VIBRATION ANALYSIS OF THE DAM PHYSICAL MODEL DUE TO THE EFFECT OF WATER SPILLING

By

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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ACKNOWLEDGEMENT

I would like to express my deepest appreciation to god for providing me the wonderful opportunity and help me successfully complete my thesis writing. The masterpiece has led to the development of Chenderoh dam which is operated by Tenaga Nasional Berhad (TNB). Therefore, I would like to thank TNB for coming up with such project title. A very special gratitude I give to my final year project supervisor, Dr Ahmad Zhafran Ahmad Mazlan, whose contributed on guiding me throughout the project especially in writing report and preparing presentation slides. He also gives me suggestion and encouragement until the end of this project. Moreover, I would like to thank FYP coordinator, Dr Mohamad Ikhwan Zaini Ridzwan for helping me on thesis format and give me updates on important criteria for final year project.

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LIST OF SYMBOLS

λ	Scale ratio or scale factor
Lm	Characteristic length in real dam
Lp	Corresponding length in the model

LIST OF ABBREVIATIONS

FYP	Final Year Project
MA	Modal Analysis
ODS	Operational Deflection Shape
FSI	Fluid Structural Interaction
HSCC	High Strength Self-Compacting Concrete
EMA	Experimental Modal Analysis
FRF	Frequency Response Function
FFT	Fast Fourier Transform

ABSTRACT

A dynamic characteristic of the dam structure is one of important criterion that need to be investigated regularly in order to monitor the reliability of the dam structure. Chenderoh dam located in Perak, Malaysia is one of the oldest dam and there is a requirement to study the dynamic characteristic of the dam. In this study, a 3D scaled dam model of the Chenderoh dam is constructed and modal analysis (MA) of the spillway section of the dam in terms of natural frequencies, mode shapes and frequency response function (FRF) are investigated using ANSYS software. Then, the operational deflection shapes (ODS) during the spilling of water through fluid structure interaction (FSI) study is investigated. The physical model is build to validated the result of MA and ODS between simulation and experiment. The result of the study is important for any disturbances induced from the vibration of the dam in the future.

CHAPTER 1

INTRODUCTION

1.1 Background Study

Spillway is a transit of water excess from the upstream to the downstream of the dam. Every reservoir has storage limit to store the water. Overflow of water from the dam reservoir will take place during heavy rain or overabundance of water approaching from rivers. To avoid this situation, an overflow of large amount of water has to be channel from the upstream to the downstream of the dam and this can be done with the help of spillway. Spillway helps to channel the overabundance of water from the full reservoir to the downstream safely without any further damage done to the dam. A spillway can be design in two ways (gated or ungated) where it can be a part of dam or separate from it.

There are two types of spillway. One is controlled spillway (gated), and another is uncontrolled spillway (ungated). Uncontrolled spillway is where water automatically flow from the upstream to the downstream of the dam once the peak of reservoir is full. Whereas, controlled spillway is the type where gates are provided in order to control the passage of water excess from the reservoir. When the reservoir is full, the water level will be same with the peak level of the spillway and the gates are used to control the release of water to the downstream area. Figure 1.1 shows the Chenderoh Dam located in Perak, Malaysia and this dam is controlled with radial and sector gate. Most of the spillways are provided with gates for better control on the dam but manually operating gates will face some problem as access to the gates by labour may not be feasible all the time during rainy season or on the late night.

Chenderoh dam is a gravity type dam, which is a huge size dam that built from concrete material. Vibration on the dam spillway structures occurs during the opening of the gates for water spilling especially for a huge sized dams. Any vibration that is caused by water displacement velocities in the range of 5 to 15 mm/s is close to the acceptable limits according to German standard DIN 41501 (commonly used reference in the field of structural vibrations). There are several sources that are related to the flow induced vibrations on dam gates during the opening of water. These sources are instability induced excitation, externally induced excitation and motion induced excitation.

Figure 1.1 : Chenderoh Dam in Perak, Malaysia (Shahid, 2010)

1.2 Problem Statement

Unwanted force and vibration induced from the spilling of water from the upstream to the downstream area may cause some parts of the dam to be failed and eventually the dam might collapse if it induces significant vibration resonance phenomenon. Since the dam is too large for the overall vibration analysis, a scaled down physical model must be built to conduct a proper vibration analysis regarding the flow induced vibration at the spillway section of the dam. Hence, this tudy will investigated the effect of flow induced vibration and compare it with the natural frequencies of the spillway section of the Chenderoh dam physical model.

1.3 Objective

In this study, there are three main objectives are set to be achieved:

- To conduct the modal analysis for the spillway section of Chenderoh dam physical model.
- To study the flow induced vibration frequency from the Fluid-Structure Interaction (FSI) of the dam physical model.
- To validate the simulation and experimental results in term of vibration.

1.4 Scope of Work

This project involves the vibration measurement in terms of modal analysis (MA) and operational deflection shape (ODS) on a physical model and simulation of the dam model using ANSYS software which mainly on the spillway of the dam. SolidWork software is used to construct the 3D drawing of the spillway. Later it is transferred to ANSYS software for modal analysis and FSI study. The data of ODS and operational frequency will be compared with the natural frequency and mode shape of MA. Finally, both data from simulation and experiment will be compared and validated.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this chapter, the following topics will be discussed:

- Type of dams, materials and spillways
- Current problem of the dam
- Example of scaled-down physical model of the dam

