Wind and Structures, Vol. 7, No. 4 (2004) 235-250
DOI: http://dx.doi.org/10.12989/was.2004.7.4.235

The efficiency and robustness of a uni-directional tuned liquid damper and modelling with an equivalent TMD

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(Received March 28, 2003, Accepted January 22, 2004)

Abstract. The current study reports the results of an experimental program conducted on a structure fitted with a liquid damper (TLD) and subjected to harmonic excitation. Screens were placed inside the TLD to achieve the required inherent damping. In the first part of the study, reduced scale models of the building-TLD systems were tested under two levels of excitation. The efficiency of the damper was assessed by evaluating the effective damping provided to the structure and comparing it to the optimum effective damping value, provided by a linear tuned mass damper (TMD). An extensive parametric study was then conducted for one of the three models by varying both the excitation amplitude and the tuning ratio, defined as the ratio of the TLD sloshing frequency to the natural frequency of the structure. The effectiveness and robustness of a TLD with screens were assessed. Results indicate that the TLD can be tuned to achieve a robust performance and that its efficiency is not significantly affected by the level of excitation. Finally, the equivalent amplitude dependent TMD model, developed in the companion paper is validated using the system test results.

Keywords: tuned liquid damper; TLD; vibration absorber; tank; screens; sloshing water; robustness; efficiency; tuned mass damper; TMD.

1. Introduction

A tuned liquid damper (TLD) is an effective passive vibration absorber for mitigating the response of a structure excited by dynamic loads. The TLD has a number of important advantages. These include: operation under both small (wind) and large (earthquake) amplitude vibrations; a low probability of failure; ease of tuning; and relatively low installation and maintenance costs. The drawbacks of a TLD are that only a portion of the entire water mass participates in reducing the structural motion and also a significant amount of space is required in order to achieve the required TLD to structure mass ratio as a result of the low density of water. A number of tall structures have been successfully fitted with TLD devices, resulting in a substantial reduction in structural motion (Noji, *et al*. 1988, Fuji, *et al*. 1990, and Wakahara, *et al*. 1992). A TLD operates analogously to the well-known tuned mass damper (TMD), with the exception that its inherent dynamic characteristics are nonlinear. Therefore, its influence on the response of a structure subjected to dynamic loads is

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more difficult to assess.

The impetus for this study originated from an experimental program conducted to investigate the effectiveness of TLD devices in reducing the dynamic response of three proposed tall buildings. A spring-mass system is constructed to simulate the scaled dynamic properties of the fundamental vibration modes of each of these three buildings. Rectangular tanks, partially filled with water, are rigidly attached to the spring-mass system. Damping screens are attached inside the tanks to increase the inherent damping of the device. Additional information regarding the damping screens can be found in the companion paper (Tait, *et al*. 2004a). By tuning the fundamental sloshing mode of the water in the tank to the natural frequency of the spring-mass system, scaled models of the prototype structure-TLD system are simulated.

The first part of this paper reports on the additional effective damping, ζ_{eff}, provided to the three structure-TLD models tested. The second part of the paper reports on a parametric study conducted for a structure-TLD model. It involves investigating the effect of the amplitude of the excitation force applied to the building and the tuning ratio, defined as the ratio between the TLD fundamental sloshing frequency and the fundamental frequency of the structure. The influence of varying these two parameters on the efficiency and robustness of the TLD device are assessed. The final portion of this paper compares experimental results to values calculated using an amplitude dependent equivalent TMD model that has been developed in the companion paper (Tait, *et al*. 2004a).

2. Experimental set-up and procedure

A schematic of the structure-TLD system used in the testing program is presented in Fig. 1. Each

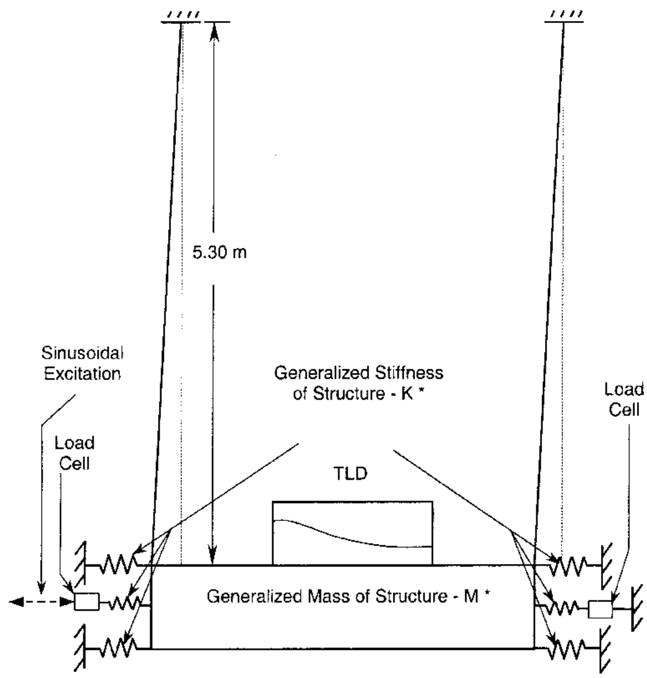


Fig. 1 Schematic of two degree of freedom structure-TLD system

of the proposed buildings is modelled as an equivalent single degree of freedom that represents the fundamental mode of vibration of the building. Free decay tests are conducted, without the TLD attached, to determine the natural frequency and the damping ratio of the modelled buildings.

The models, with TLD attached, are excited sinusoidally through a pre-tensioned driving spring. This allows the excitation force to be applied directly to the structure. The driving spring's contribution to the stiffness of the structure is accounted for in all tests conducted. Load cells are used to measure the instantaneously applied excitation force. The instrumentation of the TLD includes six wave probes to measure the free surface motion. Four load cells are used to measure the interactive base shear forces between the TLD and the structure. Two laser transducers are used to record the displacement of the structure.

All data are low-pass filtered at 5 Hz and sampled at 10 Hz. For each frequency of excitation, the system is excited for 120 seconds before data are recorded in order to allow steady-state conditions to fully develop. A total of 69 different excitation frequencies, f, are applied to the structure in order to obtain a sufficient estimate of the mechanical admittance function of the structure with an attached TLD.

