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SIMULATION OF TUNED LIQUID DAMPER USING PARTICLE FINITE ELEMENT METHOD (PFEM)

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Abstract: *Tuned Liquid Damper is a passive device which can be used in building structures to dampen structural vibrations. A tuned liquid damper is a container of water, typically placed on top of a building that uses the sloshing energy of the water to reduce the dynamic response of the system when subjected to excitation. Simulating tuned liquid dampers is challenging since modelling liquid and loss of energy due to sloshing will require special modelling techniques. The aim of the study is to apply Particle Finite Element Method (PFEM) for simulating Tuned Liquid Damper (TLD) and Tuned Liquid Column Damper (TLCD). For that, the numerical investigation is carried out for studying the performance of a tuned liquid damper subjected to sinusoidal excitation using PFEM. To support such simulation efforts, data collected from reported literature are used to validate the Particle Finite Element Method (PFEM) implementation in OpenSeesPy, which has been widely used for simulating the response of structures subjected to earthquakes. Moreover, comparisons between the simulated results and experimental data are performed so that the concerned problems and results are used as benchmarks. From the studies conducted, it is observed that PFEM can be used for simulating the response of structures with TLDs and TLCDs.*

1. Introduction

Tuned liquid dampers (TLDs) are tools used to lessen structural vibration. The energy of the structure's vibrations is dissipated by these devices using the fluid-structure interaction principle. A TLD is made up of a container that is partially filled with liquid which is tuned to the vibrational frequency of the structure. The tuning of the TLD makes sure that it absorbs the most energy possible from the vibrations of the structure. The energy is lost as a result of the TLDs liquid moving in reaction to the structure's vibrations.

To analyse problems involving fluid-structure interaction, one of the numerical techniques that can be used is the Particle Finite Element Method (PFEM). PFEM uses particles to represent the fluid, and it uses finite elements to represent the structure. The technique can simulate the complicated fluid-structure interactions that take place in TLDs, making it an excellent choice for simulations of these devices, Massimiliano Cremonesi (2020).

For implementing the PFEM, OpenSees (Open System for Earthquake Engineering Simulation) is used, which is an open-source finite element software framework for simulating the behaviour of structures and materials under different loading conditions. OpenSeesPy provides a Python interface for running OpenSees simulations, allows to write scripts in Python to automate and simplify the simulations. These consist of classes for meshing the domain, defining particles, and performing analysis. OpenSeesPy supports PFEM to simulate the behaviour of structures under various types of loading conditions, such as seismic loads or wave loads, and to model complex fluid-structure interactions. OpenSeesPy offers a versatile and effective tool for structural and geotechnical engineering with its scripting interface and built-in functions for analysis and visualisation, Minjie Zhu (2023).

2. Simulation Methodology

The simulation methodology is shown in Figure 1, where the objective of the study is to determine the performance of Particle Finite Element Method (PFEM) in simulating Tuned Liquid Damper (TLD) on a structure subjected to sinusoidal waves. The methodology consists of two models: (i) Tuned Liquid Damper with structure, and (ii) Tuned Liquid Column Damper with structure.

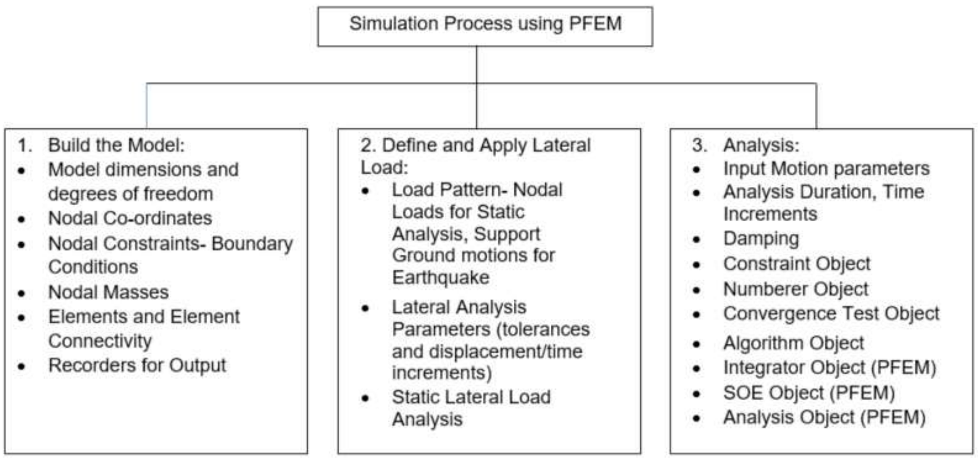


Figure 1. PFEM Simulation

2.1. Model 1: Tuned Liquid Damper (TLD) with Structure

In the model, as a connection plane, a roof plate with a dimension of 600×600×5 mm is used to connect the tank by bolts. The bottom plate has dimensions of 500×500×5mm. Four columns with 4.8×50×1000 mm dimensions are welded to the top and bottom plates, the columns are initially vertical to the ground and the whole model is shown in Figure 2 as given in the study by Dou et al. (2020). The dimensions of the tank are 0.51x0.15x0.47m.

