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Evaluate pressure drop of slat screen in an oscillating fluid in a tuned liquid damper

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ABSTRACT

Tuned liquid dampers (TLDs) are considered economical and effective dynamic vibration absorbers. Using of slat screens in TLDs can increase the inherent damping factor of TLDs. In many former numerical efforts, screens were modeled as a hydraulic resistance point as a function of the screen solidity ratio without the ability to consider the effect of the screen pattern. Clear understanding of the pressure drop across the slat screens, as the major factor for controlling the inherent damping of TLDs, enrolls a great effect on improving the performance of TLDs. Two slat screens with the same solidity ratio and different patterns could cause the different levels of the pressure drop and so inherent damping in TLDs. In the developed algorithm, the fluid flow through the screen is fully resolved and the effect of the screen pattern on the TLD's performance is taken into account. The numerical results of the developed algorithm have been validated against experimental work. Using this algorithm, a new pressure drop model for the slat screens has been developed considering the effects of the screen pattern through introducing two new concepts called the effective solidity ratio (S_{eff}) and the slat ratio (SR) which they can imply the physical significance of screen pattern.

1. Introduction

A tuned liquid damper (TLD) is a partially filled, water tank used as a passive vibration absorber. Unlike active or semi-active dampers, passive dampers do not require any external supply of power to operate [1]. The main function of a passive damping device is to improve the occupant comfort of tall structures and high rise buildings by absorbing part of the energy associated with external dynamic excitations acting on the structure due to wind, sea waves, etc. The vibration motion of the structure due to the external excitation causes the liquid inside the TLD to undergo a sloshing motion. By means of tuning the natural frequency of such motion to the natural frequency of the structure, the liquid imparts an inertia force approximately anti-phase to the external dynamic force, thereby, reducing the structure response. Therefore, coupling a structure with a TLD modifies its response in a way similar to increasing its effective damping.

TLDs have attracted significant attention due to their many advantages over other conventional damping devices. They can be used to damp small and large amplitude excitations, they are easy to install on existing structures and require low maintenance and operating cost. Therefore, TLDs have been used to mitigate vibration in many applications such as marine vessels [2], offshore platforms [3], and tall structures [4–8]. Fuji et al. [4] and Wakahara [5] studied the effect of tuned liquid dampers on the wind induced vibration of tall structures experimentally. In recent years, Tait [6–8] carried out extensive experimental study on performance of TLD outfitted by slat screens [6,7] in order to preliminary design and modeling of structure-TLD systems [8].

The sloshing motion inside TLDs has been studied extensively through numerous experimental [9–12] studies. Pirner et al. [9] conducted an experimental investigation on the effect of TLD with two degrees of freedom (horizontal displacement and rotations) on the vertical and horizontal vibrations of footbridges. This work showed that TLD will restrict undesirable horizontal and torsional vibrations of footbridges effectively. Lee et al. [10] completed another experimental study for evaluating of the performance of a TLD controlling a seismically excited building structure. In this study, a real-time hybrid shaking table testing method (RHSTTM) was used. This method didn't require a physical building structure model for performing the experiment of a TLD-Structure interaction system. Ju et al. [11] evaluated the characteristics of a TLD with wire screens and small blocks attached to the wall and proposed an equation for the equivalent damping ratio of the TLD. Deng and Tait [12] focused on the development of the equivalent mechanical model for the tuned liquid damper outfitted by two slat screens with different tank shapes under external excitation

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in the transverse direction. The equivalent mechanical properties derived in this work could model the fundamental sloshing mode only and are restricted to small response amplitudes.

Numerical investigations on tuned liquid dampers were mostly conducted using linear models, employing the potential flow theory and the shallow wave theory [13,14]. Shimuzu et al. [13] and Tait et al. [14] utilized the shallow water wave theory and potential flow theory to obtain the free surface response amplitude and the corresponding velocity of the sloshing liquid. Sun et al. [15] combined these two theories and studied the effect of liquid viscosity only within the boundary layer region. Zang et al. [16] solved a linearized form of Navier–Stokes equations by neglecting the convective acceleration terms, achieving an improvement over previous obtained predictions using the potential flow theory. They indicated that liquid viscosity has an important effect on sloshing motion near rigid walls, especially under excitation frequencies close to resonance. It is worth noting here that linear models are applicable only when interfacial deformations are small; which is expected in cases when the amplitude of the external excitation is small, or when the frequency of the external excitation is away from the natural frequency of the TLD. Consequently, in all other cases linear models become inadequate. Ramaswamy et al. [17] solved the full, nonlinear, Navier–Stokes equations using a Lagrangian approach employing the finite-element method. However, only the small amplitude oscillations were considered in this study. Accordingly, the liquid sloshing motion was assumed linear.

