

Vibration Analysis of Chenderoh Dam Physical Model Spillway Structure due to the Effect of Water Spilling: Numerical and Experimental Validation

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Abstract. Dam can be defined as a barrier built across the river to restrain and control the flow of water. However, the safety of the dam structure can be threatened by the uncertainties vibration induced from internal and external sources. Thus, in this paper, the vibration analysis in terms of Experimental Modal Analysis (EMA) and Operational Deflection Shapes (ODS) are carried out to determine the reliability of the dam structure. This study only focused on the spillway structure of the Chenderoh Dam that located in Perak, Malaysia. For the simulation, a 3D physical model with 1:20 scale is developed using SolidWorks software and simulated using ANSYS software. Whilst, for validation of the simulation results, EMA and ODS experiment are performed on the physical model of the Chenderoh Dam. The validation will be in terms of mode shape, ODS, natural and operating frequencies. From the results, the first natural frequency of the spillway occurred at 220.87 Hz with the maximum deflection of 1.6 mm and the ODS deformation happened at operating frequency of 45 Hz with the amplitude value of 0.003 m. The operating frequency value is far from the natural frequency of 220.87 Hz; thus, the transient vibration only induces a minimal effect on the spillway structure and the spillway is considered safe for the operation.

1. Introduction

The safety of the dam structure can be threatened by the uncertainties vibration induced from the internal and external sources. This includes the flow condition of water, earthquake effect, vibration of mechanical machine and other related sources. Various vibration studies and analyses have been conducted by many researchers. Such study includes eigenvalue analysis, normal condition analysis [1] as well as Experimental Modal Analysis (EMA) and Operational Deflection Shapes (ODS). Other than that, Yang [2] carried out the static and dynamic analyses to determine the maximum dynamic displacement and seismic stress of the dam. Besides, new formulas such as to calculate the frequency using an analytical method of the dam [3] and random vibration formula to analyse the dynamic characteristics of the dam [4] were introduced as well.

Simulation study is very crucial to be carried on in order to determine the vibration characteristics of the dam. Through this study, the dam structure behaviour under dynamic loading can be determined and

thus can maintain the safety of the structure [5]. Sato & Obuchi [6] carried out simulation study to compare the dynamic response of the equivalent linear and non-linear finite element (FE) method. Modal analysis is another example of simulation to study the dynamic properties such as natural frequencies and mode shapes [7]. This is very important in determining, improvising and optimizing the dynamic characteristic of engineering structures [8]. There are two ways to conduct modal and harmonic analysis; using APDL or ANSYS Workbench. ANSYS Workbench is preferable as it is much easier to use compared to APDL. There are studies of modal analysis that been carried out using ANSYS Workbench to investigate and analyse and the dynamic behaviour of a structure [9, 10]. Beside simulation, there is another method to perform modal analysis which is by EMA [11].

EMA analysis is done to determine the modal parameters such as natural frequencies, mode shapes and damping values [12, 13]. For example, Balsara & Fowler [12] have conduct a study on two electromagnetic vibrators that used as exciter with a total of 14 points for velocity and 4 points for acceleration measurement for the tests. Meanwhile, a servohydraulic vibration generator was used as the exciter and 247 points were selected and measured [13]. ODS also can be used to study the vibrations of the structure. In ODS, the deflection shapes of a structure under different operating conditions can be determined. According to Hugar and Venkatesh [14], ODS is a vibration testing and analysis which has the ability to animate the deformation characteristics of a vibrating structures of systems. Generally, ODS contains the overall vibration of any forced motion for two or more DOFs points of the structure [14, 15]. Saravanan and Sekhar [15] stated that, ODS is different from mode shape as ODS can be used for non-linear and non-stationary structural motion, while mode shape can only be used for linear and stationary motion. In this study, the vibration of Chenderoh Dam physical model will be investigated in terms of EMA and ODS using both numerical and experimental.

2. Methodology

2.1. 3D modelling of spillway physical model

In this study, a spillway 3D model with 1:20 scale has been constructed using SolidWorks 2017 software. This spillway is mainly used for regulating the water from upstream to downstream area based on the opening distance between radial gate and sector gate. This section consists of the connection bridge, sector gate, radial gate and bridge to bottom outlet as shown in Figure 1. For the normal release of water condition, only radial gate is operated. However, when there is an emergency case, both radial and sector gates will be fully opened to release the water. It is expected that different gate openings will induce different vibration responses to the whole spillway section.