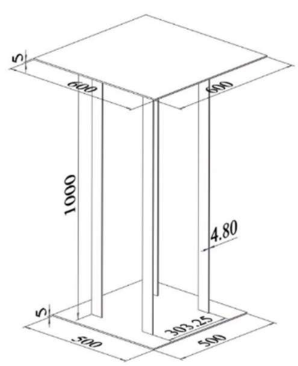


Figure 2. Model Dimensions of Structure, Dou et al. (2020)

In this study, the analytical and simulated natural frequency of the model's structure is compared with the experimental value from the journal by Dou et al. (2020). Additionally, the model with the same structural dimension but with a different tank dimension is modelled to determine the optimum water level. The TLD with different water levels are analysed to obtain the ideal water level. The tank material used in this case is steel. The dimensions of the tank are 0.55×0.4×0.32m. The acceleration provided for the analysis is 0.1g. In

OpenSeesPy, nodal points are used to model the structure and a program source code is developed for the simulation.

Analytical Calculation for Natural Frequency of the Structure

The calculation of Natural Frequency (f) of a structure can be calculated from the equation below:

$$f=\frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

Where 'm' is the total mass of the structure and 'k' is total stiffness of the structure.

2.2. Model 2: Simulation of Tuned Liquid Column Damper (TLCD) with Structure

A steel prototype structure consisting of bottom and top plates and four columns is designed in the laboratory by Sagar Mohan et al. (2022) as shown in Figure 3.The bottom plate with 300×300×10 mm dimensions is fixed to the shaking table using five bolts, one of them in the middle and others at the edge points. The top plate has 600×600×5 mm dimensions. Four columns, each of 5×50×1000 mm dimensions, are welded to the top and bottom plates. The model is analysed for a frequency of 1Hz and an amplitude of 6mm. The dimensions of the Tuned Liquid Column Damper is shown in Figure 4. The above mentioned details are used for the PFEM simulation of TLCD structure which is a 2-Dimensional model.

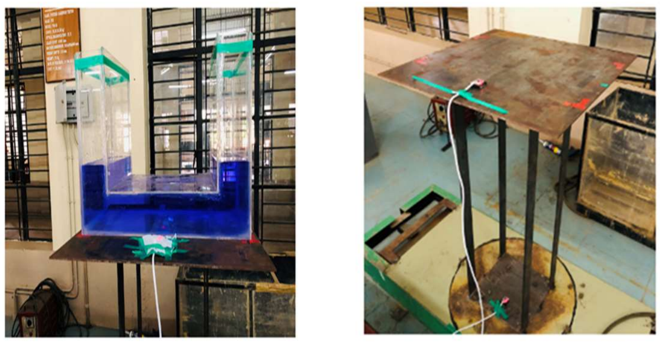


Figure 3. Experimental Set-up, Sagar Mohan et al. (2022)

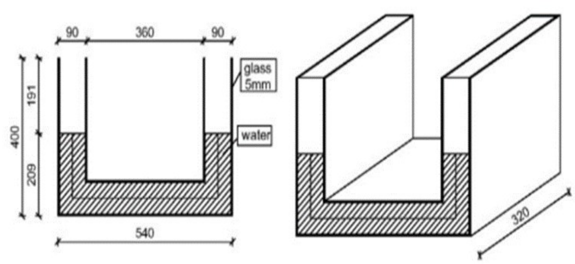


Figure 4. Dimensions of TLCD used

In experiment, the model is analysed for different water heights, i.e. at 0 mm height (Le = 540mm), 30mm height (Le= 600mm), 60mm height (Le =660mm), 90mm height (Le =720mm), 120mm height (Le= 780mm), 150mm height (Le= 840mm) and 180mm height (Le= 900mm), where Le is the length of water in the TLCD. The model with the above mentioned heights are modelled 2-Dimensionally in OpenSeesPy which is visualised through ParaView.

2.3. ParaView Visualization

The BgPVD recorder used in the simulation records the data of the simulation at each time steps into separate files and then the pvd files are run in ParaView to get the animation of the simulation. The visualisation helped to ascertain that the fluid structure interaction is as observed during experiments.

ParaView Visualisation of Tuned Liquid Damper (TLD)

The displacement of the TLD in X-direction is shown in Figure 5. The ParaView Representation of TLD for empty tank and a water level of 30% is shown below. The different colours seen in the images are used to determine the displacement value at each node. The movement of particles for each time step can be visualised through ParaView as animation.

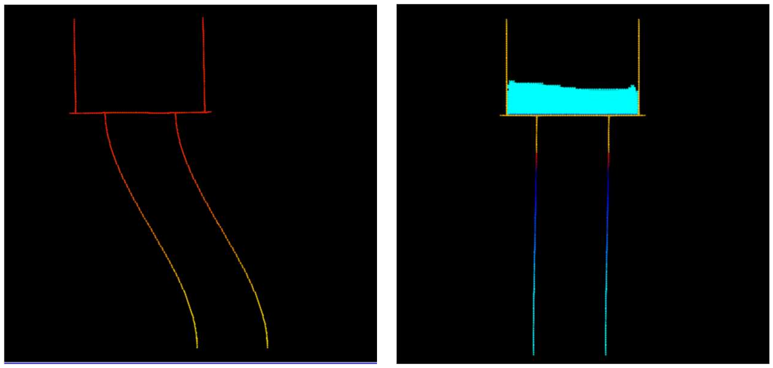


Figure 5. Displacement of TLD

ParaView Visualisation of Tuned Liquid Column Damper (TLCD)

The displacement of the TLCD in X-direction is shown in Figure 6. The ParaView Representation of TLCD for water length (Le) of 540mm and 780mm is shown below.