3. Experimental evaluation of effective damping of structure-TLD system

The TLD tank dimensions are geometrically scaled at 1:10, resulting in a $1{:}\sqrt{10}$ scaling factor for the fundamental sloshing frequency of the water, f_w. The generalized mass, M^*, of the modelled building is selected in order to maintain the same mass ratio, μ, as that of the prototype building to prototype TLD.

Assuming the TLD is located at the top of the building, the effective mass ratio is defined as

$$\mu_{TLD} = \frac{m_{TLD}}{M^*} \tag{1}$$

where m_{TLD} is the participating mass of the sloshing fluid corresponding to the fundamental sloshing mode, which can be estimated by Graham and Rodriguez (1952)

$$m_{TLD} \approx m_1 = \frac{8\tanh\left(\pi \frac{h}{L}\right)}{\pi^3\left(\frac{h}{L}\right)} m_w \tag{2}$$

where L is the tank length, h the water depth and m_w the total water mass contained inside the tank. The modelled building's generalized stiffness, K^*, is adjusted in order to maintain the correct tuning ratio, Ω, between the prototype and the model.

The tuning ratio is defined as

$$\Omega = \frac{f_{TLD}}{f_s} \tag{3}$$

where f_{TLD} is the fundamental sloshing frequency of the fluid and f_s is the natural frequency of the structure. The tuning ratio is set to approximately unity for all tests conducted in this part of the study assuming $f_{TLD} \approx f_w$, where f_w is estimated using linear wave theory and is expressed as

Table 1 Modeled building and TLD properties

Building	M^* (kg)	f_s (Hz)	h/L	m_w (kg)	m_{TLD} (kg)	μ_{TLD}(%)
BM1	2242	0.630	0.102	66.4	52.1	2.3
BM2	4041	0.565	0.156	114.7	86.1	2.2
BM3	2375	0.545	0.123	41.3	31.9	1.3

Table 2 Applied force and maximum response values

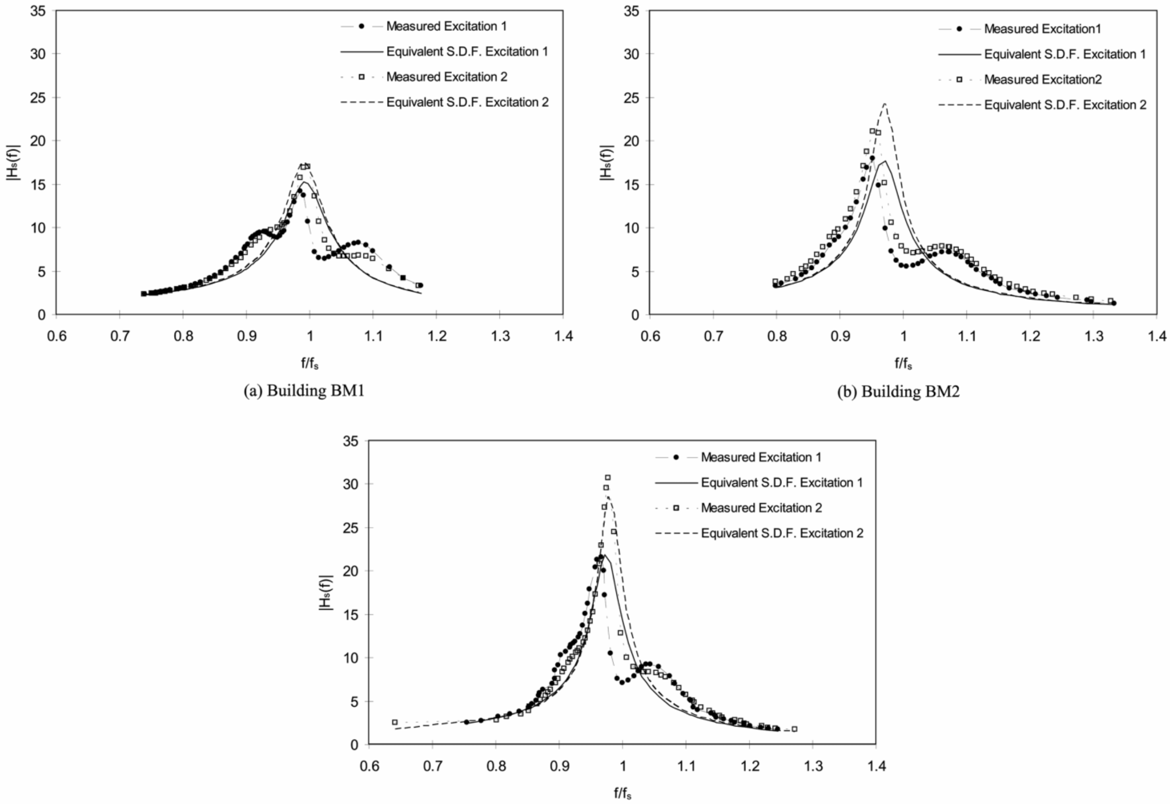
Building	Excitation 1			Excitation 2		
	Applied Excitation (N)	Max Dis. (mm)	Max Acc. (milli-g)	Applied Excitation (N)	Max Dis. (mm)	Max Acc. (milli-g)
BM1	18.0	7.3	12.0	27.5	13.3	21.0
BM2	47.8	16.8	22.0	58.3	24.1	31.0
BM3	11.0	8.0	9.0	16.3	18.4	22.0

$$f_w = \frac{1}{2\pi}\sqrt{\frac{\pi g}{L}\tanh\left(\frac{\pi h}{L}\right)} \tag{4}$$

The generalized mass of the building, M^*, the water depth to tank length ratio, h/L, the water mass, m_w, and the effective mass, m_{TLD}, approximated using Eq. (2) are provided in Table 1 for the three models tested.

