Performance of Novel Hybrid Damper for Structural Dynamic Response Reduction

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Abstract. Structures with multiple degrees of freedom (MDOF) such as high-rise buildings and multi-span bridges are susceptible to multiple modes of vibration other than that of the first major mode, as other higher modes can become more significant. Extensive research has been carried out for improving damping devices in vibrational control, but is lacking towards specifically controlling other such significant modes. This research proposes a modified Tuned Liquid Damper (TLD) for the viability of multiple vibrational mode control. The objective of this research is to design a damping device that combines the TLD and Tuned Mass Damper (TMD) into a single Hybrid Damper (HD), and observe its performance in reducing dynamic response of a structural system. Another objective is to compare the HD performance to the performance of a damped structural system with conventional TLD. Three HD structural systems were constructed, varying only with successive increase in TMD mass ratio to a decrease in TLD mass ratio. Performance of the designed HD structural system was experimentally compared to that of a structural system with and without a conventional TLD, and is described as the relative change towards the damping ratio under free vibration and relative change towards the maximum acceleration and displacement response over a range of sinusoidal load frequencies under force vibration. The results show that the HD models increased the natural damping ratio of the structure system compared to that of the conventional TLD as well as effectively reduced the acceleration and displacement response at structural resonant frequency and subsequent frequencies above. However, the HD structural systems demonstrated increased dynamic responses, as well as performing less in the same respect compared to the TLD structural system, in excitation frequencies below resonant frequency of the structure. The damper that displayed the largest effect in dynamic control was the HD with 66.67% TLD mass portion and 33.33% TMD mass portion. Principally, the proposed HD in this study exhibited dynamic properties as well as the design viability to control not only the first major mode better in comparison to a conventional TLD, but to control higher frequency modes of vibration as well.

Introduction

Background Information

Structural vibration damping is an advancing engineering field that has shown its importance to satisfy human comfort levels and structural safety required for taller structures and high-rise buildings, as well as other complex structures susceptible to vibrations. Many variations and techniques have been used for vibration control, most pertinently among passive control dampers are Tuned Liquid Dampers (TLD) and Tuned Mass Dampers (TMD), largely considered for application due to their reliability, efficiency and ease of design and installation, as well as being economically viable and environmentally mindful [1].

However so, researches continue to be conducted to improve the passive dampers. Increase in effective damping and reduced structural accelerations of the major mode of response were the common necessitate goal of most passive control researches. However, very little developments have been made to primarily achieve robustness of vibrational control with neither TLD nor TMD. As damping devices are generally tuned to only the first major mode shape of structures, other modes are generally ignored and go uncontrolled even though they can impose large contributions to the total response, especially in structures of increasing height and degrees of freedom. [2]

Problem Statement

The use of multiple dampers of the same device is generally the most effective method to increase robustness and effectiveness of the passive dampers in controlling dynamic structure response. This study introduces a novel damper which incorporates TMD into a conventional TLD to create a single hybrid system, incorporating their strengths to achieve this robustness in controlling significant mode shapes generally associated in high-rise buildings as well as bridges. A HD system proposed in this research may feature multiple TMD, catering to different mode shapes other than the major vibration mode with which the TLD will be tuned for control.

Based on previous studies involving similar concepts of multiple and supplementing damping systems, the performance of this HD can also be proposed to cater to the robustness limitation of its respective separate components without removing the advantages of either component.

Objective

Although the proposed Hybrid Damper aims for an increase in robustness towards controlling higher modes of vibration, the TLD-TMD hybrid system must first be considered towards the improvement of the conventional TLD in dynamic response control. Thus, the HD in this research will principally determine its relative performance. Hence, the objectives of this study are:

1. To design a system that combines the concepts of TLD and TMD into a hybrid damping device
2. To determine the performance of the proposed HD model to control structural vibrations experimentally
3. To compare the effectiveness of the HD structural system to the conventional TLD-structure system experimentally

Scope

This study will focus on the performance of a conventional TLD and conventional TMD for structural control as a single device. For this, the design parameters of conventional TLD and conventional TMD will be used experimentally, based on the current hypothesis that the mechanical properties and benefits of each will complement each other within a single system. The study is conducted within these boundaries:

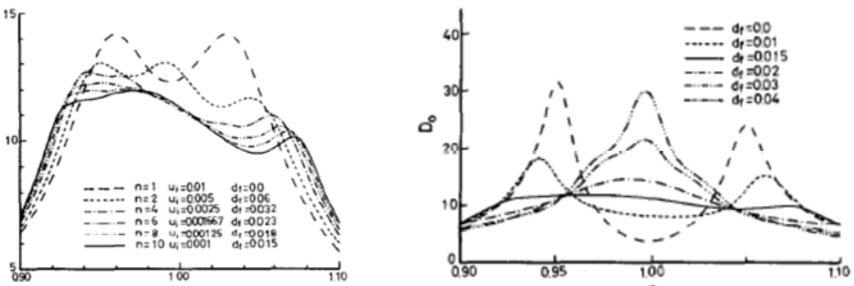
Results will be achieved through laboratory experimenting only, numerical analysis and software modelling will be absent in this research. Design parameters are based on tuned natural frequencies and mass ratio parameters of conventional TLD and TMD systems separately. Excitation will be produced in only one horizontal axis and will simulate harmonic loading via sine-wave shaker. The experiment will be limited to only a single mass steel structure which allows result in control for only the first major mode to be practical for the damping systems. Performance of the respective systems to be experimented will be based on their control of the displacements and acceleration of the first mode of vibration of the steel structure model, as well as the outcomes of the damper models towards the damping property of the structure system.

Previous Studies

Advantages that the TLD and TMD have over other systems for implementation in high-rise buildings have been studied in researches as early as [1], where it was found that TLD controlled structures would experience increase in damping compared to a structure with either optimal TMD system and one with distributed TMD system, further citing that TLD would be of the most advantages of implementation in high-rise building due to its easy installation, space saving, and economical value. However so, the research still concludes with recommendation for further research into the improvement of the TLD and distributed TMD for even greater flexibility and performance in vibrational control.

Many existing proposals are discussed in [3] towards improving the limitation of TLD in damping only the main oscillation mode, citing that current TLD improvement for the most part has not been catering to the control of simultaneous vibration modes such as with TLCD, Bi-directional Liquid Dampers and Sloshing Liquid Dampers with baffles. The research then alludes to the need for effective multi-frequency liquid dampers in complex semi-active or active dampers under computer control with parameters adjustable to most critical oscillation modes, and the development of effective tank shapes.