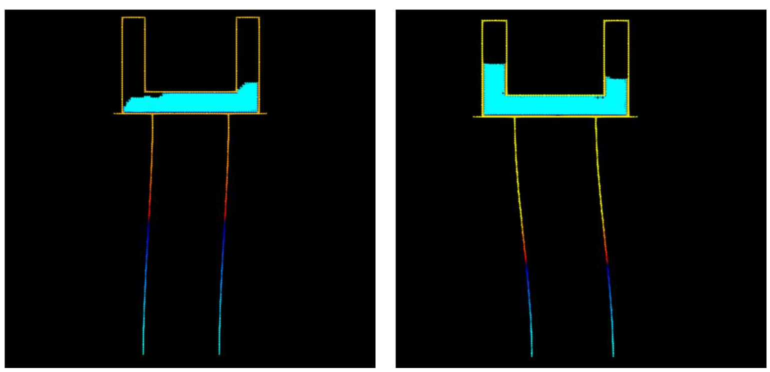


Figure 6. Displacement of TLCD

3. Analysis and Findings

3.1 Model 1: Tuned Liquid Damper (TLD) with Structure

During analysis, the recorders are used to save the time history of the displacement at each node. Fast Fourier Transform is used to extract the response in the frequency domain. The natural frequency of the structure is compared with the data from the journal Dou et al. (2020). In the journal, the natural frequency is determined through FEM and experiment. Here, the data is compared with the analytical calculation and PFEM simulated values.

Natural Frequency from PFEM Simulation and Analytical Calculation

The model is analysed as structure-alone and the structure with empty TLD. The Figure 7 shows the natural frequency determined through PFEM Simulation. The natural frequency of the structure is also calculated using equation (1). The value obtained is comparable with the simulated value.

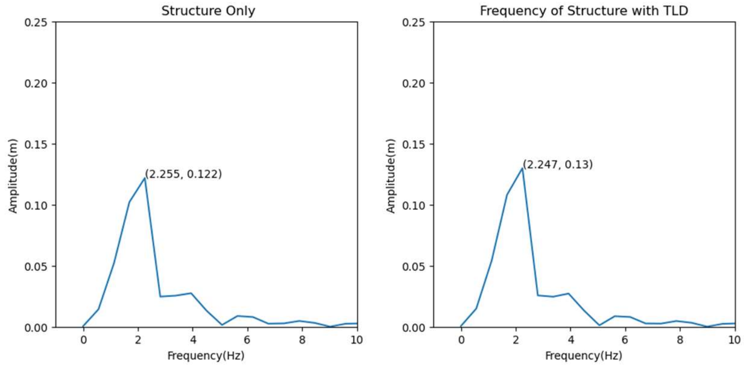


Figure 7. Natural Frequency of Structure- alone and Structure with TLD

Simulation of TLD to determine optimum water level

After confirming the similarities between the natural frequencies of simulated value and values from the journal, a different model of Tuned Liquid Damper is analysed for different water levels to determine the optimum water level for the TLD. Figure 8 shows their natural frequencies.