To investigate the robustness of the attached TLD devices, the model buildings are tested with two different amplitudes of applied excitation. The amplitude of the applied excitation, the maximum measured building displacement, and the corresponding prototype acceleration for each test conducted are given in Table 2. The mechanical admittance function, $|H_s(f)|$, for the structure-TLD systems corresponding to the two levels of excitation are given in Figs. 2(a) to 2(c) for buildings BM1, BM2, and BM3, respectively. Three peaks can be observed for BM1 subjected to the first excitation amplitude. This multi-peaked mechanical admittance function results from the nonlinear TLD and has been reported on by other researchers (Chaiseri 1990). The nonlinear TLD characteristics are discussed in Tait, *et al*. (2004a). For a linear auxiliary damper, i.e., a linear TMD, the response curves would remain constant under various excitation amplitudes. However, as the behaviour of a TLD is nonlinear, a change in $|H_s(f)|$ occurs when the amplitude of the applied excitation is changed. As Figs. 2(a) to 2(c) show, different mechanical admittance functions are obtained for the same structure-TLD system when excited with different excitation amplitudes.

The effectiveness of a TMD can be quantified by the amount of additional linear viscous effective damping, ζ_{eff}, which must be added to the single degree of freedom primary structure, in order to reduce its response to the same level as that of the structure-TMD system (Vickery and Davenport 1970). In this process, it is necessary to recognize that this effective damping is influenced by the inherent damping of the structure, ζ_s. The same approach can be used to measure the effectiveness of a TLD. For white noise excitation the effective damping is determined by the variance of the structure-TLD response, which is related to the area under the mechanical admittance function. The effective damping is given as



(a) Building BM1

(b) Building BM2

(c) Building BM3

Fig. 2 Mechanical admittance functions for 3 model buildings for 2 different excitation amplitudes

$$\zeta_{eff} = \frac{\pi}{4} f_s \frac{1}{\int_0^\infty |H_s(f)|^2 df} - \zeta_s \tag{5}$$

where $|H_s(f)|$ is the mechanical admittance function of the structure-TLD system tested. The area under the experimentally obtained response curves are numerically integrated and substituted into Eq. (5) in order to estimate ζ_{eff}. The mechanical admittance functions of the equivalent single degree of freedom systems, using ζ_{eff}, have been plotted in Figs. 2(a) to 2(c) for comparative purposes.

Table 3 shows the estimated effective damping values from the experimentally obtained mechanical

Table 3 Effective damping of structure-TLD system and TLD efficiency

Building	ζ_{eff} (%)		Optimal values - TMD			Ψ (%)	
	Exc. 1	Exc. 2	Ω_{A-opt}	ζ_{A-opt} (%)	$\zeta_{eff-opt}$ (%)	Exc. 1	Exc. 2
BM1	3.28	2.86	0.983	7.5	3.8	86	75
BM2	2.81	2.06	0.984	7.4	3.7	76	56
BM3	2.28	1.74	0.990	5.6	2.8	79	60

admittance functions. For all three structure-TLD systems, the effective damping decreases with an increase in the amplitude of the applied excitation. This indicates that under higher amplitudes of applied excitation, the TLD devices tested are less effective for a tuning ratio value of unity.

Warburton (1982) derived equations for the optimal tuning ratio, Ω_{A-opt}, the inherent damping ratio, ζ_{A-opt}, and the optimal effective damping, $\zeta_{eff-opt}$, values for a linear dynamic vibration absorber attached to a structure, having no damping ($\zeta_s = 0$), subjected to white noise excitation.

$$\Omega_{A-opt} = \frac{\sqrt{1 + \frac{\mu}{2}}}{1 + \mu} \tag{6}$$

$$\zeta_{A-opt} = \sqrt{\frac{\mu\left(1 + \frac{3\mu}{4}\right)}{4(1 + \mu)\left(1 + \frac{\mu}{2}\right)}} \tag{7}$$

The optimal effective damping, $\zeta_{eff-opt}$, for a optimal linear DVA can be determined by

$$\zeta_{eff-opt} = \frac{1}{4}\sqrt{\frac{\mu + \mu^2}{1 + \frac{3\mu}{4}}} \tag{8}$$

The optimal values for the three tested structure-TLD systems are provided in Table 3 for comparison with the experimental values. It is evident that the optimal effective damping values are not achieved. This can be attributed to the nonlinear dynamic properties of the TLD. Since m_{TLD}, f_{TLD}, and ζ_{TLD} vary with amplitude, no unique values exist. Given that each of the TLDs tested in this study has hardening type response characteristics, f_{TLD}, will increase with increased excitation amplitude. As a result of this phenomenon, Ω, which is already set higher than Ω_{A-opt}, is forced further away from the optimal value as the structure-TLD is subjected to higher excitation amplitudes. Secondly, ζ_{TLD}, will exceed ζ_{A-opt} under large excitation amplitudes as shown in Tait, *et al.* (2004a) by the plot of ζ_{TLD} versus A/L.

The efficiency, Ψ, of a TLD compared to that of an optimally designed linear TMD is expressed as

$$\Psi = \frac{\zeta_{eff}}{\zeta_{eff-opt}} \cdot 100 \tag{9}$$

The efficiency of the TLDs is 75% or greater for low excitation amplitudes and 56% or greater for larger excitation amplitudes. The efficiency values for the TLD devices are considered satisfactory as none of the TLDs are designed to have optimal parameters.

Little information on how sensitive the dynamic response characteristics of a structure-TLD system are to various parameters currently exists. This raises questions regarding the influence of the tuning ratio and the applied excitation amplitude on the robustness and efficiency of a structure-TLD system.

4. Assessing the robustness and efficiency of a TLD

In order to assess the influence of Ω and amplitude of the excitation on the robustness and efficiency of a structure-TLD system, an experimental program is conducted and reported in this part of the study. The study focuses on a building similar to BM3, previously tested with a tuning ratio equal to unity. In order to investigate the influence of both parameters a total of 19 tests, described in Table 4, are conducted. One particular test is conducted with the TLD screens removed from the tank in order to determine the efficiency of the device with a markedly reduced inherent damping.