2.2 Type of Dam, Materials and Spillways

Basically, there are two main types of hydropower dam. Firstly, the run-of-river hydropower dam which has the facility that passage the transmission of water from a waterway through a trench or penstock to turn turbine in order to generate electricity. There are several differences of run-of-river dam to other hydroelectric dam such as there is a little or no water storage in run-of-river dam. The behaviour of run-of-river dam is to generate electricity from natural or free flow of the water. However, the water will still experience some vertical fall as the dam is built in such natural landscape of places (Anderson, 2018). Figure 2.1 shows the detail visual of run-of-river hydroelectric dam

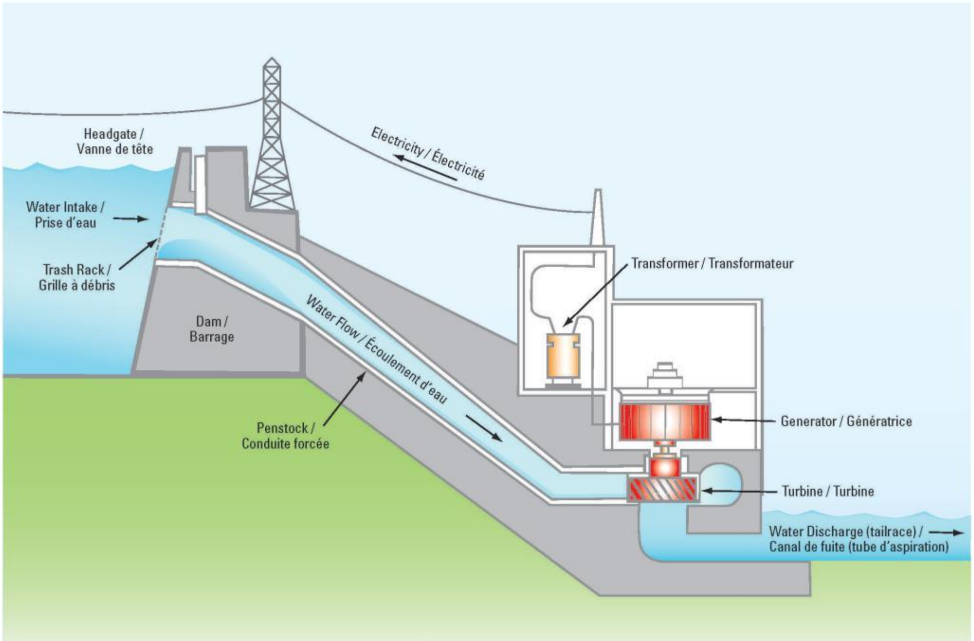


Figure 2.1 : Run-of-river hydroelectric dam (Anderson, 2018)

Chief Joseph Dam is an example of run-of-river hydropower dam. The material that used to build this dam is rock-filled concrete and the cemented rockfill. High-quality self-compacting concrete can be cemented with rockfill to build the gravity dams and arch dams. These type of rockfill dams are considered to be a durable and more economial. Stones with particle diameters size that have to be larger than 300mm are placed in layers which are 1.5-2.5m in height. The voids in the rockfill will be filled by pouring a great flow of high strength self- compacting concrete (HSCC) at the top of the rockfill. The stone size is important as it should not be too big or too small and this is to ensure better filling performance of the HSCC (F.Jin, 2005) . By summing up all this criteria, the thick slab will have advantages of low permeability, sufficient strength to bridge subsided areas of the face, high resistance to weathering and sufficient flexibility to tolerate small barrier settlement. The type of spillway that used to build in this dam is called chute spillway. A chute spillway consist of a open channel, which the water discharge continuously. The main function of having chute spillway is to prevent any damage at the low area of the dam’s wall. The chute spillway has a certain steeply angle of water passage from upstream to downstream. Usually this type of spillway have very narrow pathways for the water flow and widened at the end of the spillway to reduce the velocity of water.

Secondly, the storage hydropower dam which is typically a large system that uses a dam to store water in a reservoir. This type of dam system works by releasing water from the reservoir through a turbine, which activates a generator to produce electricity. Storage hydropower provides base load as well as the capability of shutting down and starting back at short notice according to the request if the system is on peak load. The storage capacity of the hydropower is good enough to operate the dam continuously and independently for many weeks or few months (D.Y.Sun, 2017). For example, Chenderoh dam is one of the storage hydropower that produced electricity by releasing water from the reservoir. Chenderoh dam is build using fully concrete gravity material. This material has high level of safety. A genuine debacle won’t happen in this kind of dam, regardless of the weather or any climate changes. In addition, the dam with this material can withstand the sudden impact of water surging and the maintenance cost is low. Any dam failure will not leave high negative impact compare to other types of dams and material(J.B. Xie, 2009). The shape of Chenderoh dam spillway is ogee-shaped and it is most common used spillway. It is mostly designed with gravity dams, arch dams and buttress dams. There are few types of crest as shown in Figure 2.2 for ogee shape dam. Different types of crest will influences the velocity to approach the crest area. This will have different impact on discharge efficiencies. Moreover the effect of downstream is also depends on the velocity approach at the crest. Figure 2.3 shows the cross section of spillway and the gated crests. A partial or full gate opening will change the velocity of water flow from upstream to the downstream.