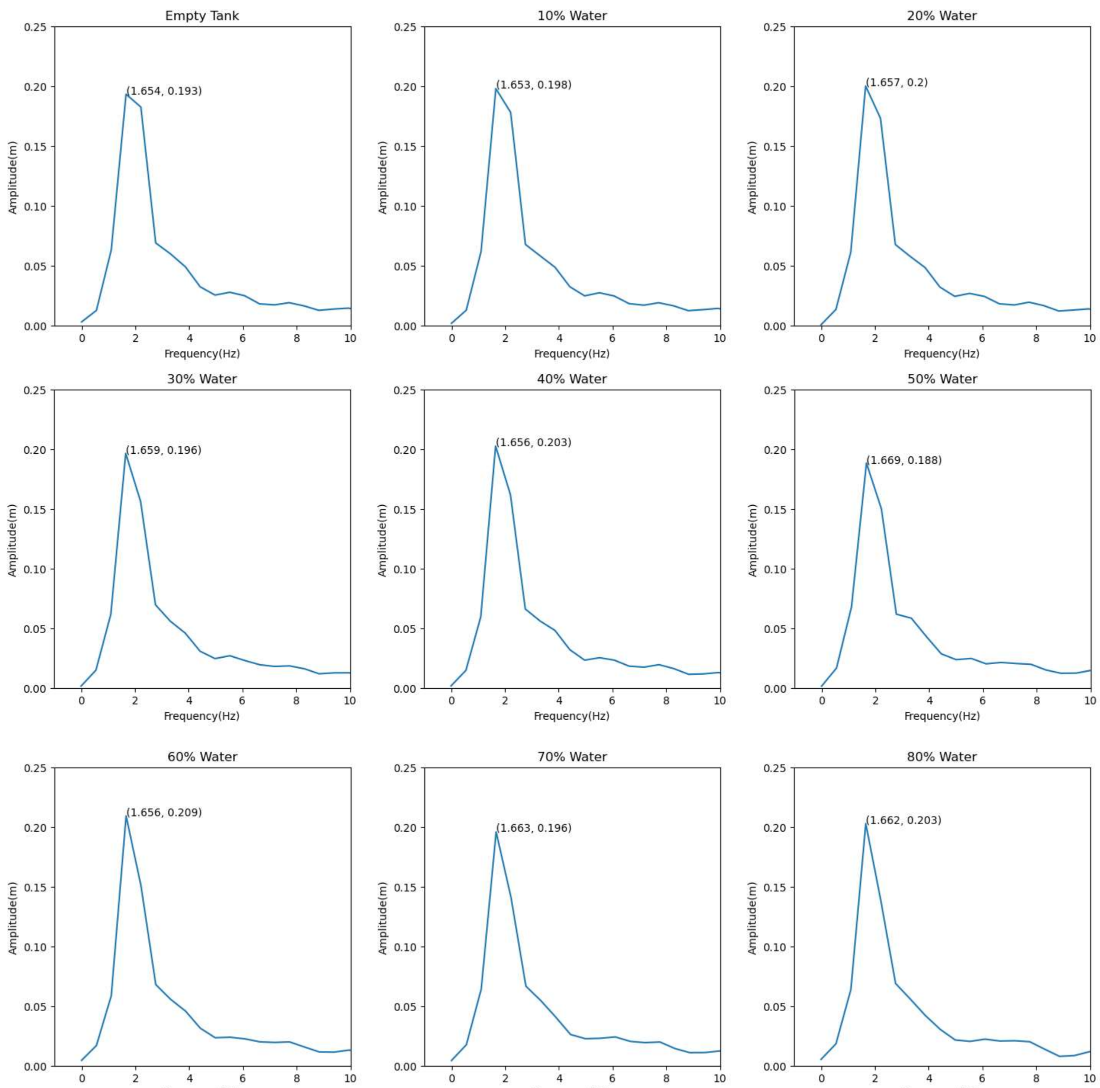


Figure 8. Natural Frequencies of TLD at different water levels

Damping Ratio

The damping ratio of the structure is determined using the equation:

$$ln\ ln\ \frac{Xn+1}{Xn} = 2\pi\zeta \qquad (2)$$

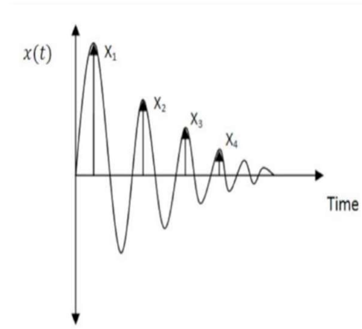


Figure 9. Damping Ratio Calculation

where ζ is the damping ratio. The damping ratios at different water levels in TLD are shown in Figure 10.

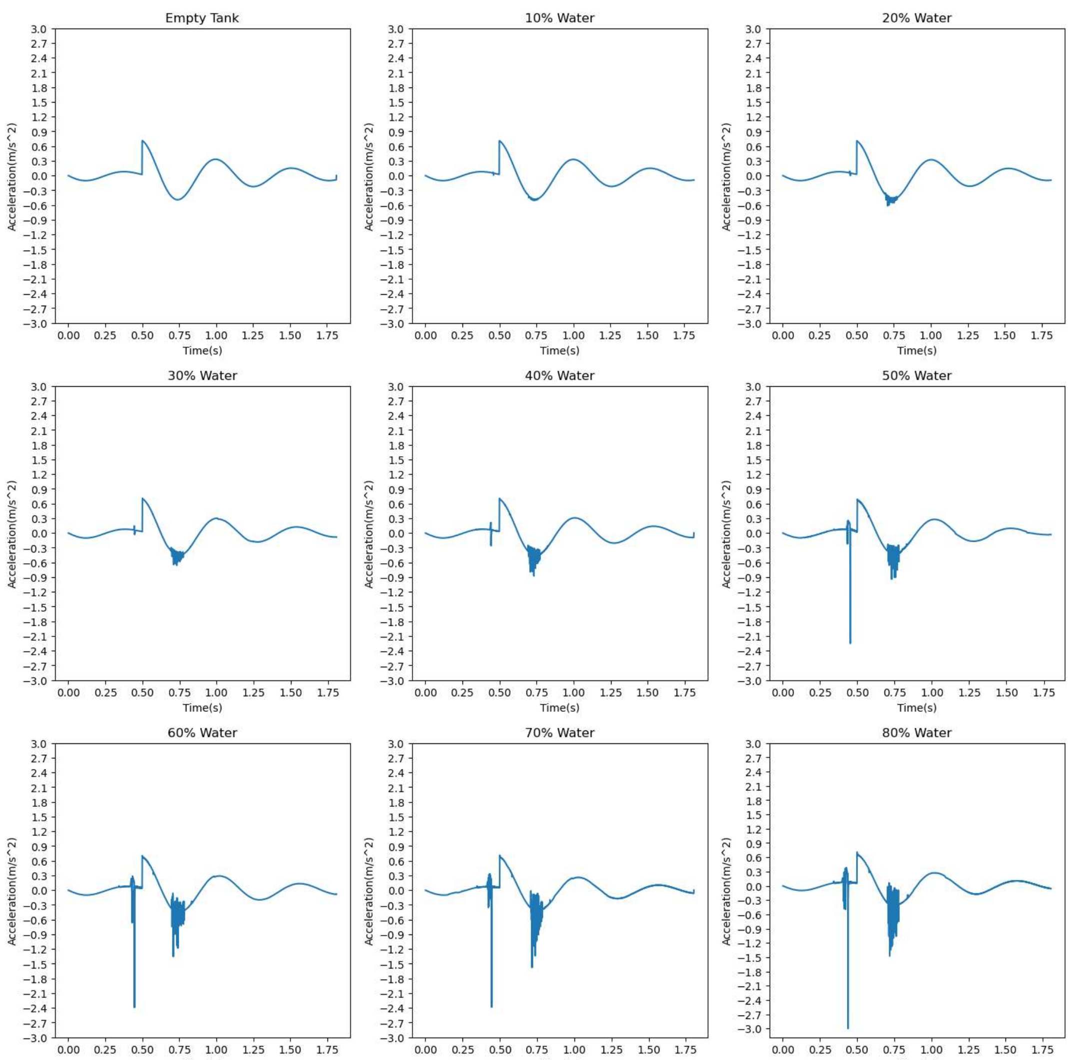


Figure 10. Damping Ratio of TLD at different water heights

The damping ratio of TLD structure when the tank is empty, 10%, 20%, 30%, 40%, 50%, 60%, 70%, and 80% of water are 0.12788, 0.11823, 0.12306, 0.13934, 0.12652, 0.16945, 0.11353, 0.14291, and 0.14869 respectively.