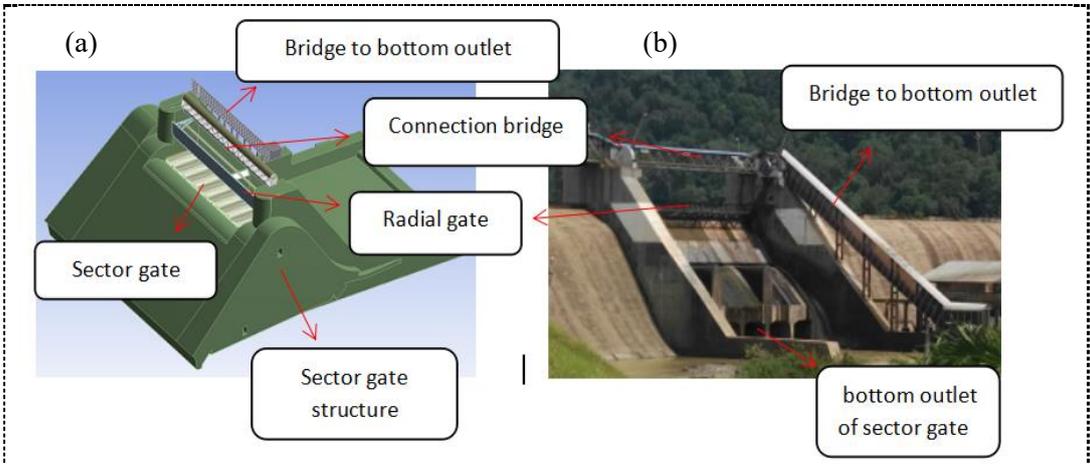


Figure 1. (a) 3D physical model of Chenderoh spillway section and (b) real photo of Chenderoh spillway section

2.2. Modal and harmonic response analyses of the spillway physical model

The modal analysis was carried out using ANSYS Workbench software. It is conducted to determine the vibration characteristics of the structure in terms of natural frequencies and mode shapes. Firstly, the 3D CAD model is imported from SolidWorks via Parasolid interface. Then, the desired materials were added along with the respective properties. In this structure, the material used is concrete and mild steel. The concrete with Young's modulus of $E = 30 \text{ GPa}$ is selected for the main spillway structure and mild steel ($E = 210 \text{ GPa}$) is selected for other steel related parts. For the boundary condition, all bottom faces of the spillway structure are set as fixed support to represent the foundation of the dam structure as shown in Figure 2. A maximum of 30 mode shapes are set to be determined.

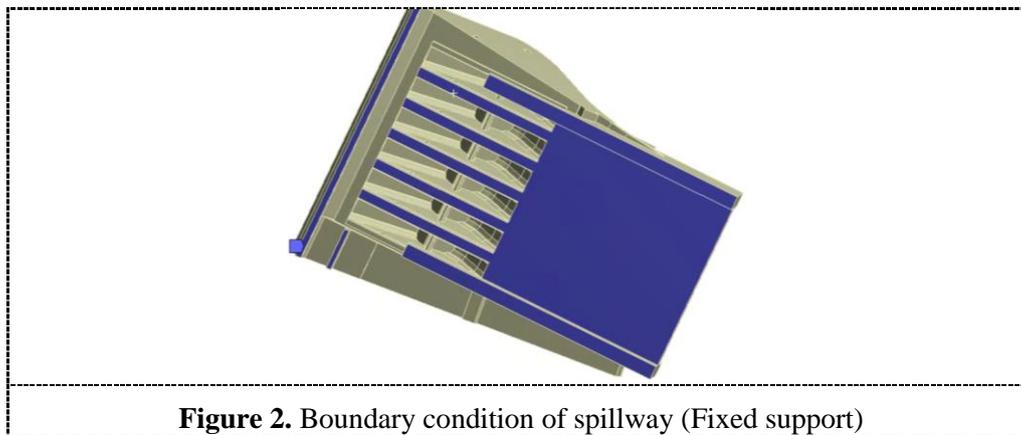
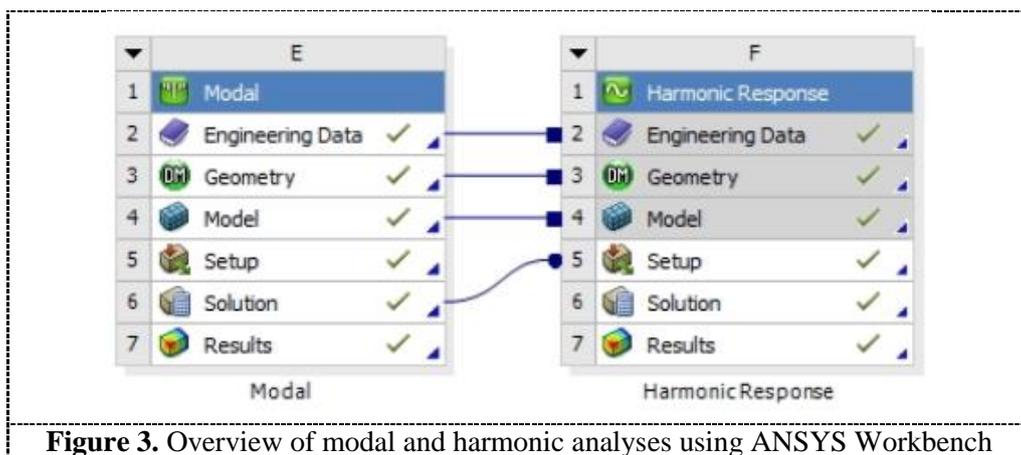


Figure 3 shows the overview of links setup between modal and harmonic response in ANSYS Workbench software. An input force with magnitude of 9.81 N is applied in x , y and z directions. These forces act as assumption of gravitational forces that reacted in all three directions since the spillway section is simulated independently. The frequency range was set in accordance to the natural frequency obtained in modal analysis. The solution interval was set to 100.