The generalized mass, M^*, of the model building is set to 2500 kg for all tests conducted in this component of the study. The natural frequency of the structure, f_s, is adjusted by modifying the generalized stiffness, K^*, with the external springs, shown in Fig. 1. This allows Ω to be varied while maintaining a constant mass ratio value. Table 5 shows the building properties for the five tuning ratio values studied.

4.1. Influence of the excitation amplitude on the structure-TLD response

Fig. 3 compares the measured mechanical admittance function of the structure-TLD system with $\Omega = 0.99$, for six different amplitudes of applied excitation. The observed shift from the two-peak

Table 4 Structure-TLD experimental test cases for parametric study

Test No.	Ω	Excitation Amplitude (N)
1	0.99	10.0
2	0.97	10.0
3	0.93	10.0
4	0.95	10.0
5	1.01	10.0
6	0.99	17.5
7	0.97	17.5
8	0.93	17.5
9	0.95	17.5
10	1.01	17.5
11	0.99	15.0
12	0.97	15.0
13	0.93	15.0
14	0.95	15.0
15	1.01	15.0
16	0.99	7.5
17	0.99	5.0
18	0.99	12.5
19 (w/o screens)	0.99	5.0

Table 5 Properties of the structures for parametric study

Set-Up #	ζ_s (%)	f_s (Hz)	Ω
1	0.06	0.551	0.99
2	0.06	0.564	0.97
3	0.06	0.585	0.93
4	0.06	0.574	0.95
5	0.06	0.538	1.01

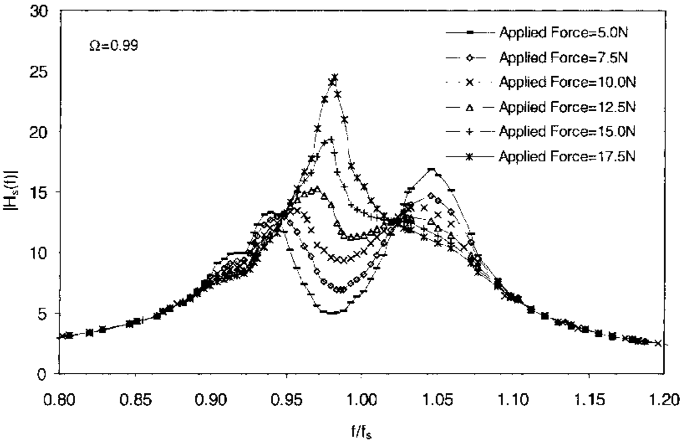


Fig. 3 Mechanical admittance function of structure-TLD system with varying excitation amplitudes

response to a single peak response with increased excitation amplitude is a direct result of the nonlinear properties of the TLD. All six curves approximately intersect at two locations, $f/f_s \approx 0.95$ and 1.02, respectively, indicating an independence of excitation amplitude at these normalized excitation frequency values. For a linear TMD, the two intersection points indicate locations where the structure-TMD system response is independent of the inherent damping of the TMD, if the primary structure has no damping. Therefore, for the TLD, at these two intersection points the response is nearly independent of ζ_{TLD}, which is a function of excitation amplitude. The same trend is found for all five tuning ratio values.

4.2. Influence of Ω on the structure-TLD response

Fig. 4 shows the dependence of the system's mechanical admittance function on Ω with an applied excitation force of 10.0 N. As Ω is varied from 1.01 to 0.93, the peak response values occur

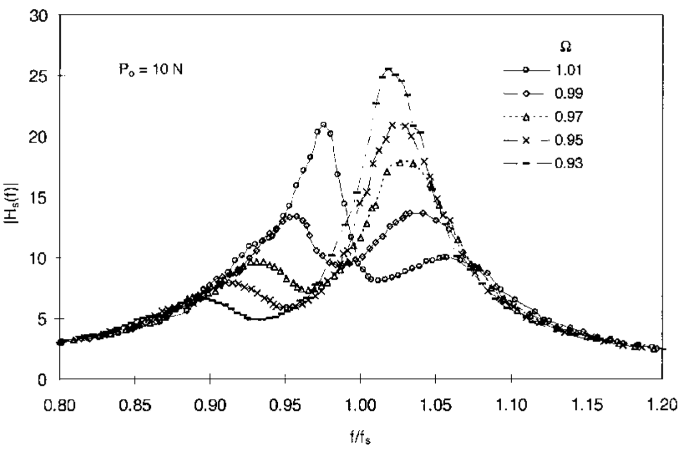


Fig. 4 Mechanical admittance function of structure-TLD system with varying tuning ratio values

at a different normalized excitation frequency values. Initially, at $\Omega = 1.01$ the peak response occurs at a value less than f_s. Setting $\Omega = 0.99$ the mechanical admittance function resembles that of an optimally tuned structure-TMD system under harmonic loading conditions (Den Hartog 1965). As Ω is lowered from 0.99, a dominant single peak re-emerges at frequencies higher than the structure's natural frequency. This particular trend is found for all three excitation amplitudes. However, a double peak having approximately equal amplitudes occurred only for the 10.0 N test case.

4.3. Estimated TLD efficiency and robustness

The efficiency of the TLD is estimated for all tests conducted. The robustness indicates the sensitivity of a TLD's effectiveness to the level of applied excitation and mistuning. Fig. 5 shows the efficiency of the TLD for 5 different tuning ratios, and 3 different excitation amplitudes. The tuning ratio, Ω, is normalized by Ω_{A-opt} allowing direct comparisons to be made with an equivalent TMD. According to Fig. 5, the greatest efficiency achieved is approximately 90%, 85% and 80% for the 10.0 N, 15.0 N and 17.5 N tests, respectively. Fig. 5 also indicates there is a trade-off between efficiency and robustness. For example, the highest efficiency value of 90%, is found to occur at $\Omega = \Omega_{A-opt}$ for the 10.0 N excitation amplitude. However, as the excitation amplitude is increased to 15.0 N and to 17.5 N, this value is reduced to 76% and 66% respectively. An increase in the applied excitation results in a significant reduction in the efficiency. However at approximately $0.96\Omega_{A-opt}$, all three excitation amplitudes lead to almost the same efficiency value of 80%. Therefore, by setting Ω to a lower value than Ω_{A-opt} a more robust TLD is achieved for this particular structure-TLD system. This may allow the TLD to be designed more effectively for both wind and earthquake loading events. It is found that the TLD is a robust damping device with 80% efficiency for the tuning ratio range of $0.97 \geq \Omega \geq 0.95$ and for the range of excitation amplitudes conducted in this experimental study.