Displacement in X-Direction

The Figure 11 shows the displacement recorded at node 2. It is observed that the displacement reduces at 30% (pink colour), 50% (purple colour) and 70% (olive colour). But, the minimum displacement is observed to be at 50%, thus, 50% is considered as the optimum water level for this TLD.

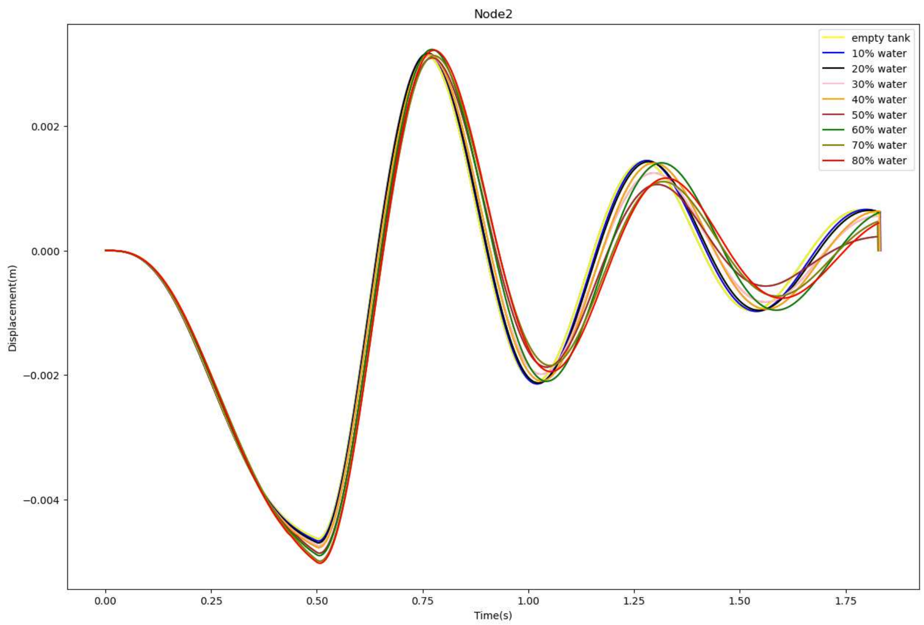
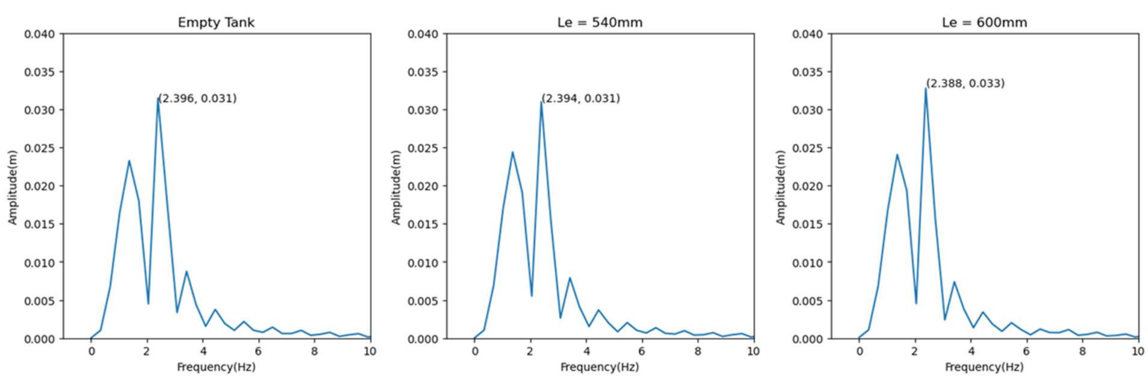


Figure 11. Displacement vs Time Graph of TLD

3.2 Model 2: Tuned Liquid Column Damper (TLCD) with Structure

Natural Frequency at Different Lengths of Water

The Natural Frequencies of the structure is calculated from Acceleration v/s Time graph using Fast Fourier Transformations (FFT) which converts the values from the graph to the frequency domain. The Figure 12 depicts the frequency response of the structure with various cases.