2.3. Fluid structure interaction (FSI) analysis of the spillway physical model

For the FSI simulation study, there are three main elements needed as shown in Figure 4. Firstly, the transient structural which used to study the deflection of the structure when fluid flow is act in the dam structure. Secondly, is the fluent where the flow and type of fluids that going to act on the dam structure.

Thirdly, the system coupling where it combines these two, transient structural and fluent together. This method is called as two-way FSI in the ANSYS software, which is more accurate and stable solution but in the other hand, the one-way method has lower computational cost.

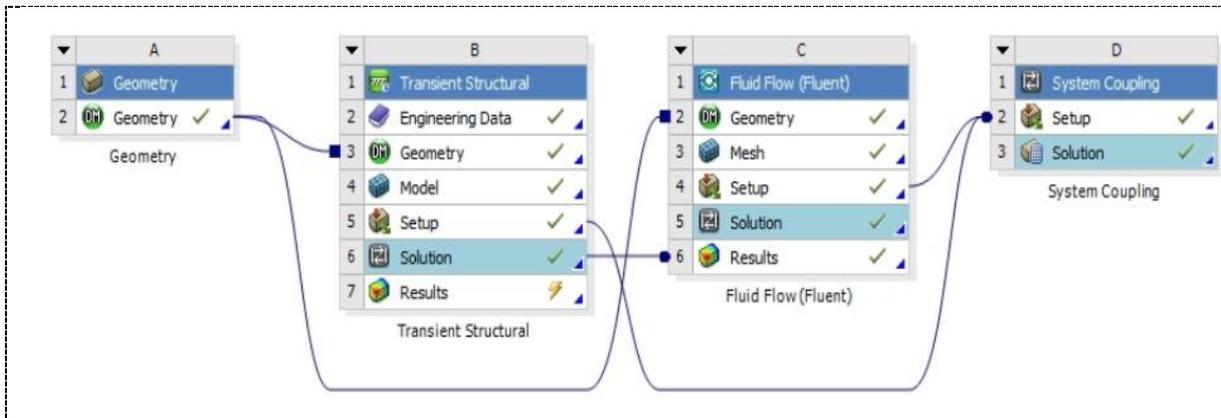


Figure 4. Linked setup between systems in two-way FSI in ANSYS Workbench

For a complicated structural design in FSI study, an appropriate type of mesh that can be used is tetrahedral mesh due to faster simulation time and much easier to be applied. For the analysis setting, the step end time is set to 5 second and the step control is changed from time to sub steps. The initial sub step, minimum sub step and maximum sub step is set as 1, 1 and 500 consequently. Boundary condition for the transient analysis is similar as in modal analysis where all the bottom faces is fixed as foundation and the standard earth gravity is set as 9.81 m/s^2 . In fluent analysis, the type of boundary system is set as velocity inlet and pressure outlet as shown in Figure 5 and 6, respectively. The velocity magnitude of fluid is set to 1 m/s^2 and the fluid is modelled as incompressible flow with pressure-based solver.

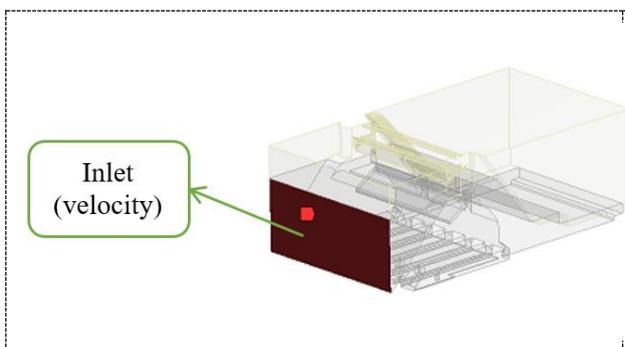


Figure 5. Inlet section for spillway part

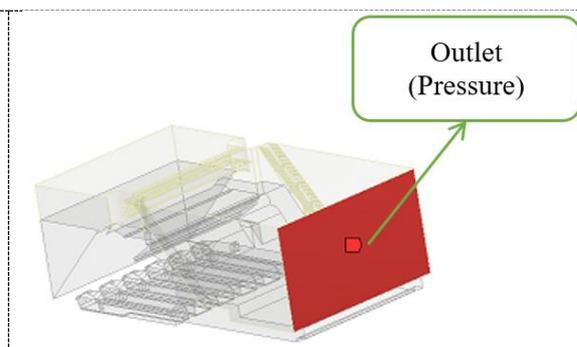


Figure 6. Outlet section for spillway part

2.4. Experimental validation of the physical model

The experimental modal analysis (EMA) is carried out using LMS Test Lab software and the result obtained was then compared with the ANSYS simulation. Both results are compared in terms of natural frequencies and mode shapes. The setup of EMA is shown in Figure 7. For EMA, an impact hammer is used to provide the input force to the structure and accelerometer is mounted to the respective node. The function of accelerometer is to measure the acceleration introduced from the structure vibration. To obtain best result, higher number of impact points are needed. Moreover, the impact hammer is knock at the same point at least 3 times to obtain the average reading for a better accuracy result. Apart from

EMA, ODS setup is almost identical except it operates with different software. Consequently, ODS measurement is performed to study fluid excitation on the structure. Therefore, several accelerometers are attached at the nodes to get the operating frequency data and deflection shapes. Figure 8 shows the setup for ODS testing. Based on the figure, the water is flowing through the passage of physical model while the test is running.