Studies provide early indication to the performance of multiple dampers within a system, in that the concepts demonstrate the improvements for the direction of better and wider frequency control. Research provided in [4] found that wider bandwidths of frequency excitation could be controlled with the use of multiple TMD, where placing higher mass ratios towards significant response modes achieved a flat peak response with minimum dynamic magnification. The dynamic response results due to increasing the number of distributed TMD as well as varying mass distribution is illustrated in Figure 1.



(a) (b)

Figure 1: Dynamic response results with (a) varying number of TMD and (b) varying distribution of TMD mass ratio

Practical proof for wider frequency control by supplementing a multiple TMD system was observed in the research conducted by [5], whereby The Trans Tokyo Bay Crossing Bridge was outfitted with TMD system for control of vertical flexural girder vibration direct from wind loads. Vortex-induced vibrations instead were of higher-order modes that required a separate system of control. Vertical plates fastened to the bridge deck acted as aerodynamic vibration control for those higher-mode vibrations with which the TMD system were not installed for. Figure 2 illustrates the multiple significant modes of vibration of the bridge over higher frequencies.

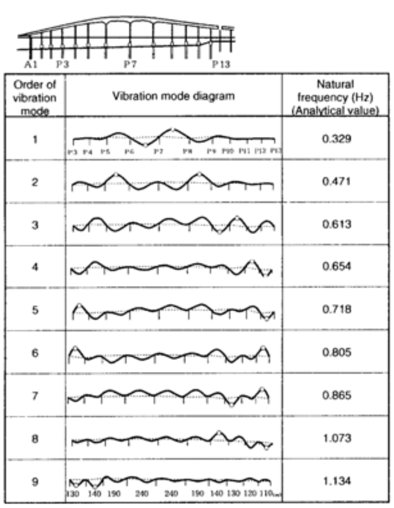


Figure 2: Vibrational modes of the Trans Tokyo Bay Crossing Bridge over multiple frequencies

A comparative effectiveness of TMD, TLCD, and a TMD contained in a liquid column was numerically studied in [2], noting that the reduction levels in structural response to dynamic wind loads were similar between the TLCD and TMD. The TMD in liquid column had the most significant reduction when the liquid column was tuned to a frequency higher than the whole damper. This allowed for control of higher modes of response with which were also concluded to be significant compared with the main controlled mode in MDOF structures.

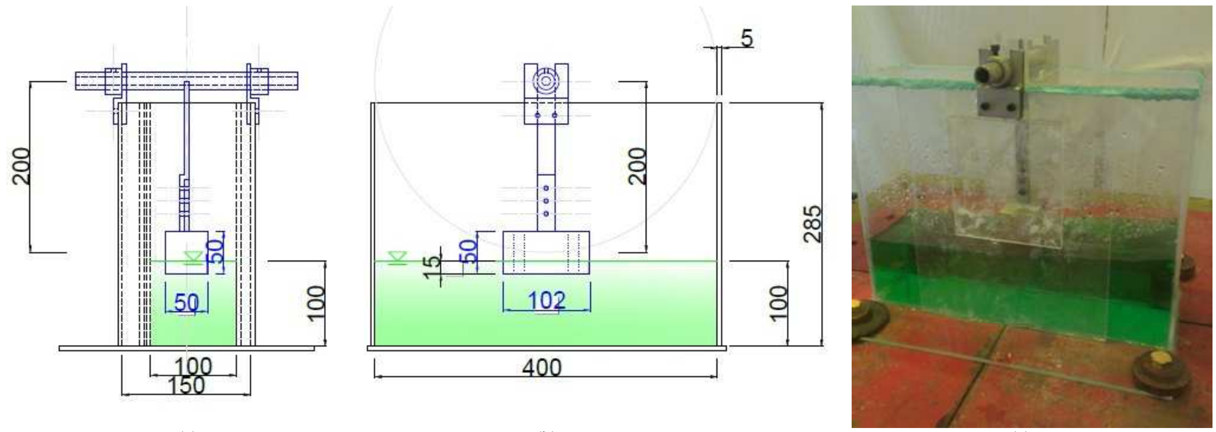
Proposed Design

The scaled structure in this experiment was a steel frame single degree of freedom (SDOF) of dimensions 0.9m length, 0.9m width and 1.15m height, with total mass of 228kg. This dimension and weight were chosen based on the shaker limitations and the general characteristic equivalent of steel structures. Free vibration test was conducted in order to determine the natural frequency and damping ratio. Natural frequency of the structure was experimentally obtained by Fast Fourier Transform (FFT) algorithm of the acceleration rate of the structure in free vibration, which was determined to be 1.12Hz. Damping ratio of the steel structure was calculated based on its logarithmic displacement decrement of the structure's free vibrational response, which was calculated to be 0.87%. As the structure is considered a SDOF structure, all dynamic properties obtained were corresponding to the structure's first mode of vibration. The steel structure in this experiment may be considered to behave similarly to that of an equivalent flexible 10 story building.

A conventional rectangular TLD tank was designed as the control damper, with the tuning frequency and mass ratio of TLD considered for the SDOF referenced structure. Using clear Perspex sheets of 5mm thickness, a tank of inner dimension 400mm length by 285mm height by 150mm width was constructed for the conventional TLD. With the intended tuning ratio of the TLD to be equal with that of the first mode of vibration of the structure for optimum dynamic control, the water depth required for obtaining a natural frequency of the TLD at 1.12305Hz would be approximated to a depth of 100mm. Considering the liquid dimension contained in the TLD, the mass of water is equal to 6kg and thus with the total mass ratio to the structure of 2.63%.

The proposed Hybrid Damper is designed as a retrofitted Tuned Liquid Damper tank, whereby a conventional TLD, that is tuned to the major mode of the controlled structure, will be outfitted with a pendulum Tuned Mass Damper partially submerged within the tank. Four damper designs were considered, one conventional TLD and three HD of gradually differing parameters. All subsequent HD designs considered in this experiment are equal in mass of its total combined components in order to match the original mass ratio of 2.63% of the conventional TLD for performance comparison. Hence, with increased mass of the outfitted TMD, the mass of liquid of the TLD is consequently reduced in design for each of the experiments. Since the structure to be controlled is a SDOF that only exhibits one mode of vibration, both the TMD and TLD components are tuned to the natural frequency of the first mode and the performance of the dampers will be compared with their ability to control the acceleration and displacements of the first mode. In this research, the first HD design considered (HD16.67*, according to abbreviation in Table* 1) will incorporate a pendulum mass of 1kg and liquid mass of 5kg; the second design (HD25) with pendulum mass of 1.5kg and liquid mass of 4.5kg; and the third (HD33.33) with 2kg and 4kg respectively. Based on Housner's equation of TLD natural frequency, only the width of the liquid in the TLD can vary without altering its natural frequency, thus the varying widths required for the liquid masses considered in each HD design is 125mm, 112mm, and 100mm, for HD16.67, HD25, and HD33.33 respectively, which will be achieved by partitioning the conventional TLD tank after the pendulum TMD component is installed. Length of the pendulum TMD component in all designs is 200mm to achieve the tuning ratio of 1 to the first mode of the controlled structure. On the other hand, constructing from mild steel, the dimension of the pendulum mass of the TMD component is chosen to be at a constant of 50mm height and 50mm width, with a variable length, to which 51mm, 76mm, and 102mm lengths are used in according the masses required in design of HD16.67, HD25, and

HD33.33 models respectively. Figure 3 shows the design of the HD33.33 model: Hybrid Damper with 4 kg of liquid and 2kg pendulum mass.