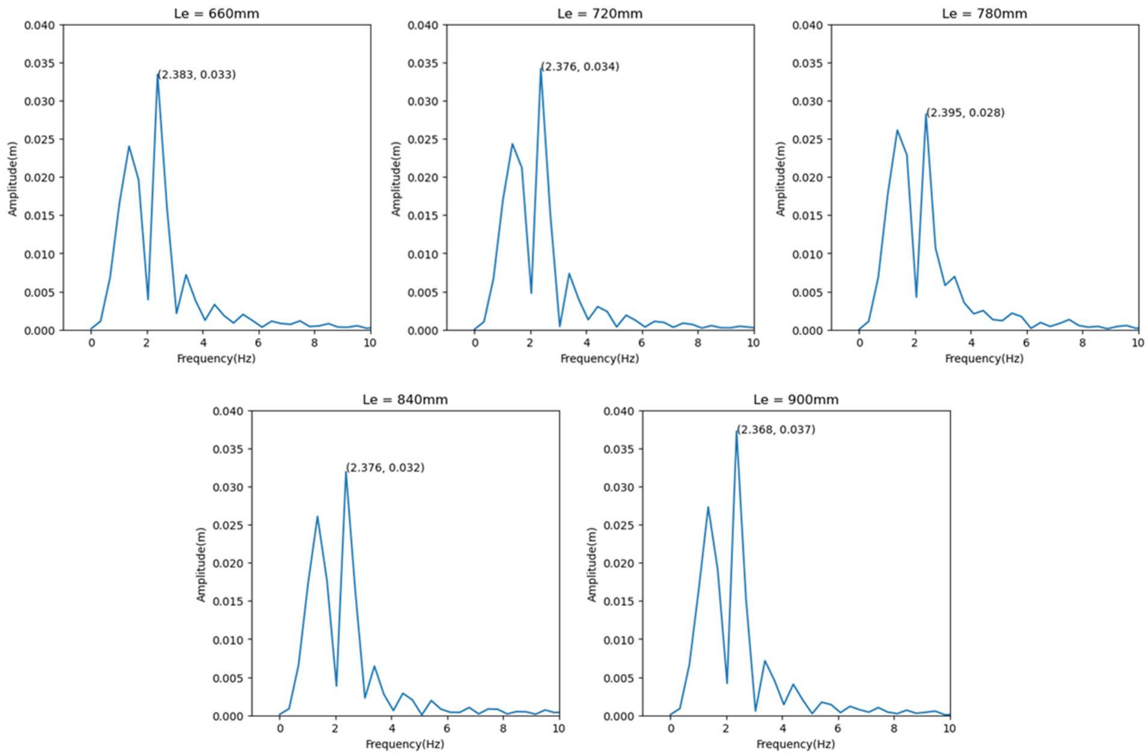
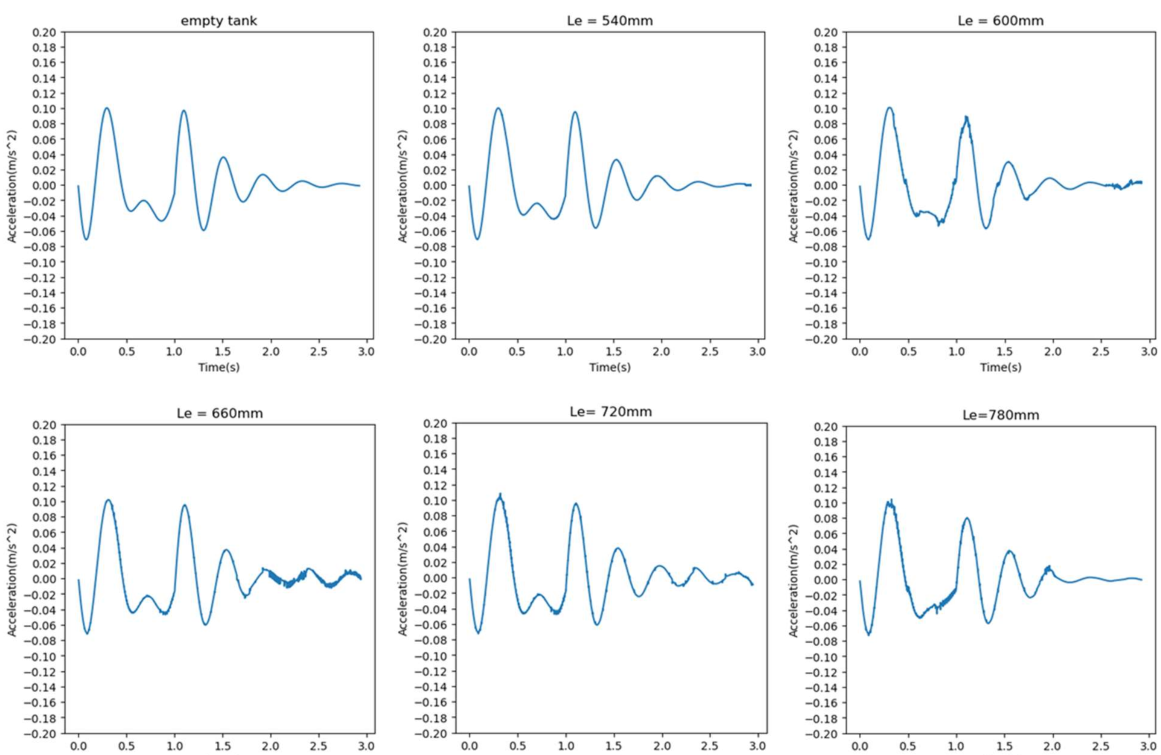


Figure 12. Natural Frequency of TLCD

Damping Ratio

The Figure 13 shows the damping ratio of TLCD at different lengths of water (Le). The value is calculated by using equation (2).