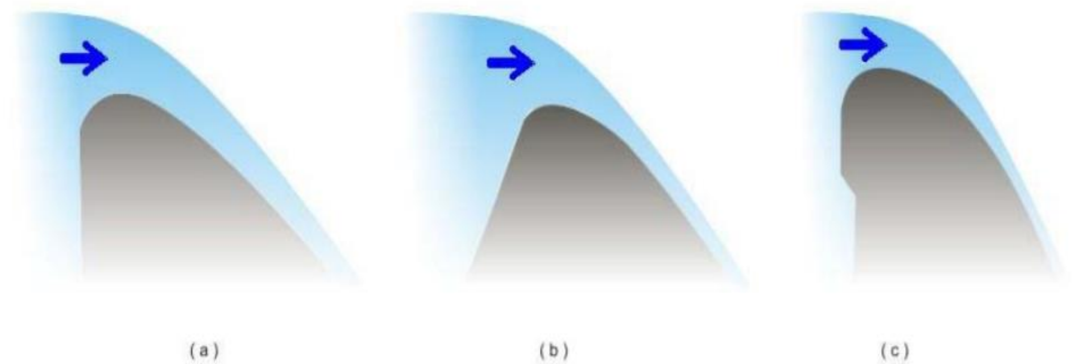


Figure 2.2 : Ogee crest control weirs with (a) Vertical upstream face (b) Inclined upstream face (c) Overhangs on the upstream (kharagpur, 2015)

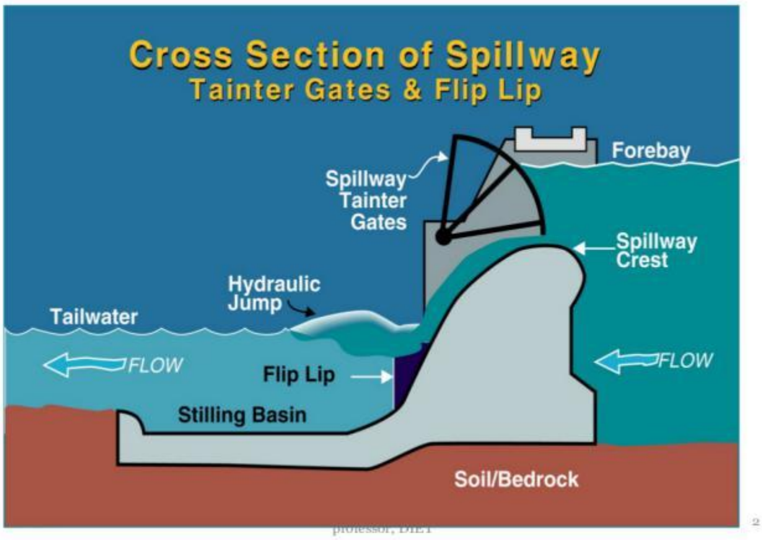


Figure 2.3 : Cross section of ogee-crest spillway (H., 2010)

2.3 Current Problem of the Dam

There is one report on the dam failure which is the Oroville Dam main spillway in February, 9, 2017 due to the leaking of water flow through the tiny holes from the dam spillway. This incident involved design and maintenance, including thin concrete, inadequate reinforcing steel and weaknesses in the foundation.

The spillway is a key part of the dam that plays major role in releasing the water when the reservoir is full or almost full. Besides, there is a large differences of the water pressure on the dam. Water pressure will increased as the flow of water is stop by a radial gate and the pressure will drops immediately when the water is release. This behavior cause the failure of Oroville spillway when dam operators opened gates that sent 55, 000 cubic feet or water per second roaring out of the reservoir after days of continuous rain drenched the Feather River watershed. The entire lower section of the spillway eroded away, and the rushing water is then eroded soft rock on the slope. Figure 2.4 shows the failure of Oroville dam (Vartabedian, 2017). Large variation in the thickness of the spillway's slab and lack of proper reinforcement along the slab causes the water seepage trickle from the spillway.

Figure 2.4 : The failure of Oroville dam's spillway (Patterson, 2018)

Furthermore, the gate opening management of the dam can cause significant problem which ended up causing structural damage or restrict operation at certain gate openings. The existing risk of gate vibration is mostly uninformed to the operators.

Hearing the humming loud noise, feeling the vibration at the walkway of spillway and observing wave formation at the water storage or reservoir is few methods of identifying vibration by operating employees. In some cases, vibration of the gates will happen under particular hydraulic conditions. Clearly unfaltering state conditions might be liable to minor hydraulic aggravations which defeat the damping forces acting on the gate and start the unsteady movement, which contribute to oscillation of increasing magnitude (Pickering, 1971). Various sources can cause gate vibration and one of it is side seal. There are other causes of gate vibration which are eddy shedding, off-centre trunnions, and venting overflow of gates.

Flow induced vibration is most common and important factor that causes damage to the spillway of the dam. This vibration is influenced by the change of pressure throughout the spillway structure which create the Newtonian force (Wachel et al., 1990). Consequently, a non-balanced force starts to evolve and the wall of spillway structure begin to vibrate. As the flow induced vibration frequency is same to the structural natural frequency, the acting force will be bigger than the force that caused by pressure differential (Mao et al., 2003).

2.4 Example of Scale-Down Physical Model of the Dam

It is very common for physical model of large objects to be scaled down and smaller objects scaled up for ease of visualization. This is done to test various aspects of a product against user requirements. Physical modelling not only allows designers to explore and test their ideas, but also to present them to others.