(a) (b) (c)

Figure 3: Design specification and dimension of the HD33.33 model in (a) front view, (b) side view and (c) picture of constructed HD16.67 model

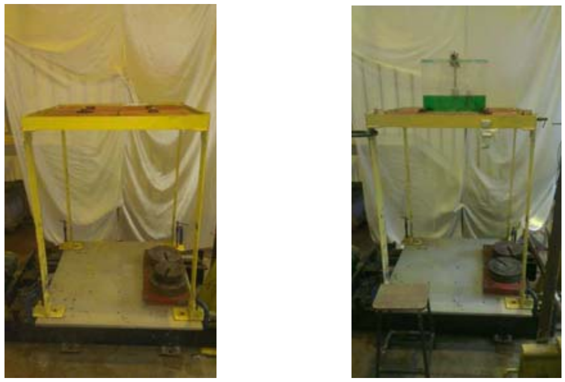
With the design of the Hybrid Dampers achieved, area and volume of submergence in the liquid mass of TLD is calculated. Incorporating a cuboid mass for the TMD shape, the front square face perpendicular to the direction of motion for the TMD component of all HD models is 50mm by 50mm for a total area of 2500mm^2. At submerged depth of 15mm, the area of the front face submerged is 750mm^2 or 30% of the total area, and thus 30% of the total volume submerged, at rest.

Table 1: Damper Abbreviation and Mass Ratio to Structure

Damper Model Abbreviation	**Pendulum Mass Percentage from Total Damper Mass (%)**	**Mass Ratio to Structure (%)**	
		Liquid Mass	Pendulum Mass
TLD	0	2.63	0
HD16.67	16.67	2.19	0.44
HD25	25	1.97	0.66
HD33.33	33.33	1.75	0.88

Methodology

This research methodology consisted of free vibration and force vibration tests for each of the systems to be experimented. The systems that were performed in respective trials are bare structure system (ST), structure with conventional TLD (ST-TLD), and three separate designs structure with Hybrid Damper (ST-HD16.67, ST-HD25, ST-HD33.33). Only displacement and acceleration response of the structure in all tests were measured. Displacement response was measured using a load varied displacement transducer (LVDT), installed on the structure frame and recorded by a data logger. The acceleration was measured using an accelerometer installed on the structure as well and recorded by a separate specific data logger. Since the structure is a SDOF structure, only one of each measuring device installed at the structure's degree of freedom, the mass at top are required for each test. The software used for displacement and acceleration reading were SDA7910 Visual Log and DEWESoft respectively. Natural frequencies are computed from the time history analysis of the acceleration response measured using the Fast Fourier Transform (FFT) algorithm with SeismoSignal software. Shaker specifications are 1.0x1.0m, 500kg capacity, and apply sinusoidal forced base displacement in a single axis. Experimental setup of the structure involves fixing the structure's four 1.15m high columns in an orientation so that bending occurs on the weak axis along the sinusoidal load direction of the shaker The single 'floor' mass of the SDOF structure is constructed at the top of the columns and the mass of 228kg required is achieved with mild steel plate installation. Damper performances are experimented with the respective models fixed to the top of the structure lengthwise to the sinusoidal load direction. Figure 4 shows the experimental setup of the structure with and without the damper installed.



(a) (b)

Figure 4: Experimental setup of (a) structure without damper and (b) structure with HD16.67 model installed

Free vibration test is carried out by applying an approximately similar initial displacement of about 30mm to the structure at rest among all damped structure tests and its ensuing motion is in the absence of any further external disturbances. Displacement of the structural motion is recorded for a set constant time and the logarithmic damping ratio is calculated. Acceleration is obtained to compute the natural frequency. In the force vibration test, the bare structure and its structural systems with the various dampers tested were all subjected to a similar sinusoidal displacement. For each of these experiments, a load tuning ratio to structure's natural frequency was in range of approximately 0.8 to 1.15 was applied at an amplitude of 55mm, with a total of 17 point intervals of tuning ratios tested in that range. An additional set of LVDT of accelerometers were installed at the shaker to ensure the required sinusoidal load was applied. Displacement and acceleration during force vibration were consequently measured during structural response.

Results and Discussion

The vibration tests were carried out and the displacement and acceleration response of the structure under the experiment excitations were recorded. In order to fulfil the research objectives, the performance of the HD models are based on their relative reduction of the dynamic responses under force vibration to that of the structure response without the respective damping devices, as well as the change in dynamic response control of the structure to that of the conventional TLD. Effectiveness is deemed as larger reductions of structural response are achieved. The damping ratio of the structure system with and without the respective models will also be analysed in order to observe the change in structure behaviour under dynamic motion.

Performances in Free Vibration

Figure 5 shows a sample of time histories of structural displacement of the bare structural system, structural system with a conventional TLD, and a structural system with a Hybrid Damper. As illustrated, both systems using the conventional TLD and HD exhibit a large increase in cyclic decrement of the structural response to free vibration compared to the motion of the bare structure. However, a beating phenomenon was observed in the damped systems tested. A beat phenomenon occurs when two frequencies are close to each other. Attaching the TLD to the structure creates a system with two degrees of freedom, of which both have frequency modes close to the natural frequency of the structure alone. A beat phenomenon can also be observed with the installation of the HD in the structure system, although the amplitude modulation is perceptively similar to the structure-TLD system in that two close frequencies are present in the vibrational response, even though the addition of a TMD component along with the TLD in a HD to the structure creates system with three degrees of freedom rather than two.