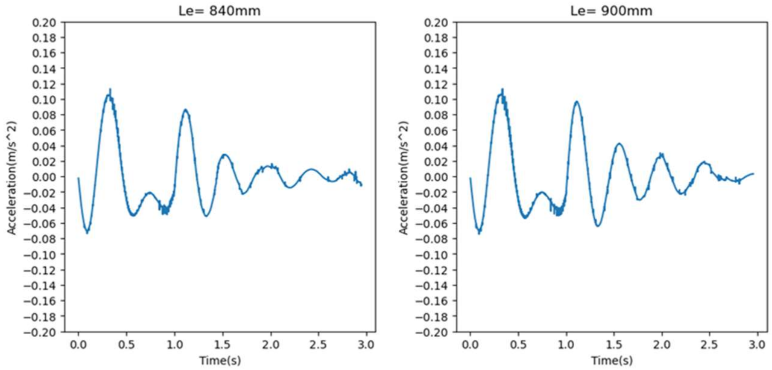


Figure 13. Damping Ratio of TLCD at different water lengths

The damping ratio of TLCD at empty tank, 540mm, 600mm, 660mm, 720mm, 780mm, 840mm, and 900mm is found to be 0.129, 0.1589, 0.1748, 0.150, 0.156, 0.114, 0.1657,and 0.1311 respectively.

Displacement in X-direction

The Figure 14 shows the displacement vs time graph of the TLCD at different water lengths. Various colours are used to depict the displacements at different water lengths. The colour corresponding to each water level is defined in the legend. Using node recorders, the displacement at each time step is plotted in the graph for node 2. It can be observed that the displacement is reduced when it reaches 600mm (represented in black colour) and then it gradually increases till 780mm. Again, the displacement reduces at 840mm (represented in purple colour). The displacement at 600mm is lesser than the displacement at 840mm, thus 600mm is considered as the optimum water level for this TLCD.

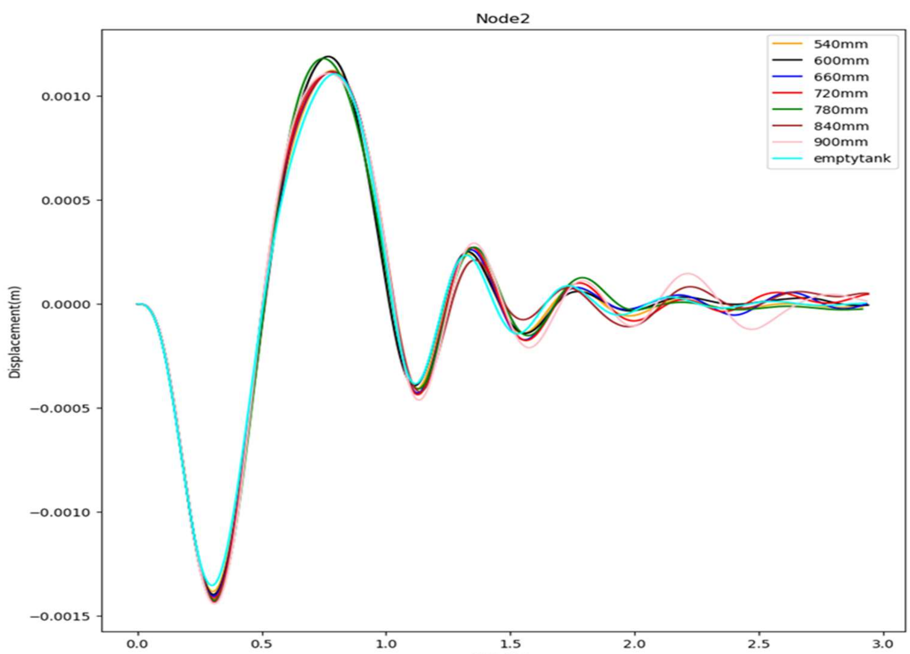


Figure 14. Displacement vs Time Graph of TLCD

4. Results and Discussions

4.1. Model 1: Tuned Liquid Damper (TLD) with Structure

Natural Frequency

The comparison of natural frequency of the Tuned Liquid Damper is shown in Table 1. The values obtained through FEM and experiment as mentioned in the journal by Dou et al., 2020 are compared with the values obtained through analytical calculation and value simulated through PFEM.

Table 1. Comparison of Natural Frequency

Model	**Natural Frequency (Hz)**			
	FEM [Dou et al.,2020]	Experiment [Dou et al.,2020]	Analytical Value	Simulated Value (PFEM)
Structure- alone	2.53	2.5	2.1903	2.255
Structure with Tank	2.01	1.98	2.129	2.247

From Table 1, it is clear that the values obtained through PFEM simulation and analytical calculation are comparable with the results reported in literature.

Simulation of TLD to determine optimum water level

The natural frequency for various water levels are determined using Fast Fourier Transformation. Table 2 shows the values of natural frequency for TLD.

Table 2. Natural Frequency of TLD at Different Water Levels

Sl. No	**Percentage of Water (%)**	**Height of Water (mm)**	**PFEM Simulated Value (Hz)**
1	0	0	1.654
2	10	40	1.653
3	20	80	1.657
4	30	120	1.659
5	40	160	1.656
6	50	200	1.669
7	60	240	1.656
8	70	280	1.663
9	80	320	1.662

Damping Ratio

From the Acceleration v/s Time Graph, the damping ratio can be calculated using the equation (2). Table 3 shows the estimated damping ratio for the different cases studied. From Table 3, it is observed that the maximum damping ratio is obtained at 50% of water in the tank i.e. at 200mm height of water. Therefore, 200mm is considered as the ideal height of water for this TLD.