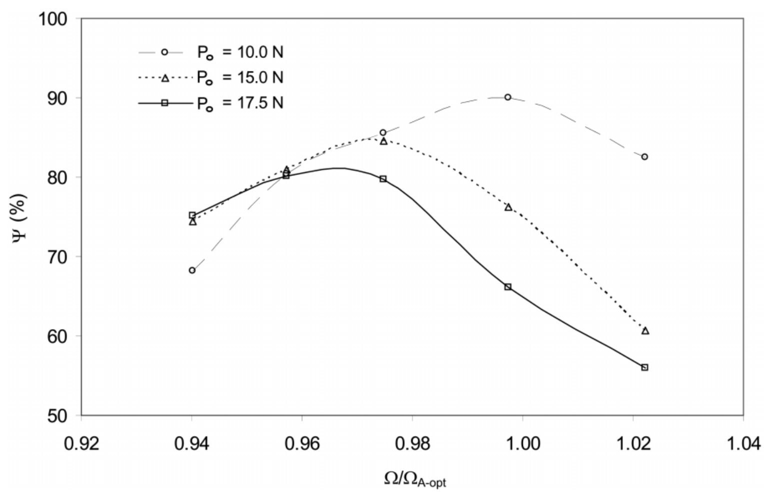


Fig. 5 Influence of tuning ratio on the efficiency of a TLD for different excitation amplitudes

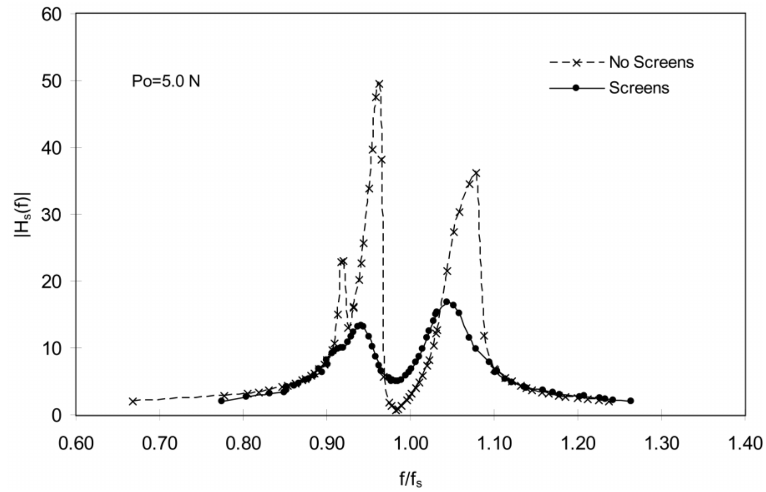


Fig. 6 Influence of damping screens on structural response

5. The influence of screens on structure-TLD efficiency

In order to assess how the damping screens alter the response of the structure, a test is conducted with and without screens inside the tank. In both cases, the applied excitation and the tuning ratio are equal to 5.0 N and 0.99, respectively. Fig. 6 indicates that a significant reduction of the structure's maximum dynamic response occurs when damping screens are added to the TLD. The optimal damping for an equivalent TMD, ζ_{A-opt}, is estimated to be approximately 5.7%. Without the screens, ζ_{TLD} is experimentally found to be approximately 1.0-1.5%. However, with the addition of the screens, $\zeta_{TLD} \approx \zeta_{A-opt}$ under small excitation amplitudes. This plot confirms the improved performance of this TLD equipped with damping screens.

The efficiency of the TLD is increased from 28% to 90% with the addition of screens. This results in a reduction in the peak response from 8.38 mm, without screens, to 2.87 mm with screens. These results show that a TLD must possess a level of inherent damping near the optimal inherent damping ratio value otherwise its efficiency will be significantly reduced.

6. Verification of equivalent amplitude dependent TMD model

As a result of the nonlinear dynamic properties of a TLD, a structure-TLD system's response characteristics are not easily determined. A simplistic model in which the performance of a TLD is matched by an equivalent TMD with amplitude dependent parameters is introduced (Tait, *et al*. 2004a). This approach is evaluated in this part of the study using the above test data.

6.1. Application of model to the structure-TLD system

The proposed model is validated for steady-state sinusoidal excitation. A structure-TLD system with the TLD tuned to a particular mode of the structure is shown in Fig. 7(a). The structural response of this mode can be characterized by a generalized mass M^* and a generalized stiffness K^*, as illustrated in Fig. 7(b). An auxiliary amplitude dependent spring-mass-damper is used to

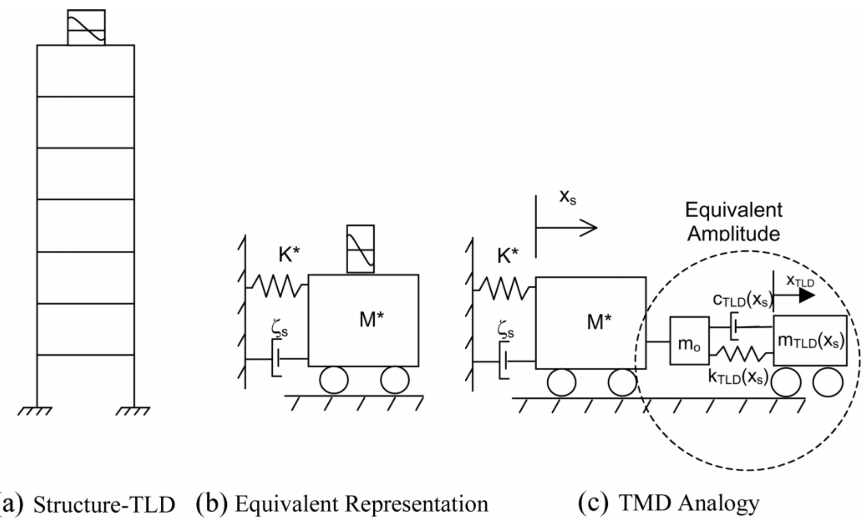


Fig. 7 (a) Structures-TLD, (b) equivalent representation, (c) TMD analogy

represent the TLD as illustrated in Fig. 7(c). The equations of motion for the two degree of freedom system in Fig. 7(c) are given by Eq. (10) as