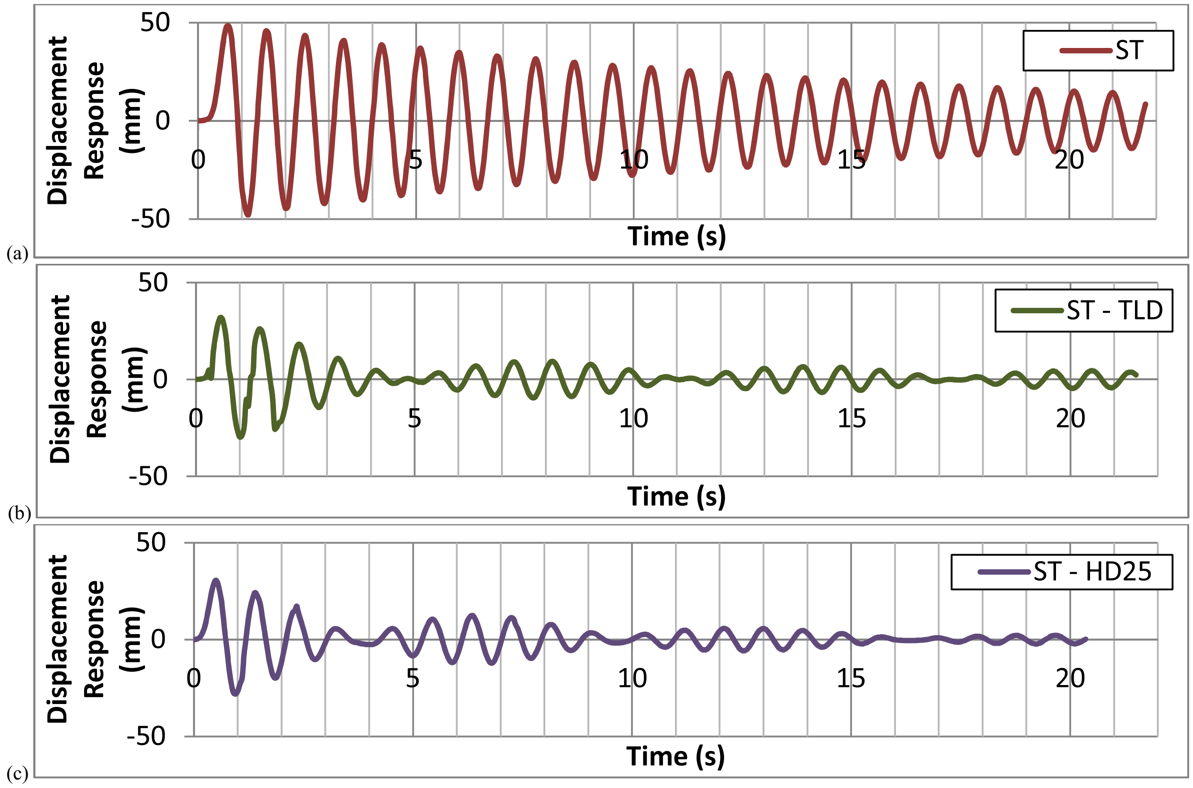


Figure 5: Time history of displacement response of (a) bare structural (b) structure-TLD system (c) structure-Hybrid Damper system with TMD mass portion of 25%.

It is difficult to calculate an accurate value for damping ratio from a time history response that modulates with a beating frequency. Thus, reasonable estimate values of damping ratio were obtained from the time history graphs of each free vibration test by calculating the logarithmic decrement of only the oscillation within the first initial beat. The number of period oscillations considered for calculating the damping ratio was also kept constant for all time history responses at 3 cycles. It is observed that all three HD models had increased the damping ratio of the structure system more than that of the conventional TLD, with the largest increase in damping produced by the HD with a quarter mass TMD, up to 8.86%. The HD with TMD mass percentage of 16.67, and the other with 33.33, both increased in effective damping ratio to a conventional TLD system from 5.69% to 6.59% and 6.89% respectively.

The values of damping ratio in increasing mass percentage of the HD are illustrated in Figure 6, with the Pendulum Mass percentage of 0% referring to the conventional TLD. The graph trend indicates a gradual increase in TMD mass portion incorporated in a HD will increase the structure system's rate of oscillating decay up to a point, of which the effectiveness of free vibrational damping subsequently decreases again. Based on the results obtained in this research, the addition of a TMD component into a conventional TLD system that is also tuned to the first major mode of the structure increased the damping ratio of the structure in all cases, with the most effective mass ratio of TMD to the total damper mass for vibrational damping at 25% in this experiment.

Since a linear increase in TMD mass ratio to damper at 100% will generally be considered as a conventional TMD system, which has been studied in previous research to perform below multiple damper systems in vibrational damping, a drop in effectiveness with increased mass after a certain point is to be expected, although the point of drop off in effective damping above 25% of total damper mass cannot be verified and thus requires further inquiry in future studies.

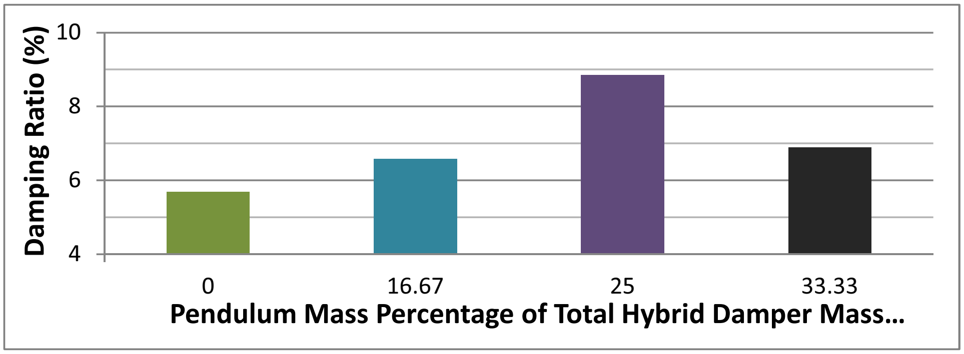


Figure 6: Damping ratio of the structure-damper systems

Performances in Force Vibration

Discussions of the results for displacement and acceleration responses under force vibration will be divided corresponding to three excitation areas: below resonant frequencies, at resonant frequency, and above resonant frequencies.

Displacement Response Control. Figure 7 shows the comparison of the displacement response of the systems experimented under a range of excitation ratios. According to the figure, frequency excitations below the resonance frequency, where frequency ratio of excitation is below the value of 1, it is apparent that all Hybrid Damper designs increased the structural displacement response. A trend can be observed in this range where increase in TMD mass ratio results in increasing displacement response to excitations. However, at frequency ratios at structure resonant frequency and above, the reduction of displacement response is significant with all damper models, with increasing in TMD mass ratio largely observing increasing reductions. Peak in displacements were 161.3mm, 131.8mm, 116.9mm, 102.4mm, and 90.85mm for the undamped structure, TLD structure system, HD16.67 system, HD25 system, and HD 33.33 system respectively. The displacement response for all the structural systems can be considered excessively large in comparison to other researches of structural models under similar force vibration tests, as well as an absent of 'double peaks' of dynamic response, of which, occur when the usage of a TLD in the system increases the degree of freedom to two. One justification can be made from the amplitude of sinusoidal excitation selected in this research, where a value of 55mm can be excessive for a structure of 1150m height. Also to note, TLD behaves non-linearly due to its liquid motion under vibrations, in which behaviour is displacement dependant. However so, the comparative performance of all HD structural system can still be made under the same load conditions.