Thé et al. [18] solved the governing equations of the motion of a viscous, incompressible, free surface flow problem using the finite-volume method. They tracked the interface of free surface using an adaptive grid. They did not consider large deformations of the free surface and only cases with moderate surface deformations were considered. Yamamoto and Kawahara [19] solved the Navier–Stokes equations using an arbitrary Lagrangain–Eulerian (ALE) formulation. Siddique et al. [20] modeled free-surface flow inside a TLD using an analytical mapping technique, where an analytical mapping function was used to transform the irregular physical domain (deformed interface) into a rectangular computational domain. They considered cases of large surface deformations.

Although a TLD has a simple construction, the liquid sloshing motion inside the TLD is highly nonlinear and complex and the physics of this motion depends on many interrelated variables. These variables include the nature of the applied external excitation if it is random or harmonic, and its amplitude and frequency as well as the tank geometry, liquid layer depth, and liquid properties. In order to design an efficient TLD, such a motion has to be well predicted and well controlled by means of a set of TLD tuning parameters. These parameters are:

1. The TLD mass ratio, which is defined as the ratio of the effective liquid mass to the structure generalized mass,
2. The sloshing motion natural frequency,
3. The TLD damping ratio (inherent damping).

The typical TLD mass ratio in the case of tall structures is between 1% and 5%. The TLD must be tuned in such that its fundamental sloshing frequency matches the structure's natural frequency. The optimum damping ratio at the typical TLD mass ratio is in the range of 5% to 15%. The main source of such damping is wave breaking and viscous dissipation in the boundary layer at the TLD walls. The inherent damping of any TLD without any additional damping devices is significantly less than such optimum value. Moreover, wave breaking makes TLD's performance highly non-linear and unpredictable. Therefore, there is a need to increase the TLD inherent damping using external damping devices. The effect of such devices on TLD's performance has attracted significant attention.

Ghaemmaghami et al. [21] studied the dynamic behavior of annular tuned liquid dampers without using any external damping device in the wind towers. They found that the damping properties of the annular TLD are highly dependent on the amplitude of excitation. Higher excitation amplitudes result in lower effective damping values.

Several approaches have been proposed and investigated to increase the TLD inherent damping including the use of: (1) rough surfaces [22], (2) bars [23,24], and (3) nets or screens [25–27]. Ju [22] evaluated the characteristics of the water sloshing damper with embossments on the tank walls experimentally and proposed an equation for the equivalent damping ratio of TLD. You et al. [23] conducted another experimental study to investigate the characteristics of the shallow water sloshing motion in a rectangle tank. To increase the damping ratio of the rectangular water tank, they installed triangle sticks at the bottom of water tank to increase the damping ratio of TLD. Huang et al. [24] conducted an experimental work on a TLD with an embedded transverse cylinder. They could show that the sloshing mass was effectively increased and the dynamic performance of such a TLD was better than the ordinary TLD.

Warnitchai and Pinkaew [25] showed through another experiment that screens are an effective damping device in increasing the damping ratio of TLD in both the small and large amplitude excitations. Therefore the use of screens offers an economic and easy way to implement and control the level of achieved damping in a TLD.

Tait et al. [26] conducted a numerical analysis to simulate tuned liquid dampers with slat screens. The presented method to determine the loss coefficient of screen in this study, could not take into account the effect of screen pattern. Cassolato et al. [27] applied the same method utilized by Tait et al. [26] to investigate the concept of using inclined slat screens to adjust the damping ratio of tuned liquid dampers. They developed an amplitude dependent mechanical model to calculate the steady state response of the fluid when the tank is subjected to base excitation. They could show that the loss coefficient of a screen decreases as the angle of inclination increases. This model also could not determine the effect of screen pattern on damping effect of screen.

Kaneko and Ishikawa [28] investigated the effect of screens on the TLD's performance using a nonlinear numerical model that was developed using the shallow wave theory. They assumed the flow to be inviscid, incompressible and irrotational. They modeled the screen as a point resistance with the pressure drop proposed by Baines and Peterson [29] model. This model couldn't consider the effects of the screen pattern.

In the late 1950s, Keulegan and Carpenter published work on the forces acting upon plates and cylinders in oscillating flow [30]. Their work involved calculating the inertial and drag coefficients of cylinders and plates in simple sinusoidal flow. They were unable to find a relation between the Reynolds number and drag force, however they were able to show a correlation between drag coefficient of plate or cylinder and a period parameter known as Keulegan–Carpenter (KC) number. The KC number was defined as: $KC = (U_m T/D)$, where U_m is the maximum amplitude of velocity at the object after one half cycle of oscillation, T is the excitation period, and D is the width of the object perpendicular to the flow. They showed that for a KC number less than 30, the loss coefficient becomes dependent on the KC number and there is rapid increase in the drag coefficient as the KC number approaches to zero. Conversely, as the KC number increases past 30, the drag coefficient approaches a near constant value. This work was conducted on single plate not a slat screen. Although the slat screen can be considered as set of individual plates but the flow patterns of the neighbored slats have influence on each other and so the results of this study cannot be extended for the slat screen.