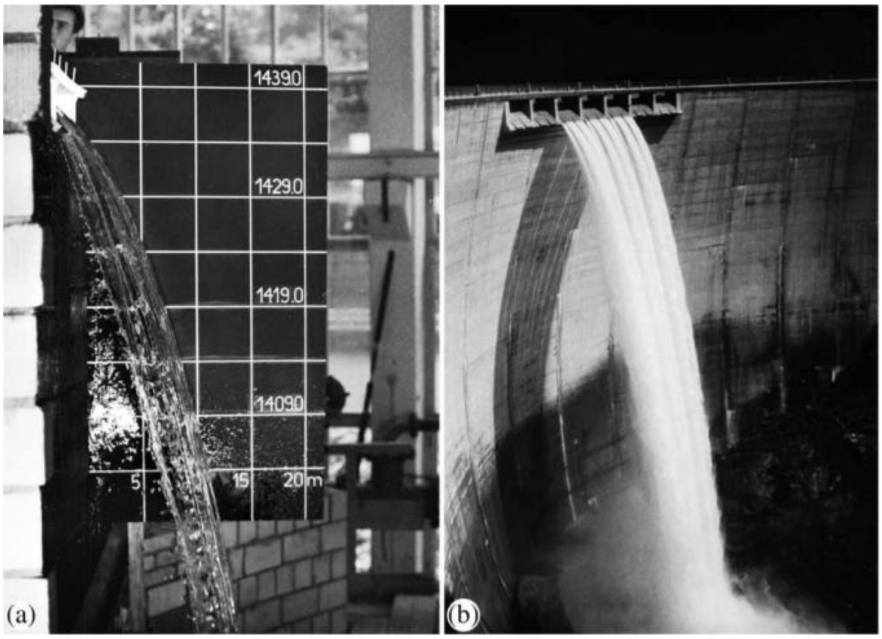


Figure2.5 : Overflow spillway of Gebidem Dam, Valais, Switzerland.(a) Physical hydraulic model at scale 1:30.(b) Real Dam (Stol'nikov, 1968)

Figure 2.5 shows the overflow spillway of Gebidem Dam and a physical hydraulic model at scale of 1:30 (Novák and Cabelka, 1981). The scale effects for a specific phenomenon increased with the scale ratio or scale factor as shown in following equation :

$$\lambda = \frac{L_P}{L_M} \qquad (2.1)$$

Where Lp is the characteristic length in the real dam and Lm is the corresponding length in the model. The inverse of equation (2.1) defined as the scaled $1:\lambda$. In scaled effects, there are four element that we have to emphasize. Firstly, a model with $\lambda \neq 1$ always results in scale effects if the same model fluid is employed since only on of the relevant force ratios can be satisfied. Secondly, the larger the scale ratio λ, the more incorrect modeled force ratios deviate from the prototype ratios. Thirdly, the size of scale effects depends on the investigated phenomenon or parameter in a given model study since the relative importance of the involved forces may differ. One parameter is not considerably affected by scale effects, and it does not necessarily mean that other parameters are also not affected. Finally, the fluid forces in the model are more dominant than in the real dam where the scale effects normally have a ‘damping’ effect (Novak, 1984). The basic of the similarity theory between physical hydraulic models and real-world prototype have been reviewed including mechanical, Froude and Reynolds similarities (Kundu, 2004). The most relevant force ratios to obtain the dynamic similarity including the Froude, Reynolds, Weber, Cauchy and Euler numbers. Four approaches namely inspectional analysis, dimensional analysis, calibration and scale series are available to obtain the model-prototype similarity.

2.5 Summary

From the literature, it can be summarized that there are two main types of spillway and hydropower dam around the world. Besides, storage hydropower dam is widely used with reinforced concrete slab material which has high durability that is used to construct a bigger scale of dam structure. In this literature study, it was abstract that the common problem faced by the dam is mainly on vibration upon large releasing of water. Flow induced vibration can also cause failure to the dam. In addition, the gate vibration can arise as there is improper gate seals at the peak of dam. Finally, scale down physical model of the dam plays major role in this study by allowing researcher to explore, test their ideas and also present them to others.

CHAPTER 3

METHODOLOGY

3.1 Overview

In this section, the methodology of the study is presented including :

- 3D drawing of the spillway
- Modal analysis of the spillway
- FSI study of the spillway
- Experimental validation method

Figure 3.1 shows the flowchart of the methodology for this study.

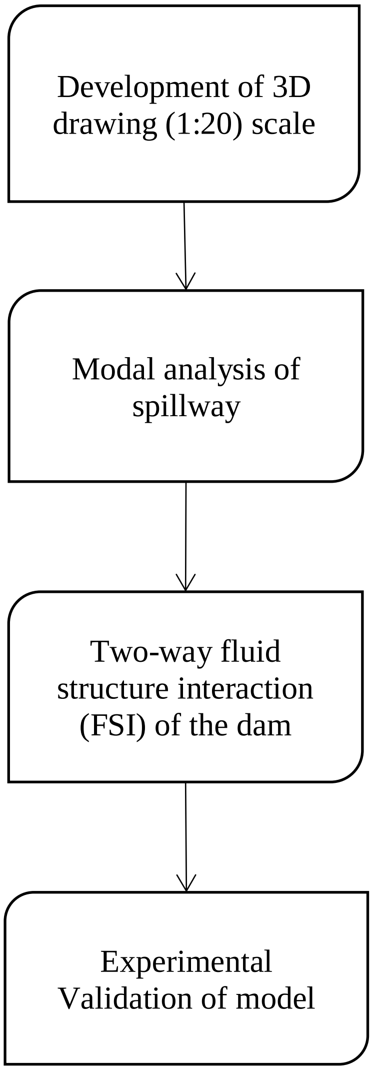
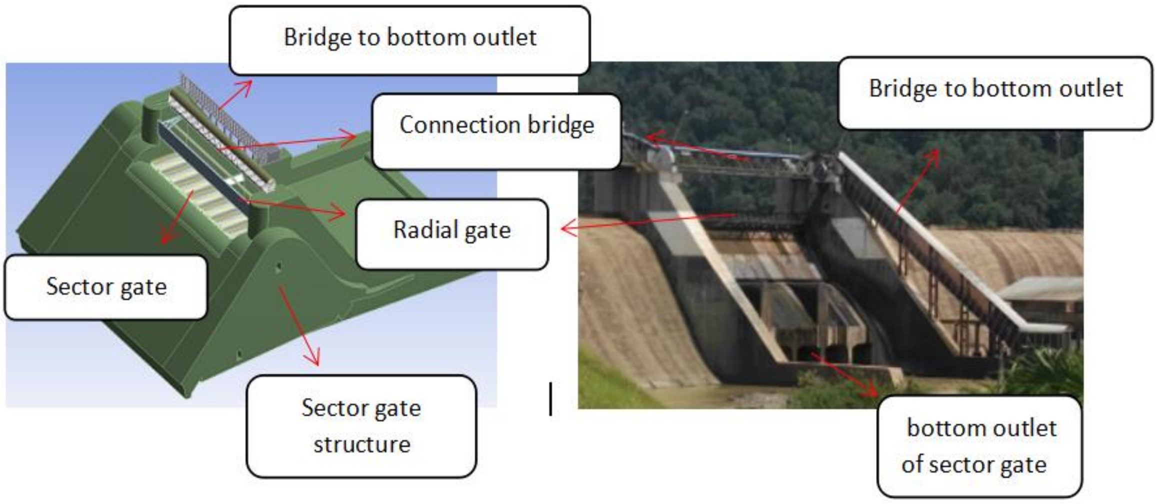