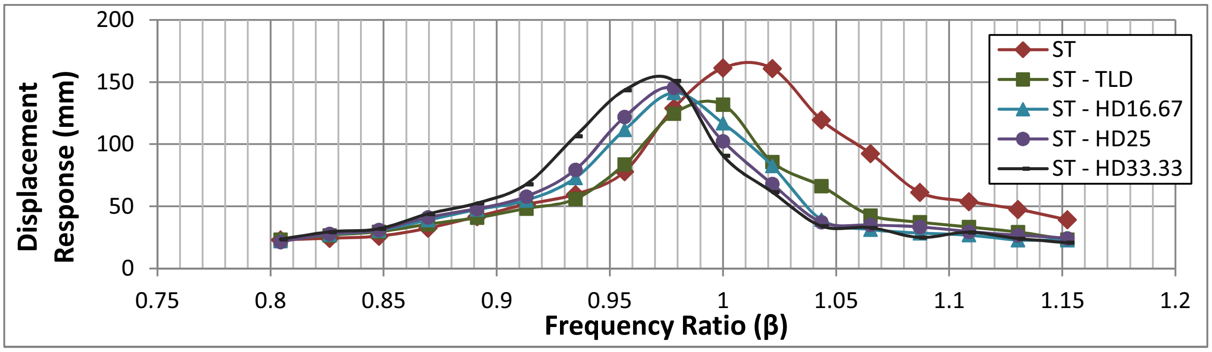


Figure 7: Displacement responses of structural systems against a range of frequency ratio

Figure 8 describes the displacement control of the structure for each structure-damper system in terms of percentage change, where negative values indicates increase in dynamic response compared to the free structure under the same excitation, and positive values indicates reduction of dynamic response, or increase in effectiveness. The Hybrid Damper with 33.33% pendulum mass portion resulted in the largest percentage change during excitations below structure resonant frequency with -84.16% at frequency ratio of 0.9565. At this ratio, HD16.67 and HD25 systems also resulted in their largest drop of performance, at -43.04% and -56.45% respectively to that of the structure without the damper. The conventional TLD structure system provided fluctuating albeit marginal effective control to the displacement response along this excitation range, with the HD systems following a similar curve trend of increasing divergence up to their respective peak in ineffective control. Also worthy of noting is that the trend in effectiveness difference across this range predicts that the HD of each design provides no control of structure displacement response at roughly the same excitation ratio of around 0.985.

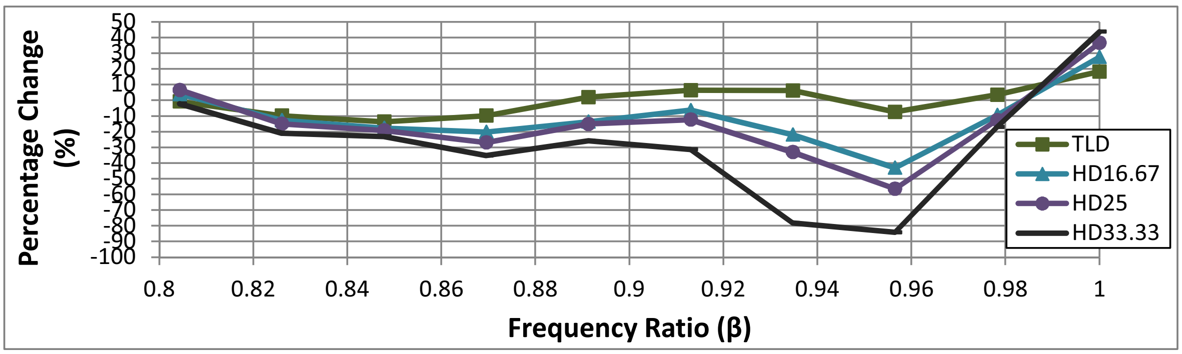


Figure 8: Performance in displacement response control at frequency ratio range below resonance

In order to evaluate the performance of the Hybrid Damper models comparative to that of a conventional TLD, Figure 9 describes the trend in effective difference of each Hybrid Damper model to the structure with TLD performance as its reference. Results indicate that performance in controlling displacements compared to the structure system with TLD gradually differs negatively as the excitation frequency at intervals approach structure resonance, with a sharp decrease in effectiveness observed by the Hybrid Damper with 33.33% TMD mass ratio with a -90% percentage change at the excitation ratio of 0.9348. HD16.67 and HD25 systems resulted in -33.13% and -45.61% change in effectiveness than the TLD system at the frequency ratio of 0.9565, with a relatively stable trend of decreasing in performance.

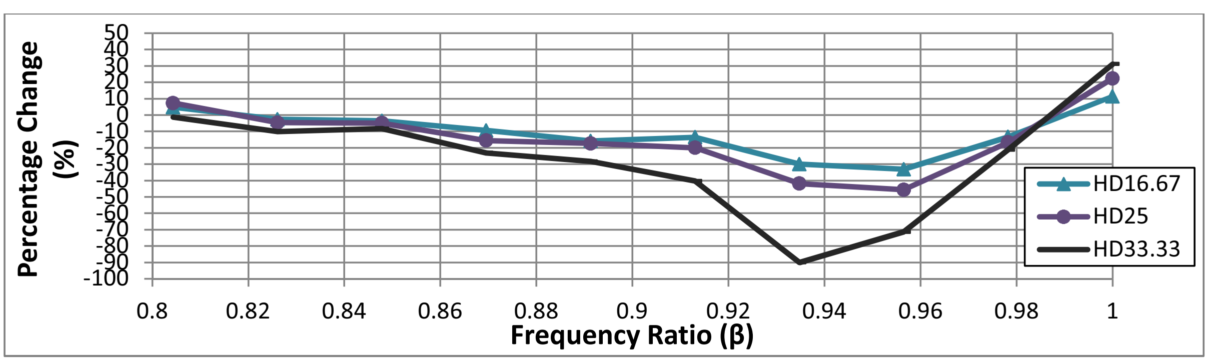


Figure 9: Performance difference compared to structure with TLD at frequency ratio range below resonance for displacement control

According to Figure 8 and Figure 9 at resonance frequency of the structure the effectiveness of the Hybrid Damper to displacement response of the structure converses from the control and performance change at ranges below. Results show that increase in pendulum mass proportion of the Hybrid Damper demonstrates an increase to the displacement control of the structure at this load frequency. Structure with TLD and structure with Hybrid Damper of 16.67%, 25%, and, 33.33% pendulum mass portion correspondingly performed with 18.29%, 27.53%, 36.55%, and 43.68% change in reduction towards maximum structure displacement response at this frequency. Calculation of difference in performance yields the reduction of displacement response at structure resonance were 11.31%, 22.31%, and 31.07% better compared to the conventional TLD system's control for the ST-HD16.67, ST-HD25, and ST-HD33.33 respectively.