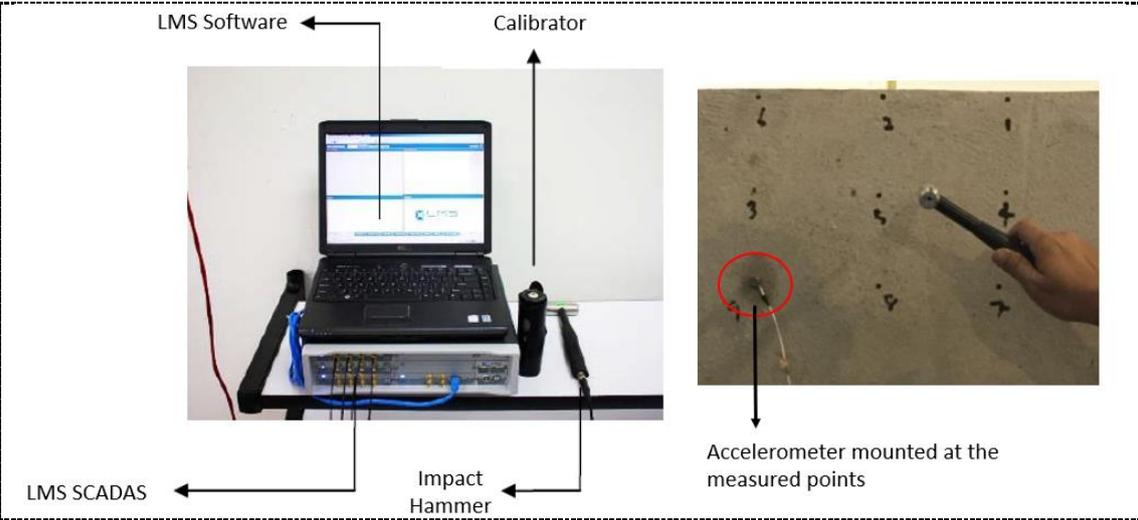


Figure 7. Experiment setup of EMA

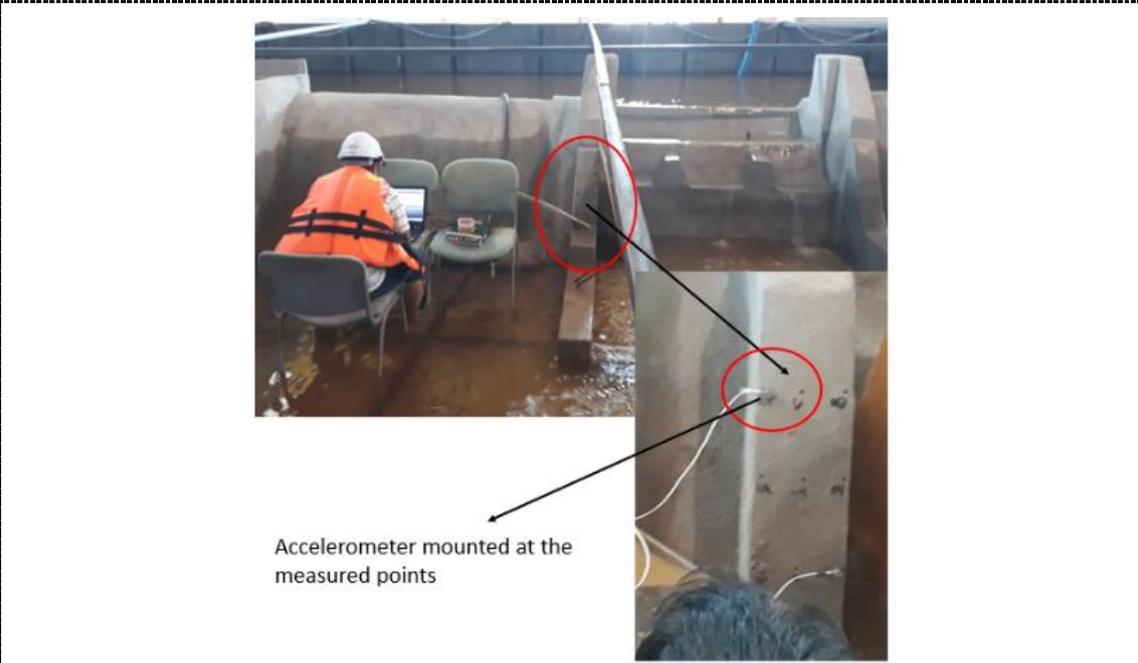


Figure 8. Experiment setup of ODS

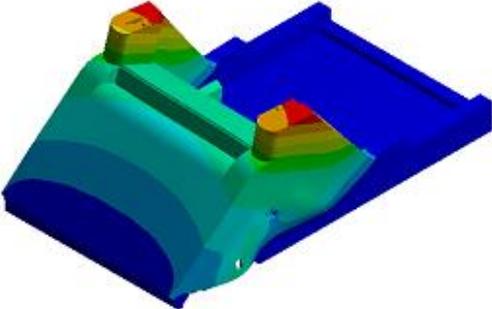
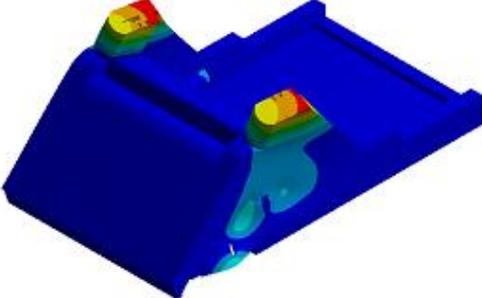
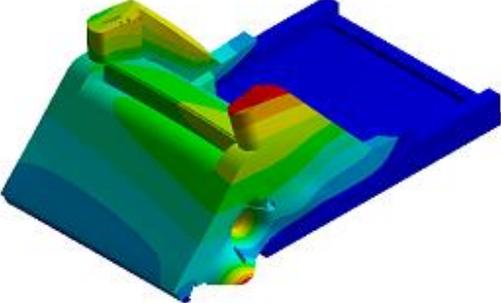
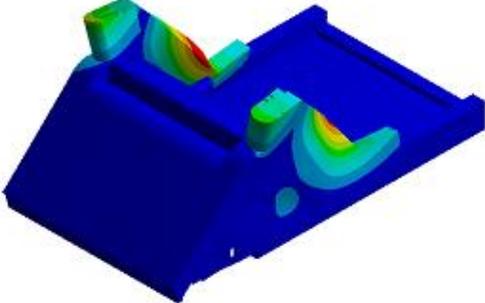
3. Results and Discussion

3.1. Modal and harmonic analyses of the spillway physical model

Table 1 shows the six most significant natural frequencies and mode shapes of the spillway physical model. The 1st mode take place at the natural frequency of 220.87 Hz with the maximum deflection value of 1.6 mm. The 4th ,5th ,8th ,11th and 17th modes occurred at 397.83 Hz, 424.18 Hz, 484.64 Hz,

593.2 Hz and 705.61 Hz, respectively, with the highest deflection occurred at 4th mode with 3.9 mm. The red colour zone on the spillway structure indicates the highest or maximum deflection of the part.

Table 1. First six most significant frequencies and the mode shapes.

Modes No.	Mode Shapes	Natural Frequency	Deflection Values
1		220.87 Hz	1.6 mm
4		397.83 Hz	3.9 mm
5		424.18 Hz	1.4 mm
8		484.64 Hz	3.8 mm