Figure 3.1 Flowchart of the methodology

3.2 3D model of the Spillway Section of Chenderoh Dam Physical Model

Spillway is a dam structure used to provide the controlled release of water from the upstream to downstream area. It is also known as a passageway which surplus water escape based on the opening distance between head gate and sector gate. It usually located in the middle of the overall dam structure. For normal release of water condition, only radial gate is operated. When there is an emergency condition, both radial and sector gates are fully opened to release the water. It is expected that different gate opening will induce different vibrational forces to the whole dam structure.



(a) (b)

Figure 3.2 (a) 3D model of spillway section and (b) real picture of spillway

Figure 3.1 (a) and (b) shows the scaled down model and the real picture of the Chenderoh dam spillway section. This spillway section include the parts such as sector gate, radial gate, connection bridge and sector gate structure. The 3D model has been constructed including all the important dimensions using SolidWork software.

3.3 Modal analysis of the spillway model

For the modal analysis, the modal toolbox is selected from the ANSYS workbench as shown in Figure 3.3. In engineering data selection, the desired material is selected according to the real structure material. In this case, the cemented material with Young's modulus of E = 30 Mpa is selected for the main spillway structure. The steel material is selected for other parts such as radial gate, sector gate and support while the desired geometry is imported and meshed. The boundary condition is fixed for all bottom layer of the spillway to represented the foundation of real dam, as show in Figure 3.4. From this study, the natural frequencies and mode shapes of the spillway can be determined (Brebbia and Dominguez, 1994).

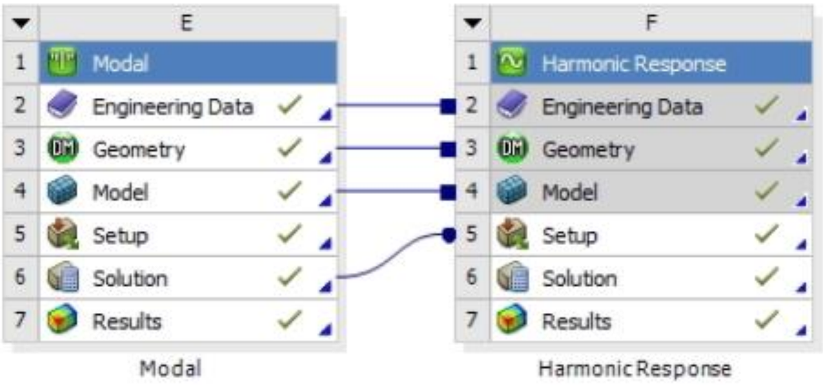


Figure 3.3 : Overview of modal and harmonic analysis using ANSYS workbench

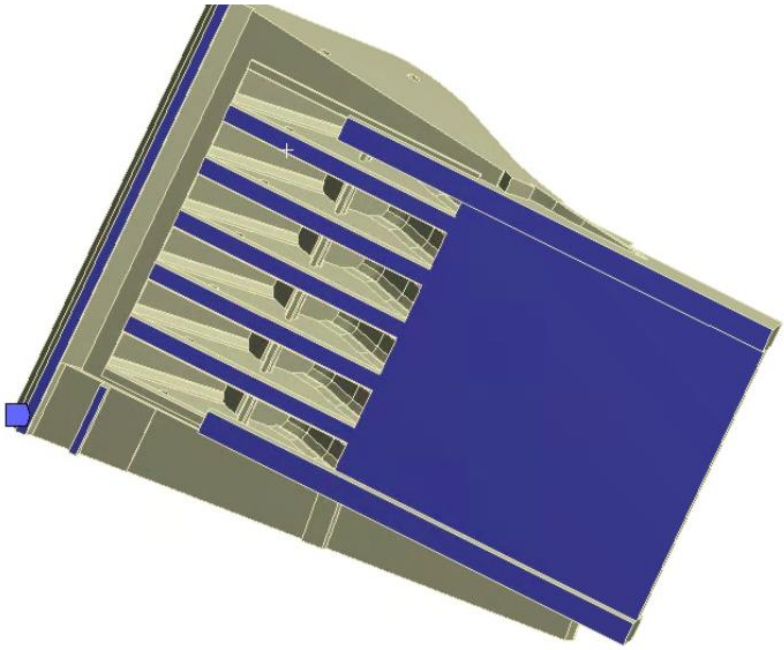


Figure 3.4 : Boundary condition of spillway (Fixed base)

3.4 Fluid-Structure Interaction (FSI) of the spillway model

For the FSI simulation study, there are three main elements needed as shown in Figure 3.5. First is the transient structural which used to study the frequency of the structure when fluid flow is act in the dam structure. Secondly, is the fluent where the flow and type of fluid that going to act on the dam structure are set. 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. Two way of coupling solution is more accurate and more stable whereas, one way method has lower computational cost.