Figure 10 illustrates the percentage changes of displacement response to the structure system above the resonant frequency of each of the damper systems. At this range, all dampers effectively reduced the displacement of the structure, with the lowest performance by the TLD at 56.23% at frequency ratio of 1.0435, and the Hybrid Dampers' performance increasing thereof with each increase in TMD mass portion, resulting in displacement reduction of 67.07% for the HD16.67 system, 68.79% for the HD25 system, and 71.42% for the HD33.33 system; all of which also occurring at frequency ratio of 1.0435. Effectiveness for displacement reduction gradually reduces and converges together across all damper systems after the peak in effective displacement control, and that the discrepancy between the models in that range is relatively minor.

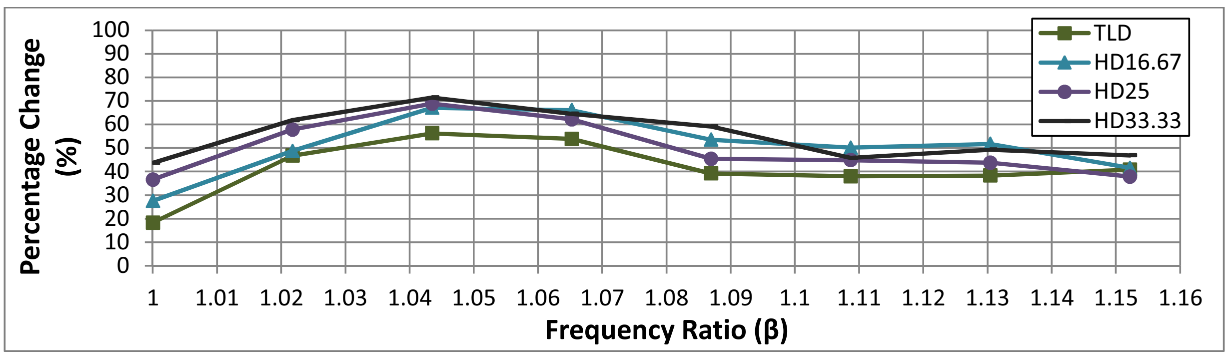


Figure 10: Performance in displacement response control at frequency ratio range above resonance

Performance of the Hybrid Damper comparative to the TLD is illustrated in Figure 11. Although a consistent pattern does not seem to occur because of performances after frequency ratio of 1.475 interchanging between the models, the results can still be presumed to have a reasonably consistent percentage change trend. In any case, all Hybrid Dampers performed better than the conventional TLD. Largest performances increased by each Hybrid Damper were 26.55%, 28.68%, and 34.7% for the HD16.67, HD25, and HD33.33 respectively.

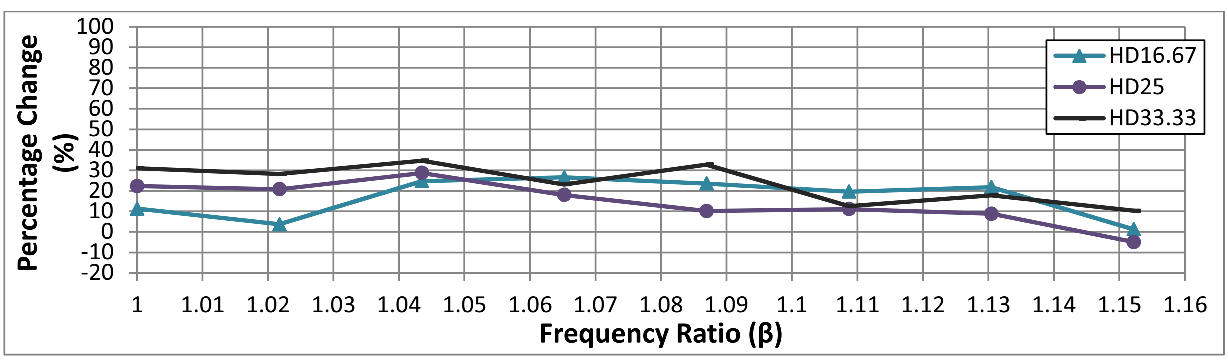


Figure 11: Performance difference compared to structure with TLD at frequency ratio range above resonance for displacement control

Acceleration Response Control. Figure 12 compiles the acceleration response of all structure systems experimented under force vibration. As can be seen, the Hybrid Damper models performed roughly the same across the entire range in acceleration response control. The Hybrid Dampers performed by increasing the acceleration response at excitation frequency ranges below the resonant frequency, but reducing acceleration responses at the resonant frequency and at the range of frequencies above, in respect to the conventional TLD and structure system with no damper. Largest accelerations of 5.6159m/s^2, 5.239 m/s^2, 4.01 m/s^2, 3.076 m/s^2, and 2.888 m/s^2 were detected for the undamped structure, TLD structure system, HD16.67 system, HD25 system, and HD 33.33 system respectively. Similarly discussed in *4.2.1,* acceleration response of the structural systems under force vibration were also excessively large, due in part to the extreme load conditions set in this research. The comparative performances of the damped structural systems for acceleration response control are thus made under the same conditions.

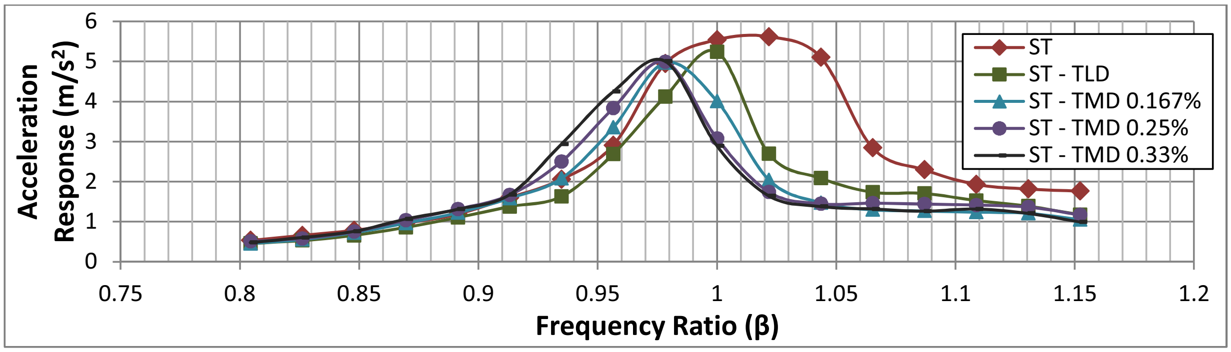


Figure 12: Displacement responses of structural systems against a range of frequency ratio

Results of percentage change by the damper performance in acceleration control below resonant frequency are graphed in Figure 13. Similarly to the results of displacement response control, the conventional TLD performed effectively across this entire range, whereas the Hybrid Damper models largely affected the acceleration response negatively. However, the trend of performances is roughly similar in shape. The largest difference of control resulted from the Hybrid Damper with 33.33% TMD mass portion, with a -46.12% change in acceleration occurring at frequency ratio of 0.9565. HD33.33 and H16.67 systems' also resulted in the largest negative percentage change at the same frequency ratio, with -53.49% and -27.67% respectively. It is also shown that all the Hybrid Dampers similarly provided little to no acceleration control around the same frequency ratio of 0.98.