Table 3. Damping Ratio of TLD at Different Water Levels

Sl. No	Percentage of Water (%)	Height of Water (mm)	Damping Ratio
1	0	0	0.12788
2	10	40	0.11823
3	20	80	0.12306
4	30	120	0.13936
5	40	160	0.12652
6	50	200	0.16945
7	60	240	0.11353
8	70	280	0.14291
9	80	320	0.14869

The values from Table 3 are plotted in a bar chart for the graphical representation. The Figure 15 shows the damping ratio for different water levels. Maximum damping ratio can be observed at 50% of water in the tank.

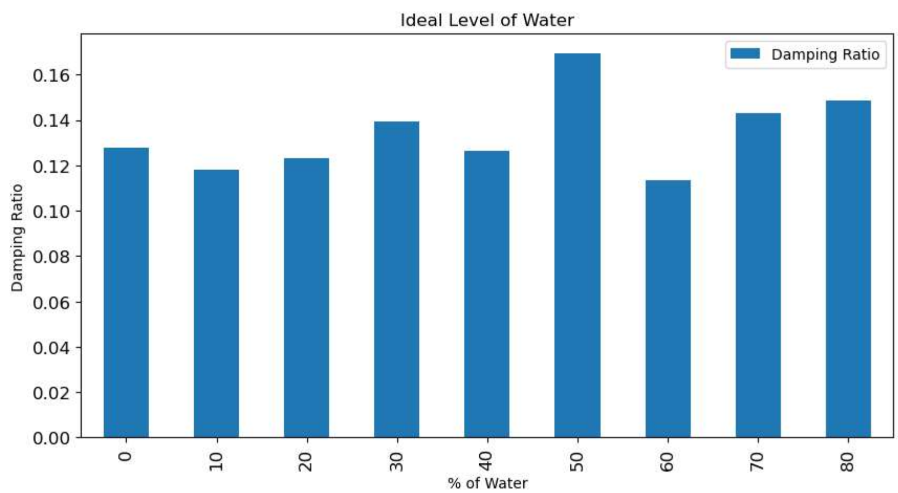


Figure 15. Ideal Water Level for TLD

4.2. **Model 2: Tuned Liquid Column Damper (TLCD) with Structure**

Natural frequency

The natural frequency of TLCD at each length is calculated. Table 4 shows the comparison of values from the report by Sagar Mohan et al., 2022 and the simulated data. The simulated value is approximately matching to the reference data.

Table 4. Comparison of Natural Frequency- TLCD

Sl. No	Length of Water (mm)	Mass Ratio (M_f/M_s)	Experimental Value (Hz)	Simulated Value (Hz)
1	540	_	2.644	2.394
2	600	0.791	2.464	2.4

Sl. No	Length of Water (mm)	Mass Ratio (M_f/M_s)	Experimental Value (Hz)	Simulated Value (Hz)
3	660	0.870	2.323	2.383
4	720	0.950	2.235	2.376
5	780	1.029	2.153	2.395
6	840	1.108	2.088	2.376
7	900	1.187	2.020	2.368

Damping Ratio

From the Acceleration v/s Time Graph, the damping ratio is calculated using the equation (2). Table 5 shows the estimated damping ratio for the different cases studied.

Table 4. Damping Ratio of TLCD

Sl. No	Length of Water (mm)	Damping Ratio
1	0	0.1290
2	540	0.1589
3	600	0.1748
4	660	0.1500
5	720	0.1560
6	780	0.1140
7	840	0.1657
8	900	0.1311

The highest value for damping ratio is obtained when the length of the tank is 600mm. Therefore 600mm is considered as the ideal length of water for the simulated TLCD. The above values are plotted in a bar graph to find the maximum value of damping ratio which is represented in Figure 16.

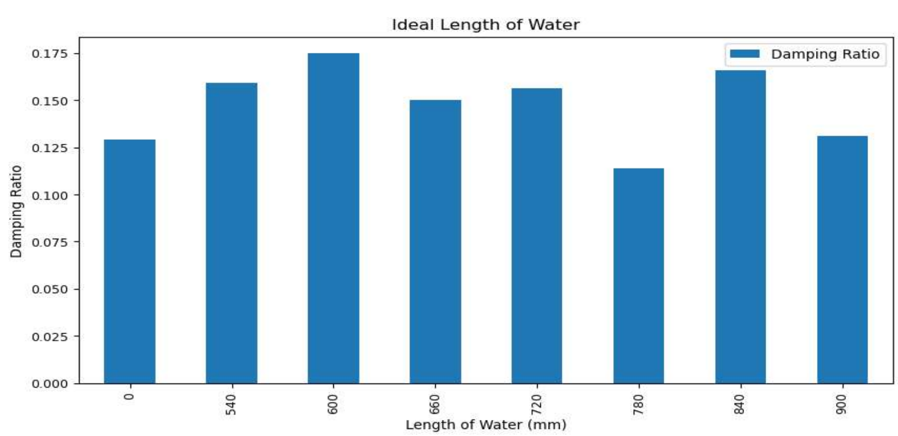


Figure 16. Ideal Length of Water for TLCD

5. Conclusion

Particle Finite Element Method can be used to simulate Tuned Liquid Dampers and Tuned Liquid Column Dampers. The natural frequencies of structure- alone and the structure with tank are compared with the journal data of Tuned Liquid Damper. The values do not deviate much from the simulated values. The maximum deviation observed is 13%. Similar results are obtained from the studies conducted on Tuned Liquid Column Dampers. The values of the frequency of vibrations obtained are close to the experimental reference data. Therefore, it can be concluded that it is possible to simulate a Tuned Liquid Damper in OpenSeesPy with PFEM. The main drawback experienced during the simulation is the computation time which takes longer to complete a small period of analysis.

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