaters and porous wave-makers (Huang, 1991; Huang and Chao, 1992; Huang et al., 1993; Hsu et al., 2005). According to Darcy's law (Nield and Bejan, 2013), the resistant force resulted from the viscosity and permeability is equivalent to a damping force linearly proportional to the fluid velocity. Abbaspour and Hassanabad (2010) verified this force decreased the dynamic reaction of liquid in storage tank very rapidly. Therefore, it is more convenient to adjust the specific porosity and permeability to achieve the required damping.

The analytic method for porous TLD system is developed in this paper. The governing equations and boundary conditions are introduced in Section 2; the equivalent mechanical model which takes the damping effect into account is established in Section 3; several examples are verified and discussed in Section 4; and some conclusions are briefly drawn in Section 5.

2. Sloshing in porous media

2.1. Governing equations of liquid within porous tanks

The free surface motion in an isotropic porous media inside a rectangular tank subjected to a horizontal excitation along the x-direction can be simplified as a two-dimensional sloshing problem. Assume this tank has length L and water depth h as shown in Fig. 1. The skeleton of porous media is rigid and fixed with the tank and water inside is incompressible; the continuity and momentum equations of water within the porous tank are (Nield and Bejan, 2013):

$$\nabla \cdot \vec{u} = 0 \tag{1}$$

$$\rho\left[\frac{\partial \vec{u}}{\partial t} + (\vec{u}\cdot\nabla)\vec{u}\right] = -\nabla P - \frac{\gamma\mu}{\kappa}(\vec{u} - \vec{v}) + \rho\vec{g} \tag{2}$$

in which $\vec{u}$ is the intrinsic fluid velocity, $\vec{v}$ the velocity of tank, γ the porosity, μ the dynamic viscosity, κ the permeability, P the pressure, ρ the fluid density, and g the gravitational acceleration. The intrinsic fluid velocity is defined as the fluid velocity over a volume element consisting of fluid only, the porosity is defined as the fraction of the total volume of the medium that is occupied by void space, and the permeability is defined as a quantity measuring the influence of a substance on the fluid flux in the region it occupies. The second term on the right-hand side of Eq. (2) resulting from Darcy's law implies the linear damping force proportional to the velocity of fluid relative to the tank. Assuming the flow field is irrotational, the velocity potentials φ and ψ can be defined as:

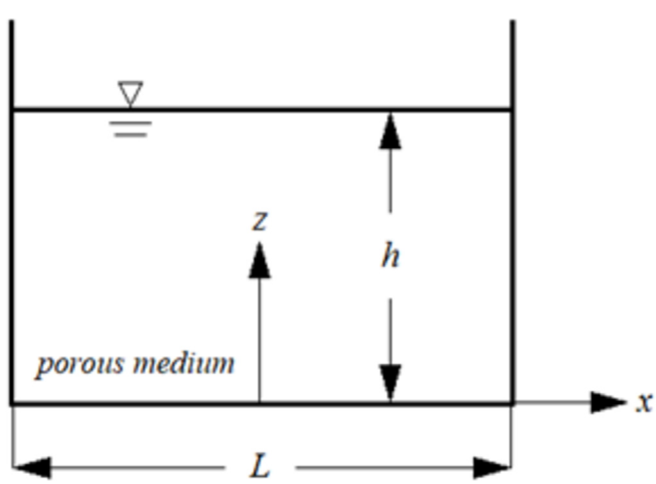

Fig. 1. Coordinate system and definition of length and filling depth of a rectangular tank.

$$\vec{U} = \nabla\varphi \tag{3}$$

$$\vec{v} = \nabla\psi \tag{4}$$

where $\vec{U} = \gamma\vec{u}$ is the average of the fluid velocity over the total volume of the medium. Due to the continuity of fluid and rigid-body excitation of tank, both velocity potentials satisfy the Laplace equation such as:

$$\nabla^2\varphi = 0 \tag{5}$$

$$\nabla^2\psi = 0 \tag{6}$$

2.2. Boundary conditions

The kinematic and dynamic boundary conditions of the free surface can be described as (Nield and Bejan, 2013):

$$\frac{D\vec{R}}{Dt} = \vec{u} \text{ on the free surface} \tag{7}$$

$$\frac{\partial\varphi}{\partial t} + \frac{1}{2\gamma}\nabla\varphi\cdot\nabla\varphi + \gamma\alpha(\varphi - \psi) + g(z - h) = 0 \text{ on the free surface} \tag{8}$$

where $\vec{R}$ is the location of particle on the free surface, and $\alpha = \frac{\mu}{\kappa\rho}$. Since the given excitation is horizontal and unidirectional, the impermeable condition can be expressed as:

$$\frac{\partial\varphi}{\partial z}(x, 0, t) = 0 \text{ on the bottom} \tag{9}$$

$$\frac{\partial\varphi}{\partial x}\left(\pm\frac{L}{2}, z, t\right) = \vec{v} \text{ on the side walls} \tag{10}$$

3. Analytic solutions

3.1. Homogeneous solution of linear waves in rectangular porous TLD

The linearized kinematic boundary condition on the free surface in porous media can be simply obtained by substituting Eq. (3) into Eq. (7) as (Huang et al., 1993):

$$\frac{\partial\eta}{\partial t} = \frac{1}{\gamma}\frac{\partial\varphi}{\partial z} \tag{11}$$

where η is the vertical deviation from the mean free surface. Combining Eq. (11) and the linearized dynamic boundary condition, i.e. the linearized form of Eq. (8) (Beck, 1972), the velocity potential at $z = h$ satisfies:

$$\frac{\partial^2\varphi}{\partial t^2} + \gamma\alpha\left(\frac{\partial\varphi}{\partial t} - \frac{\partial\psi}{\partial t}\right) + \frac{g}{\gamma}\frac{\partial\varphi}{\partial z} = 0 \tag{12}$$

If only the relative motion between fluid and tank is considered, the velocity potential of tank can be given as a constant (such as a stationary tank), therefore $\partial\psi/\partial t = 0$. Since the tank is only subjected to lateral force, the even-mode fluid motions will vanish due to the antisymmetrical fluid motion. Hence the general solutions of fluid motions from the Laplace equation are of the form:

$$\varphi_n(x, z, t) = D_n \sin a_n x \cosh a_n z \, e^{s_n t}, \quad n = 0,1,2... \tag{13}$$

where D_n is a constant determined from the initial condition and $a_n = (2n + 1)\pi/L$. Therefore, φ_n has to satisfy the constraint of Eq. (12)