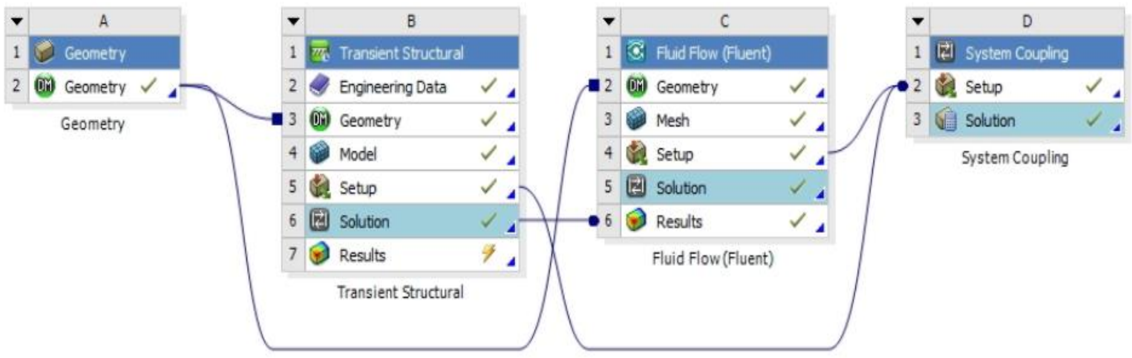


Figure 3.5 : Linked setup of ANSYS workbench for FSI study

For complicated design and structure, hexahedral mesh is used over tetrahedral mesh to capture all the flow features due to its high accuracy and time saving properties which is more handy when it comes to collecting of data. 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 1, 1 and 500 consequently. Boundary condition for the transient analysis is similar as 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 3.6. The velocity magnitude of fluid is set to $1 \mathrm{m/s^2}$ and the fluid is modelled as incompressible flow with pressure based solver. Figure 3.7 shows the fluid domain of the spillway section.