$$\begin{bmatrix} M^* + m_0 & 0 \\ 0 & m_{TLD} \end{bmatrix} \begin{Bmatrix} \ddot{x}_s \\ \ddot{x}_{TLD} \end{Bmatrix} + \begin{bmatrix} C^* + c_{TLD} & -c_{TLD} \\ -c_{TLD} & c_{TLD} \end{bmatrix} \begin{Bmatrix} \dot{x}_s \\ \dot{x}_{TLD} \end{Bmatrix} + \begin{bmatrix} K^* + k_{TLD} & -k_{TLD} \\ -k_{TLD} & k_{TLD} \end{bmatrix} \begin{Bmatrix} x_s \\ x_{TLD} \end{Bmatrix} = \begin{Bmatrix} F_e \\ 0 \end{Bmatrix} \tag{10}$$

where M^*, C^*, K^* and, x_s are the generalized mass, generalized damping, generalized stiffness and displacement of the primary structure. The external forcing function, F_e, is applied to the primary structure and is assumed, for this case, to be sinusoidal. The quantities $m_{TLD}(x_s)$, $c_{TLD}(x_s)$, $k_{TLD}(x_s)$ and, x_{TLD} are the equivalent TMD mass, damping, stiffness and displacement values. The variable m_0 represents the non-participating portion of the fluid. These parameters can be obtained from the amplitude dependent curves given in the companion paper (Tait, *et al.* 2004a).

An iterative procedure is employed to find the structural response amplitude for each excitation frequency. An initial estimate of the primary structural displacement is made, allowing parameters of the equivalent TMD to be calculated. Subsequently, the equations of motion are solved and a new estimate of the structural displacement is calculated leading to new values of the TMD properties to be used in the following iteration. This iterative procedure is continued until the structure's displacement converges to a solution. The structure-TLD interaction model is verified by comparing the results of the conducted structure-TLD experiments to the analytical results obtained from the equivalent amplitude dependent TMD model. Comparisons include the structure's mechanical admittance function, phase angle between the structure's response and the applied excitation, θ_s, the structure-TLD interaction force, and the energy dissipated by the TLD.

The results of the numerical simulation for test 12 (see Table 4) of the structure-TLD system are shown in Figs. 8(a) to 8(d) along with the experimental values. Fig. 8(a) compares the measured and calculated values of the mechanical admittance of the structure-TLD system. The shape and

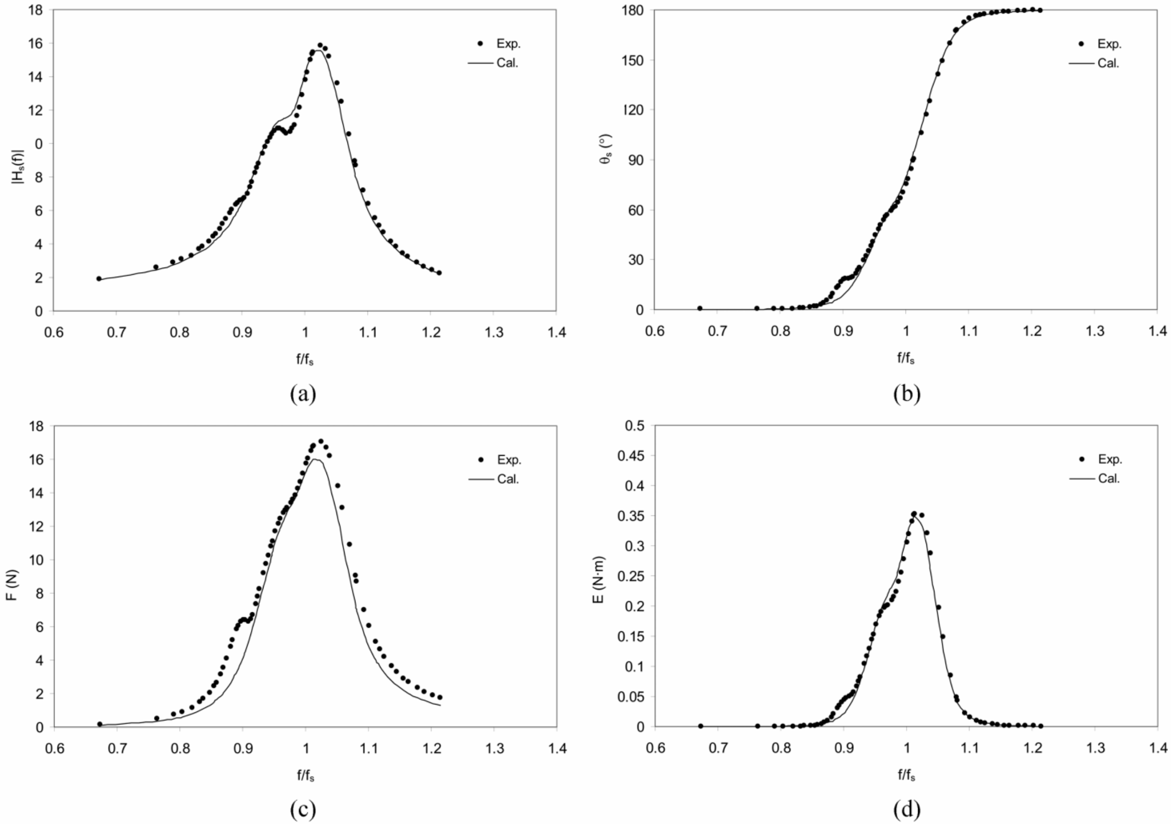


Fig. 8 Comparison of model and experimental response parameters test 12
Po = 15.0 N Ω = 0.970

amplitude of the calculated response curve is in good agreement with the measured values. The numerical model's estimated peak displacement amplitude of 7.5 mm is in excellent agreement with the measured structure-TLD system's peak amplitude of 7.6 mm.