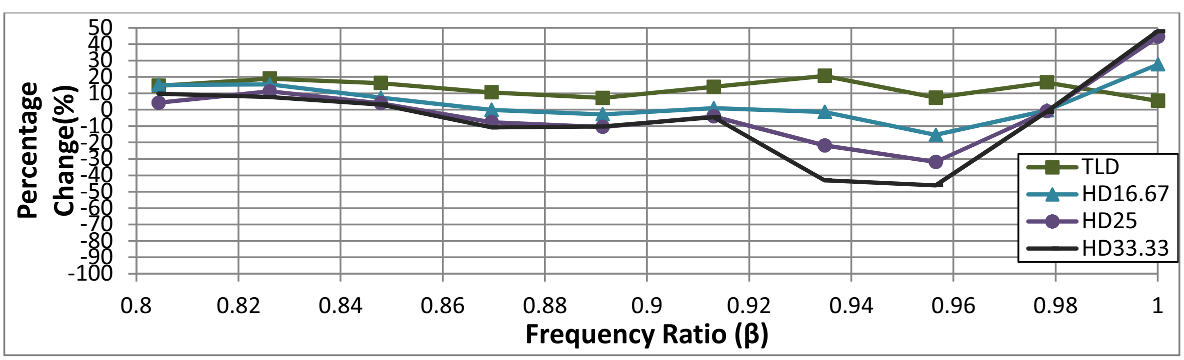


Figure 13: Performance in displacement response control at frequency ratio range below resonance

Figure 14 shows the percentage change of incorporating TMD mass portions to the conventional TLD within a range of frequency ratios below resonance for acceleration response control. The trend of performance change to the conventional TLD gradually decreases similarly for each Hybrid

Damper model, abruptly diverging at frequency ratio of 0.913 and peaks in percentage change at 0.9348 before converging in performance approaching resonant frequency. The largest percentages of performance change compared from the conventional TLD system at this the frequency ratio of 0.9348 are -80.27% for the HD33.33 system; -53.49% for the HD25 system; and -27.67% for the HD16.67 system.

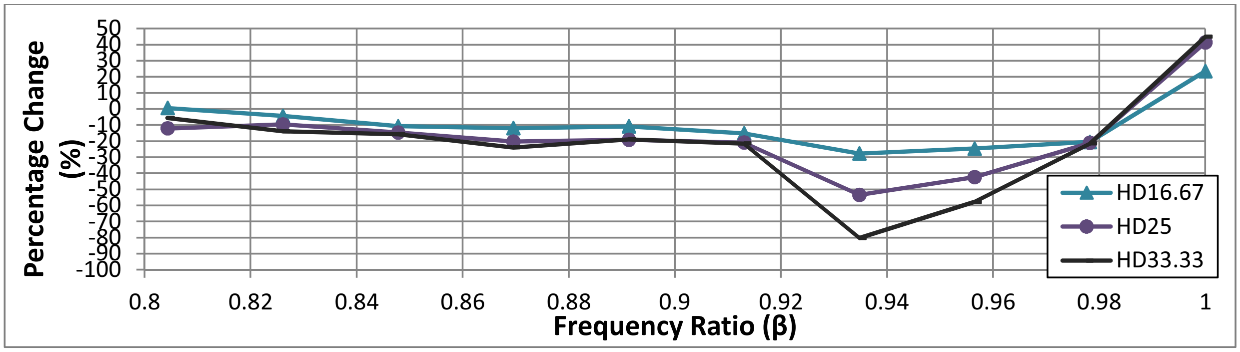


Figure 14: Performance difference compared to structure with TLD at frequency ratio range below resonance for acceleration control

As for acceleration control at resonant frequency of the structure, Figure 13 describes the Hybrid Damper models decrease the acceleration with each increment increase in TMD mass portion, as well as performing better in this regard to the conventional TLD, similar to the results in displacement control. The HD16.67 system reduced the acceleration response of the structure by 27.63%, HD25 by 44.49%, and HD33.33 by 47.87%. Comparing the acceleration response reduction of the structure to that of the conventional TLD at 5.46%, the Hybrid Dampers effectiveness of control observed an increased in performance of 23.45%, 41.29%, and 44.86% respectively, as illustrated in Figure 14 at frequency ratio of 1.

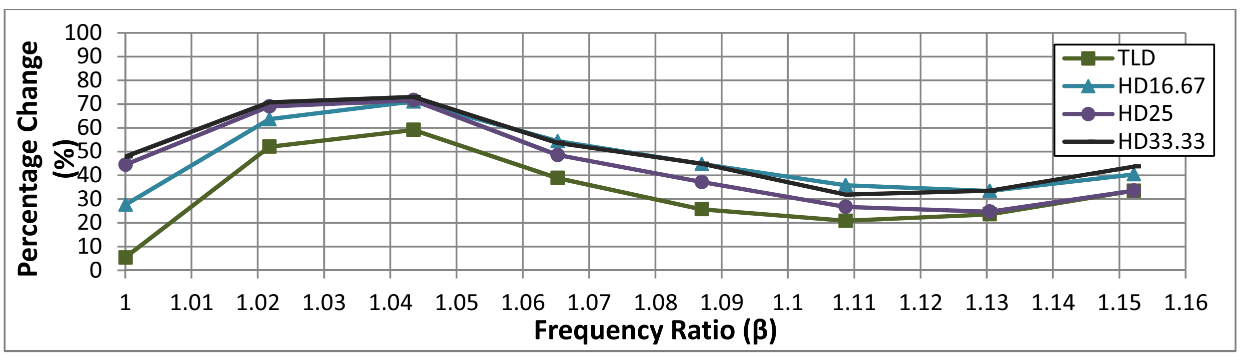


Figure 15: Performance in acceleration response control at frequency ratio range above resonance

The percentage change of damper models on acceleration response control in a range of frequencies above resonant frequency of the structure is graphed in Figure 15. Curve trend of percentage change is similar across the experiment range of load frequencies in that the reduction of acceleration steadily increases from resonant frequency and peaks at frequency ratio of 1.0435 for all damped structure systems. The peak effective reduction of acceleration for the conventional TLD is 52.08%. As for the Hybrid Dampers, HD16.67 peaked with 71.11%, HD25 with 71.65% and HD33.33 with the largest reduction at 72.99%.