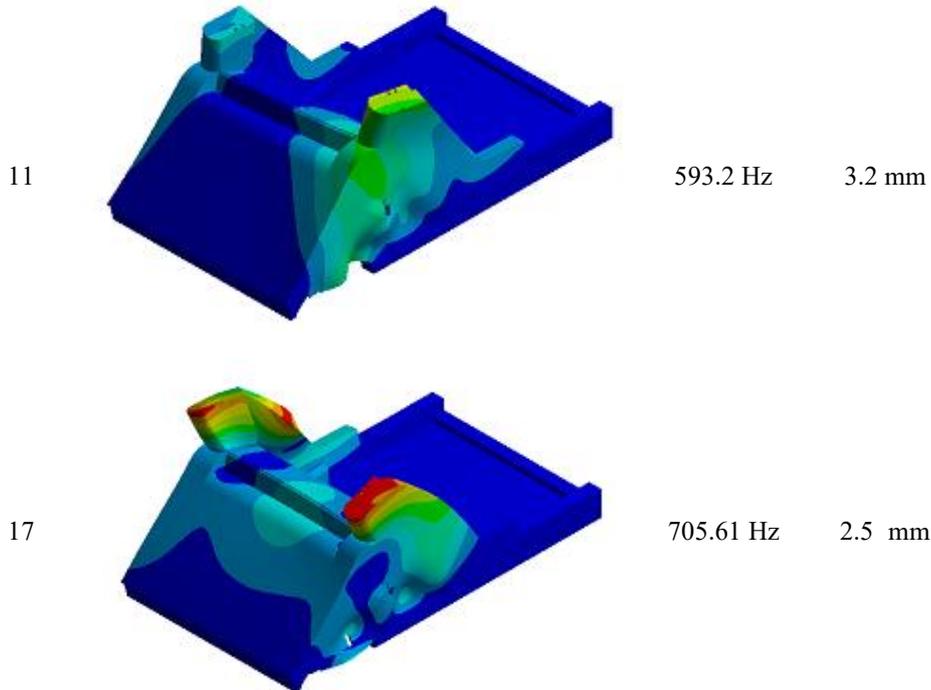
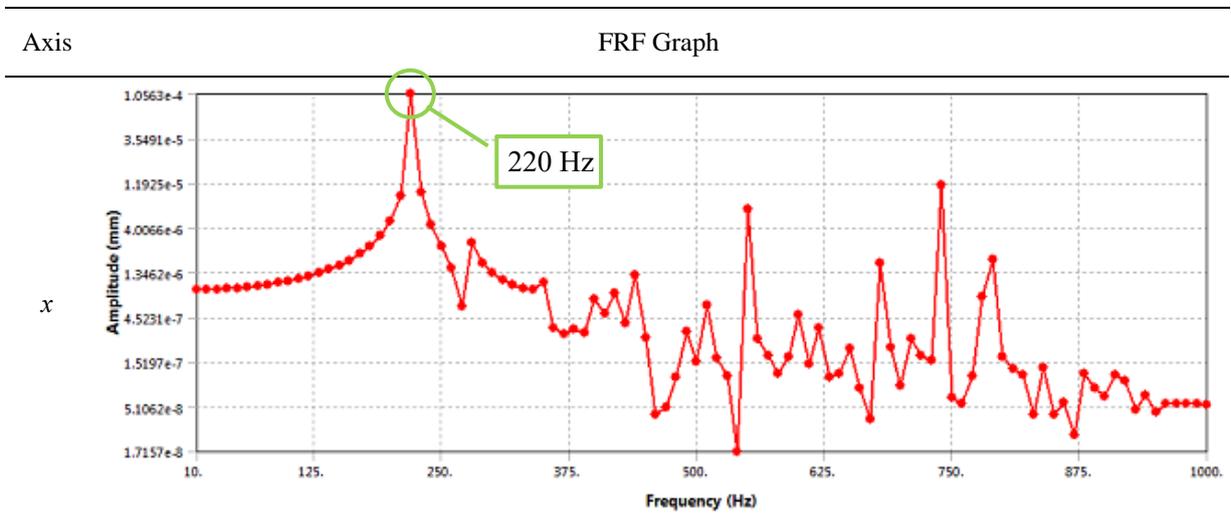
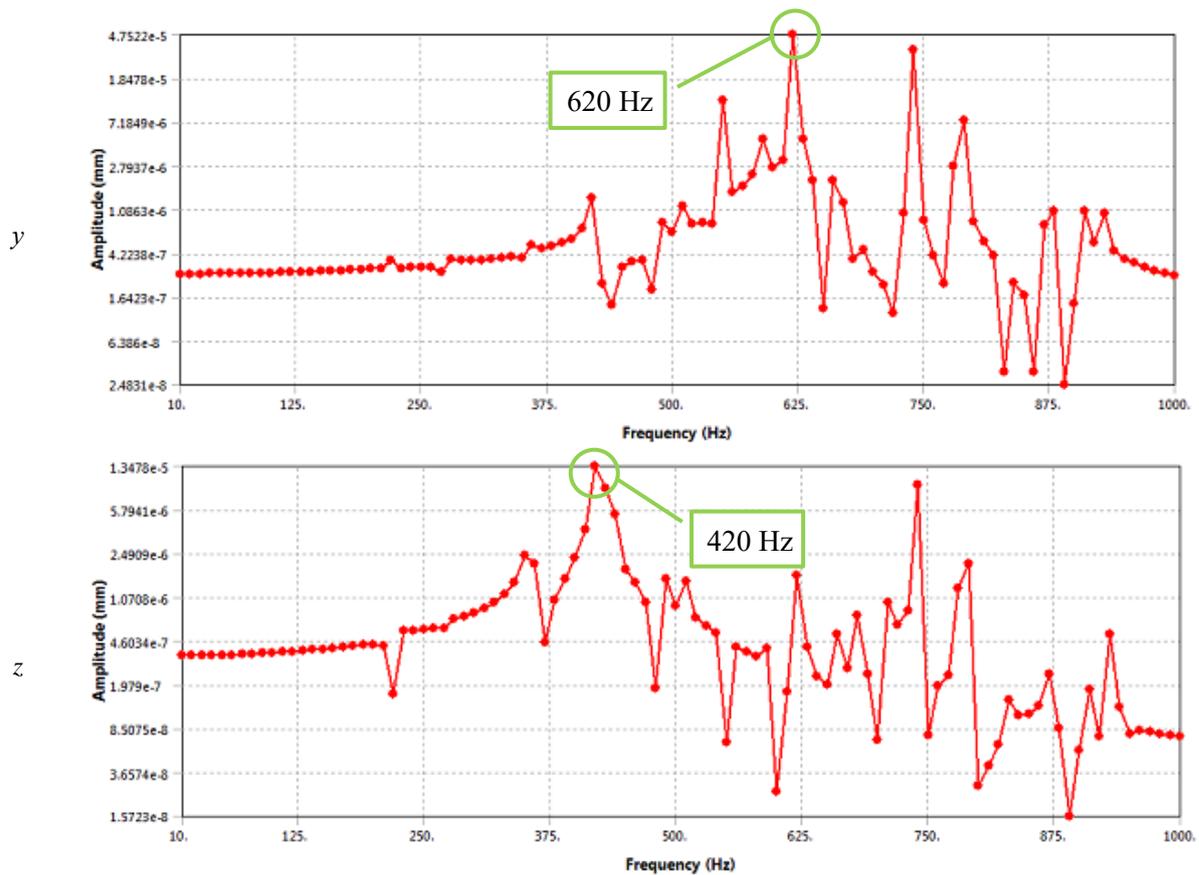


Table 2 shows the FRF of the spillway in x , y and z axes directions. The highest natural frequencies for each direction occurred at 220 Hz, 620 Hz and 420 Hz, respectively with the maximum deflection value of 1.056×10^{-4} mm, 4.75×10^{-5} mm and 1.35×10^{-5} mm. The most significant vibration occurred in x axis direction which 220 Hz of natural frequency and deflection of 1.056×10^{-4} mm.