The calculated phase angle between the excitation and the structure response is shown in Fig. 8(b). The model results are in excellent agreement with the measured values for all tests conducted. For the peak response frequency, the estimated value for the phase angle is within 2% of the measured value.

An accurate prediction of the interaction shear forces between the structure and the TLD is necessary in order to simulate the effect of the damper on the structure's response. Both the calculated and experimentally measured interaction shear force values are shown in Fig. 8(c). The value of 16.1 N shear force estimated by the model, at the frequency corresponding to the peak response, is approximately 6% less than the measured value of 17.0 N. The energy dissipated by the TLD is calculated based on the response predicted by the model. The same quantity is evaluated using the experimental results. The experimental and the model predictions are provided in Fig. 8(d) and show excellent agreement. The higher TLD sloshing harmonics and their influence on the structure-TLD response are not captured by the proposed model. This explains why there are differences between the model and experimental values near $f = 0.5$ Hz.

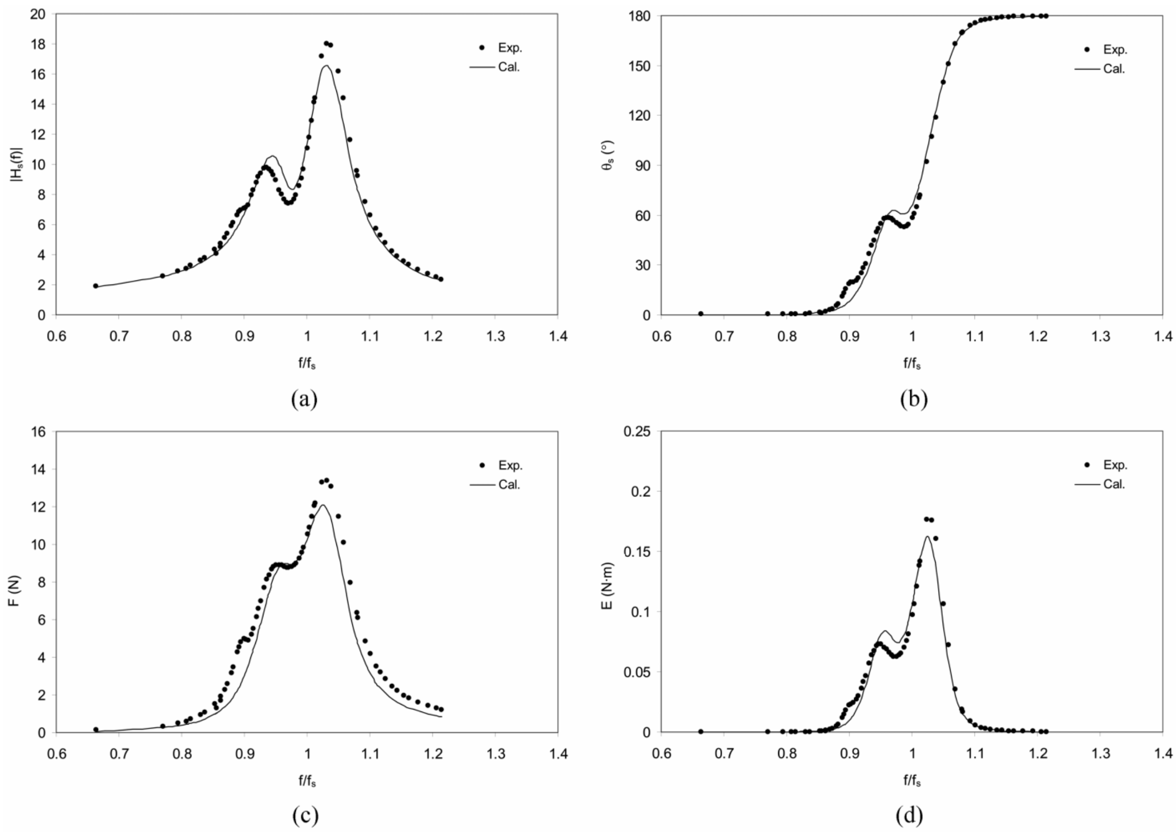


Fig. 9 Comparison of model and experimental response parameters Test 2
Po = 10.0 N Ω = 0.970

Figs. 9 and 10 show the structural response for $\Omega = 0.970$, for tests 2 and 7, respectively. The estimated values of the peak response are within 10% of the measured value for the 10.0 N test and within 2% for the 17.5 N test. The model is found to be in good agreement with experimental values for all test cases. Better estimates of the dissipated energy are obtained compared to that of the interactive shear forces. This is a result of the model being based on an equivalent energy-dissipating amplitude dependent TMD.

The estimated effective damping, ζ_{eff}, from the numerical model is directly related to the primary structure's response amplitude. As noted above, for all tests conducted, the structural response is well predicted. Fig. 11 compares values of ζ_{eff} from both the numerical model and the experimental tests for all three excitation amplitudes. The results show that the estimated values of the effective damping are in good agreement with experimentally obtained values. The maximum relative error between the numerical and experimental values is found to be less than 10% for all tests conducted in this study.