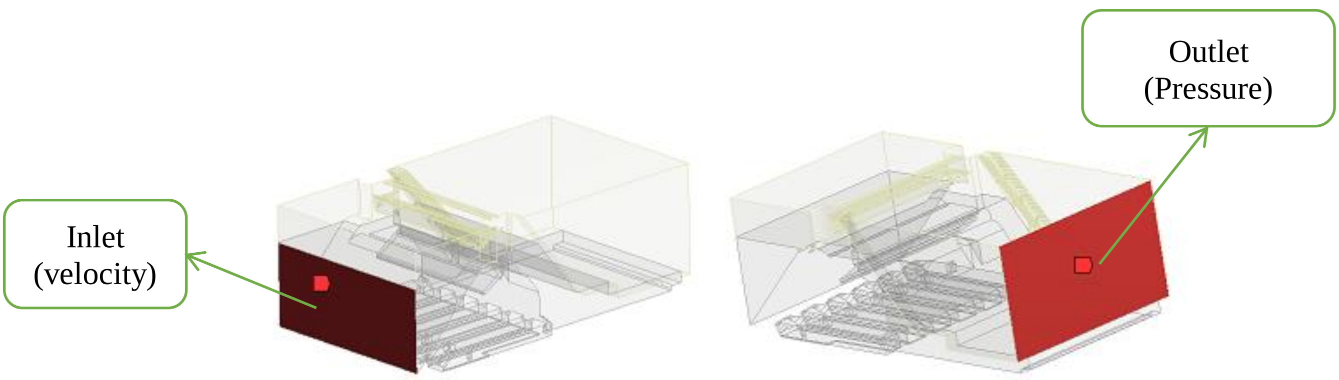


Figure 3.6 Inlet (left) and outlet (right) section for the spillway part

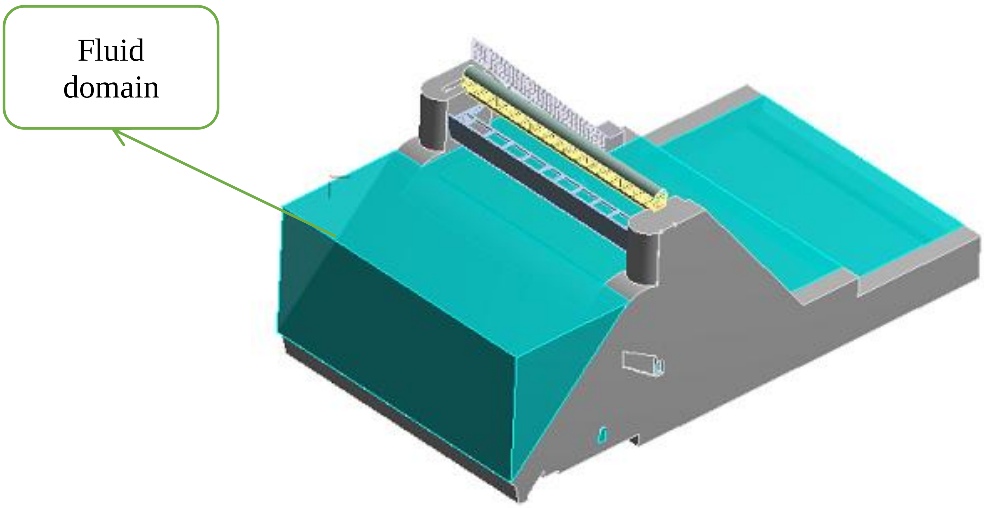


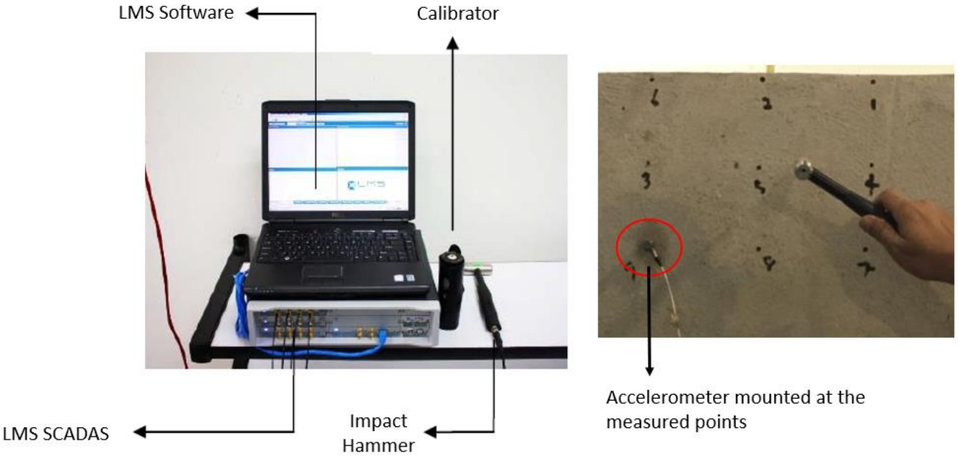
Figure 3.7 Fluid domain of spillway section

3.5 Experimental validation of the model

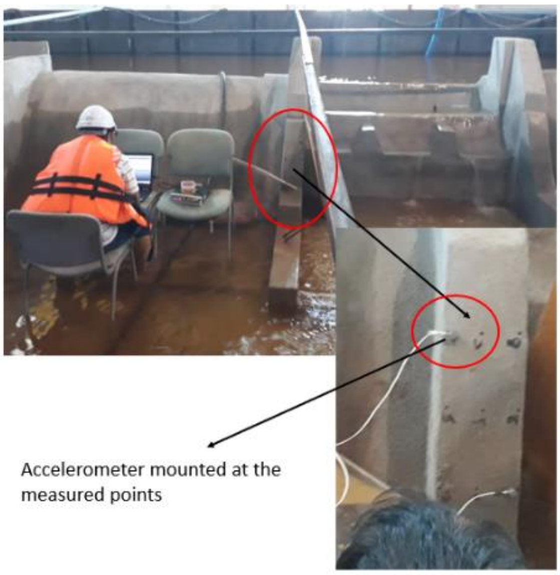
In this section, the experimental modal analysis (EMA) is carried out using LMS Test Lab software. The result obtained was then compared with the ANSYS simulation using concrete material of E = 30 GPa. Both results are compared in term of natural frequencies and mode shapes.

The setup of EMA is shown in Figure 3.8 (a). For EMA, an impact hammer is used to provide the input force to the structure and accelerometer is mounted to the particular node. The function of accelerometer is to measure the acceleration introduced from the structure vibration. To obtained 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 better outcome.

Apart from EMA, ODS setup is almost identical except it operates with different software. Consequently, ODS measurement is perform 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 3.8 (b) 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.



(a)



(b)

Figure 3.8 : Experiment setup of (a) EMA and (b) ODS

CHAPTER 4

Result and Discussion

4.1 Overview

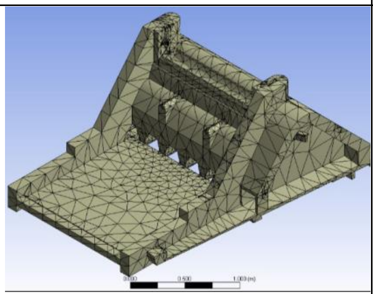
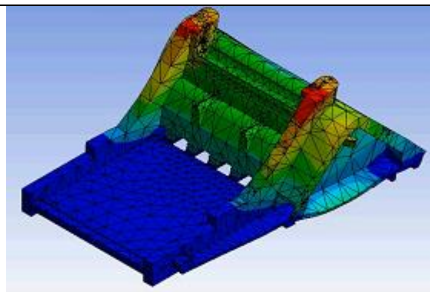
In this chapter, the following results will be discussed :

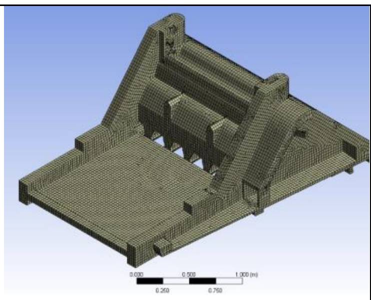
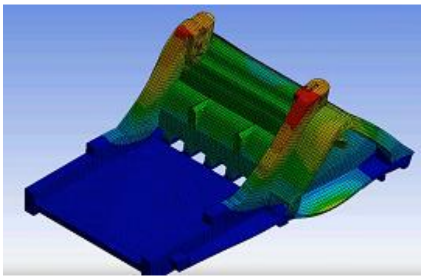
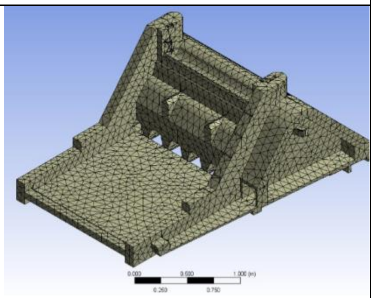
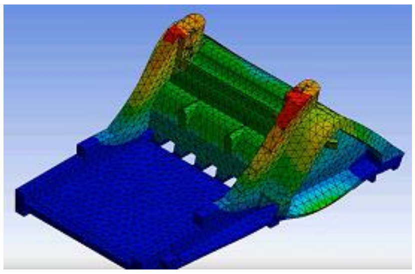
- Modal analysis of the spillway model
- ODS of the spillway model
- Experimental validation results