Table 2. FRF graph of spillway in x , y and z axis.

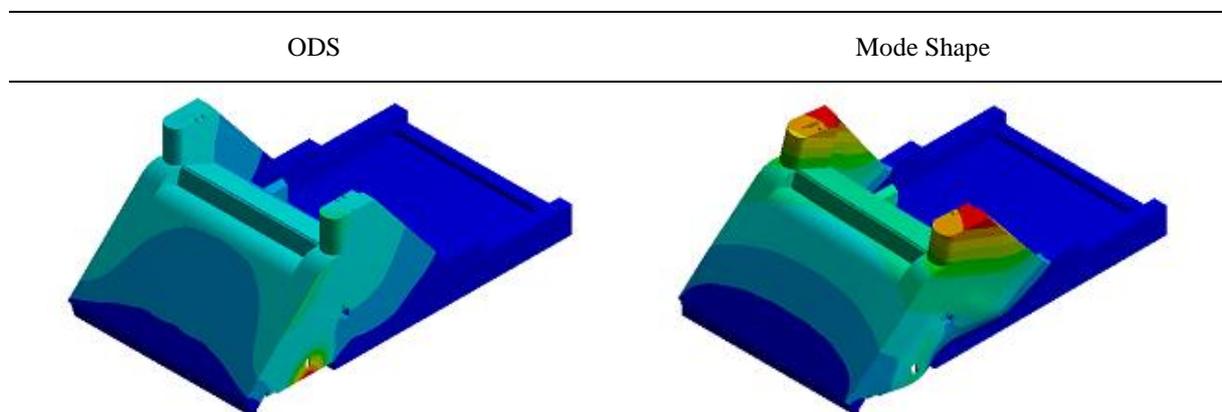


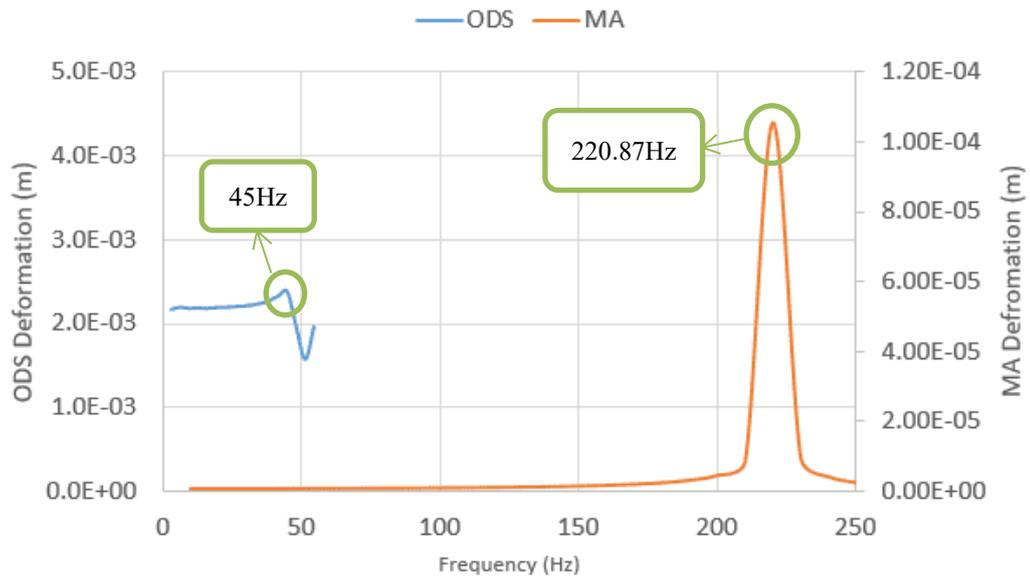


3.2. Comparison between MA and ODS of the spillway physical model

Based on the modal analysis result, any vibration or external force frequencies that occurred at 220.87 Hz must be avoided due to the resonance phenomena. Any vibration that occurs at 220.87 Hz frequency will cause the spillway of the dam to undergo failure. Based on the Table 3, the ODS result shows that, the deformation amplitude value of 0.003 mm occurred at the operating frequency of 45 Hz and this operating frequency is far from the natural frequency of 220.87 Hz. Thus, in this case the transient vibration will induce minimal effect to the spillway structure and the spillway is considered safe to operate.

Table 3. Relationship between ODS and mode shape of spillway model.





3.3. Experimental validation results of spillway physical model

From the EMA conducted at the front divider of the spillway section, the mode shape obtained can be observed in Figure 9 and it occurred at the natural frequency of 273 Hz. Whilst, for ODS, the result of comparison between simulation and experiment is shown in Figure 10. From the result, it can be said that both experiment and simulation are in acceptable range since both are operated in the range of 45 - 52 Hz (13 % of error) of operating frequencies and have an almost similar deflection shape. The amplitude for simulation is 0.0024 m whereas for experiment is in the range of 0.001 to 0.0025 m. Therefore, when the water is spilled from the upstream to downstream of the dam, the transient vibration effect at operating frequency of 52 Hz is not coincides with the natural frequency of 273 Hz. This will result in slightly deflection but there is no resonance phenomenon happened.