Comparative performance of the acceleration control of the Hybrid Damper models to the conventional TLD is shown in Figure 16. HD33.33 and HD25 show a linear decrease in performance improvement of the TLD as the frequency ratio increases from resonance, with the Hybrid Damper with higher TMD mass portion of 33.33% with the best improvement overall.

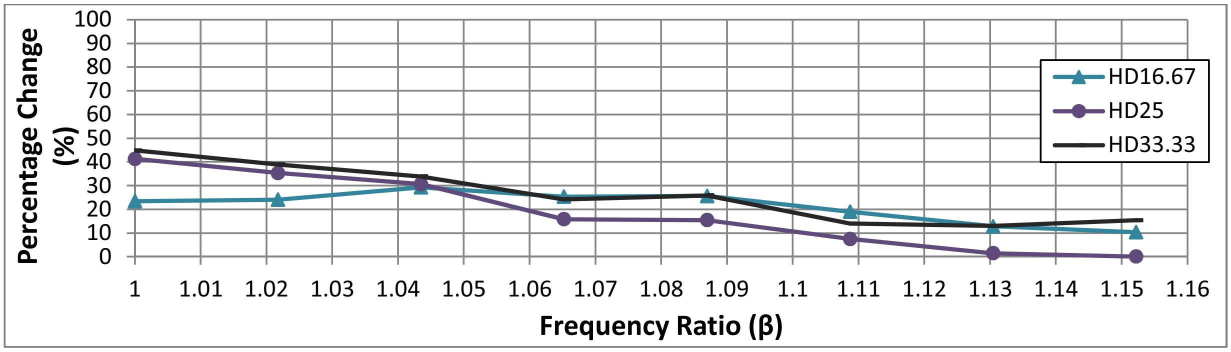


Figure 16: Performance difference compared to structure with TLD at frequency ratio range above resonance for acceleration control

Conclusion and Recommendations

In this experimental study, the focus was the improvement of the conventional TLD design in controlling structure dynamic response by introducing a supplementing TMD to form a hybrid damping device, intending for a device that has a prospect for wider frequency control, mainly of other mode shapes. Three designs of increasing TMD mass portion of the total mass of Hybrid Dampers were considered in order to compare the performance to a conventional TLD of the same mass.

To summarise the results adhering to the objectives of this research: Firstly, an operational model of a HD concept, combining a conventional TLD and a pendulum TMD, was successfully constructed in that the liquid within the tank and pendulum TMD were both successfully tuned to the first major mode of the structure as well as be designed for variations in mass ratio in all models within the limiting dimension of the TLD tank. Secondly, it can be concluded that damping ratio of the structural system is increased when the HD model is introduced and the effectiveness of the HD to reduce dynamic response is apparent in excitation frequency ratios at structural resonance and above. Across the entire frequency ratios tested above resonant frequency, the HD models exhibited the most effective performances at frequency ratios close to the resonant frequency. However, the HD models were the least effective for dynamic response control in frequency ratios below resonance, whereby each increase in mass portion of TMD further increased the structural response. Lastly, performance of the HD models compared to the conventional TLD to reduce dynamic response of a structural system is concluded to be superior in frequency ratios at resonance and above, as well as higher in increasing the structural damping ratio, but the effectiveness at frequency ratios below resonance was reduced with each increase in mass portion of TMD.

These results show an indication for the Hybrid Damper's practical use in the control of significant modes of vibration other than that of the first major. For MDOF structures such as high-rise buildings, higher modes of vibration occur at frequencies above resonance in the first major mode. The Hybrid Damper's proven effective performance within those ranges predicts its suitability for such cases.

The discrepancies and uncertainties within the results are not within the scope of this research to be verified from further analysis, but were still enough to provide a predominant conclusion that could still be made to adhere to this study's objectives. However so, a number of factors present in this research should still be discussed to yield insight of such results. Firstly, the inherent properties of the HD models constructed for this particular research may have led to the discrepancies and uncertainties in performance such as the allowance of water spillage during vibrations due to incomplete tank sealing, the limited TMD clearance within the TLD tank which allowed for the mass to hit the wall during motion, partial submergence of TMD during vibrations and instances where the TMD was not submerged in water during vibrations as pictured in Figure 17, as well as the general non-linearity of liquid sloshing of the TLD added to the fact that the structural systems were tested under relatively extreme excitation amplitudes. Another difficulty arose from the occurrence of beat phenomenon. Under force vibration, the time history response of the structural system will undergo transient response as the shaker increases in sinusoidal load from rest, after the transient period, varying amplitude modulations still occurred during steady state response, presumably from the beat frequencies present in the system. Determining the exact point of maximum response in displacement was difficult due to the limited recording time set in the experiment methodology. For the accelerometer, sounds and external vibrations may cause distortions in the reading due to the sensitivity of the measurement device. A correction factor can be applied using Seismosignal's baseline correction algorithm, but the actual acceleration response of structural system is lost.

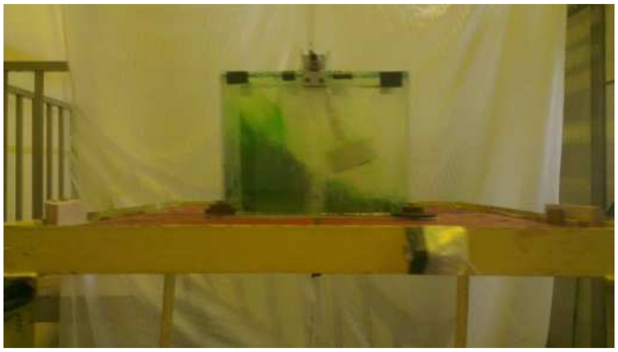


Figure 17: Example of an instant where TMD is completely not submerged in liquid during vibration

Based on the observation and performance of the Hybrid Damper within this research, a number of recommendations can be made for future complimenting studies:

1. A HD with multiple TMD with varying mass portion
2. A HD with multiple TMD of distributed tuning frequency
3. Performance of HD under significant modes of vibration in a MDOF structure
4. Performance of multiple HD
5. Effect of different TMD shapes and volume of submergence towards HD performance
6. Optimum parameters and design for HD

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