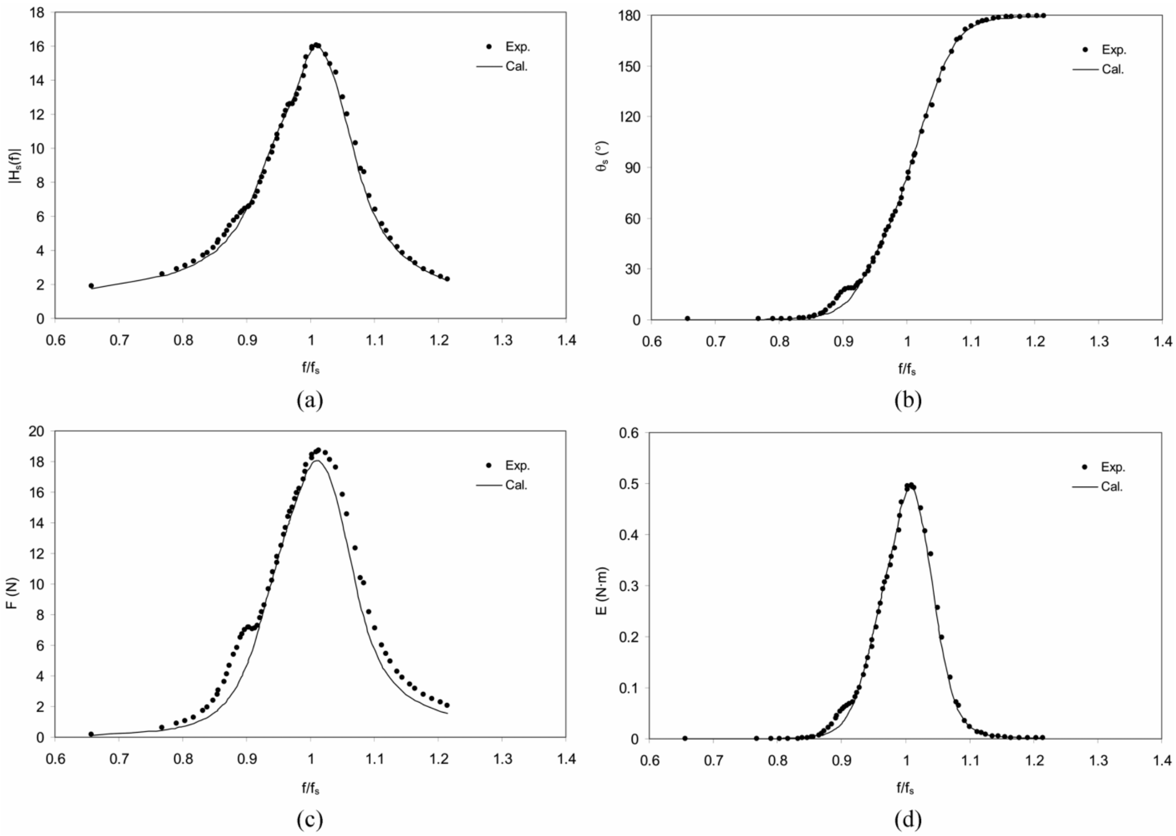


Fig. 10 Comparison of model and experimental response parameters Test 7
Po = 17.5 N Ω = 0.970

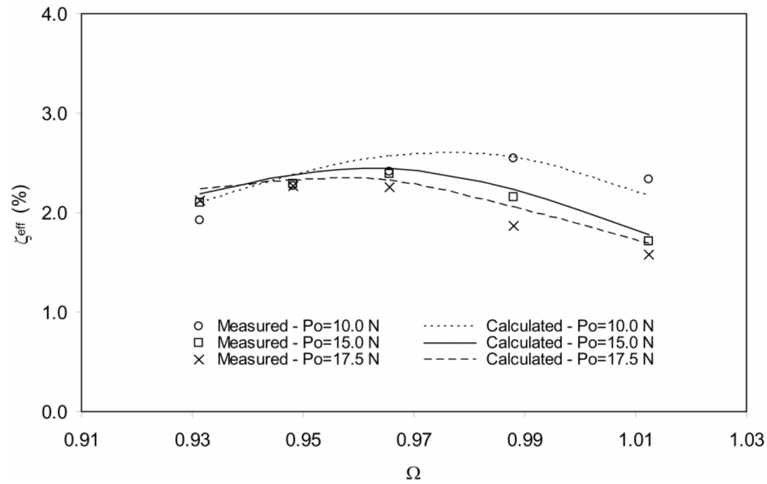


Fig. 11 Comparison of effective damping values from equivalent TMD model and experiments

7. Conclusions

Tests have been conducted to examine the performance of the prototype structure-TLD systems. Three different structure-TLD systems have been examined and the efficiency of the TLD, defined as the ratio between the effective damping provided by the TLD and the optimal effective damping of a linear dynamic vibration absorber is assessed. It is found that the efficiency of the TLD is dependent on the amplitude of the applied excitation.

A parametric study is conducted to investigate the influence of the excitation amplitude and the tuning ratio on the efficiency and robustness of a TLD. The efficiency of the TLD is found to vary with both parameters studied. A maximum efficiency of over 90% is obtained when the amplitude of the applied force is small and the tuning ratio is set equal to the optimal linear TMD value. However, the efficiency declines at this tuning ratio when the amplitude of the applied excitation force is increased. The robustness of the TLD increases significantly when it is tuned at values lower than the optimal tuning ratio value. For the particular TLD investigated it is found that at a tuning ratio approximately 5% less than the optimal value, the efficiency remains at 80% for all excitation amplitudes tested.

An equivalent TMD model is validated, with its estimated mass, stiffness and damping parameters being related to the response amplitude of the structure. The properties of a TLD are related to the fluid motion inside the tank, however, relating the properties to the response amplitude of the structure allows a more simplistic model to be incorporated. The building response is estimated using an iterative procedure where the equivalent TMD properties are updated until a solution is obtained. The model accurately predicts the building response: phase angle between the building response and applied excitation force, the interaction shear forces between the building and the TLD, and the energy dissipated by the TLD. The estimated efficiency calculated by the model is within 10% of the experimental values. However, the proposed amplitude dependent TMD model requires shake table test results for estimation of its properties. A predictive approach for estimating the performance of the TLDs for structural applications prior to testing is currently being developed.

Acknowledgements

The authors would like to thank P.C. Case and the technical staff at the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario for their assistance during experiments. They are also grateful for the work done by the University Machine Shop in preparing the required testing equipment. This study was partially supported by the Natural Sciences and Engineering Council of Canada.

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