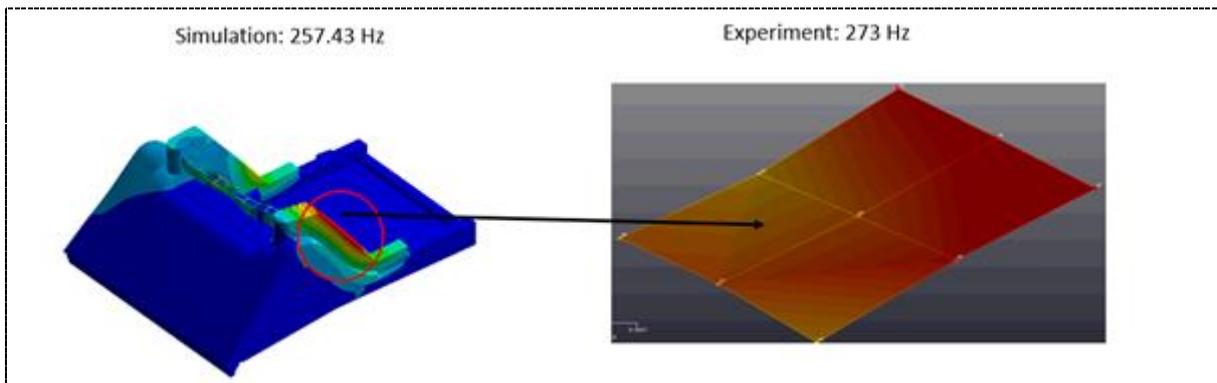


Figure 9. MA of spillway model (front divider) between simulation and experiment

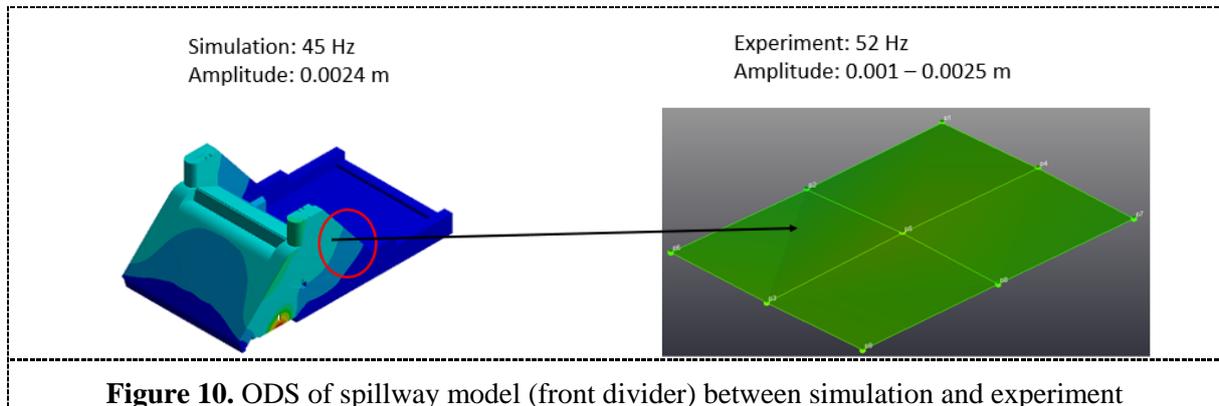


Table 4 shows the percentage differences between experiment and simulation result for the spillway section (front divider). The percentage differences for MA and ODS is 5.7 % and 13.46 %, respectively, which is generally below an acceptable error percentage of 20 %. From this result, the natural frequencies, mode shapes, operating frequency and ODS for the spillway section shows an agreement with the build physical model.

Table 4. Validation between experimental and simulation results.

	Experiment	Simulation	Percentage Differences
EMA	273 Hz	257.43 Hz	5.7 %
ODS	52 Hz	45 Hz	13.46 %

4. Conclusion

Based on this study, the following conclusions were drawn:

1. The modal analysis of the Chenderoh dam physical model (spillway section) has been successfully conducted. Tetrahedral meshing is used and six most significant natural frequencies of the spillway are determined. The highest natural frequency is at 4th mode number of 397.83 Hz with the deflection value 3.9 mm and the lowest natural frequency value is at 424.18 Hz with deflection value of 1.4 mm.
2. The ODS study from FSI of the dam spillway physical model has been successfully carried out. The operating frequency of 45 Hz has been achieved for the ODS with the deformation of 0.0024 m. By comparing the ODS and mode shape, it is realized that, the spillway of the dam is safe to run and there are no resonance phenomena.
3. The experimental validation of MA and ODS have been successfully carried out. The natural frequency and operating frequency obtained from EMA and ODS is 273 Hz and 52 Hz, respectively, which is 5.7 % and 13.46 % of percentage differences compared to the simulation results. The results of both experiment and simulation is acceptable since the percentage differences is below 20 %.

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