4.2 Modal Analysis of the spillway model

Table 4.1 shows the three types of meshing and their corresponding natural frequency results for the spillway model of dam structure. The automatic mesh generates natural frequency of 119.2 Hz whereas for hex dominant and tetrahedral mesh, the natural frequency is 115.7 Hz. Hence, both hex dominant and tetrahedral mesh is reliable for this simulation process. Hex dominant is preferred to be used in this dam simulation study compared with tetrahedral due to the complicated large scale of structure where the simulation can be run in shorter time. The graph of the meshing sensitivity analysis is also shown below in Figure 4.1.

Table 4.1 : Comparison of different type of meshing and the natural frequencies for 1:20 scale of spillway model

Types of Meshing	Meshing Pictures	1st Natural Frequency	Mode Shapes
Automatic		119.2 Hz	

Hexahedral		**115.7 Hz**	
Tetrahedral		115.7 Hz	

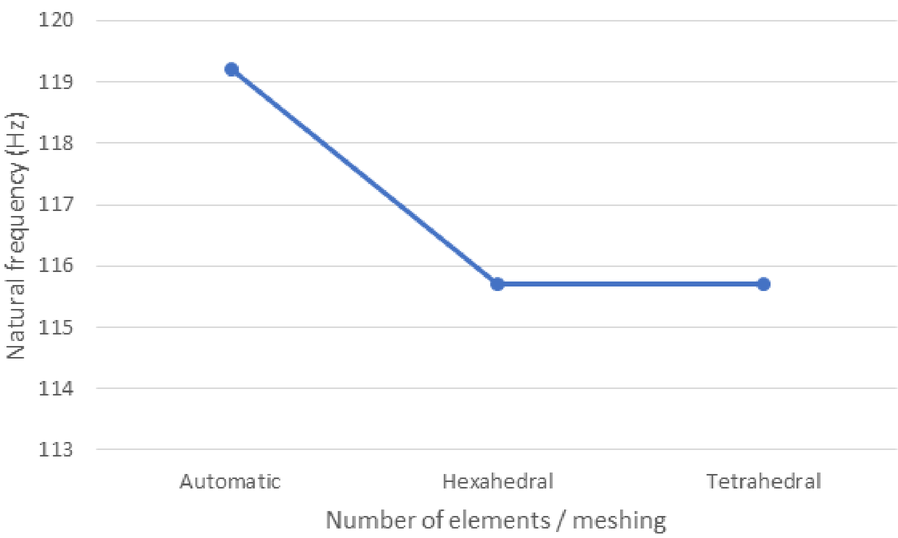


Figure 4.1 : Meshing sensitivity analysis (1:20 scale)

Figure 4.2 shows the meshing of spillway model for the scale of 1:20. The number of meshing element as shown in the figure is above 300000 element units. In this project, two types of studies have been carried out. Firstly, the general modal analysis to find the six most significant natural frequencies of the spillway and secondly is the harmonic analysis to obtain the frequency response function (FRF) graph in three (X, Y, and Z) axes direction.

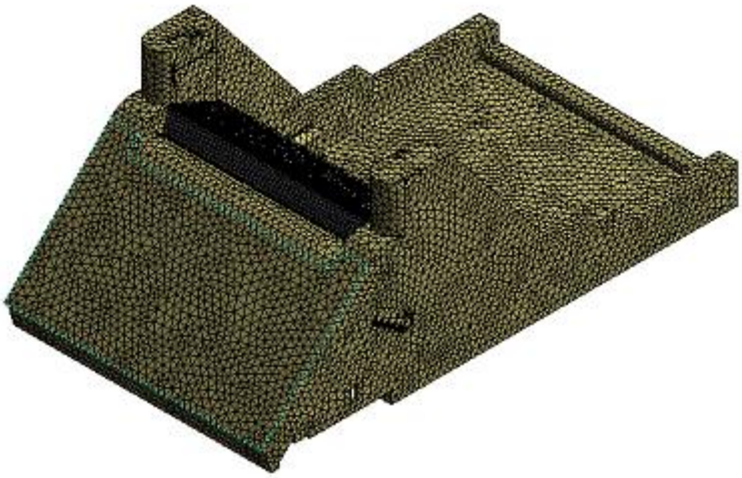
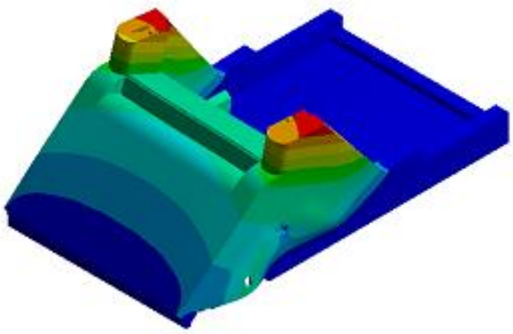


Figure 4.2 : Meshing picture of the spillway

Table 4.2 shows the six most significant natural frequencies and mode shapes of the spillway section. The 1st mode take place at the natural frequency of 220.87 Hz with the maximum deflection value of 1.6mm. 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 3.9mm. The red colour zone on the spillway structure indicates the highest or maximum deflection of the part.

Table 4.2 First six most significant frequencies and the mode shapes

Modes No.	**Mode Shapes**	**Natural Frequency**	**Deflection Values**
1		220.87 Hz	1.6 mm

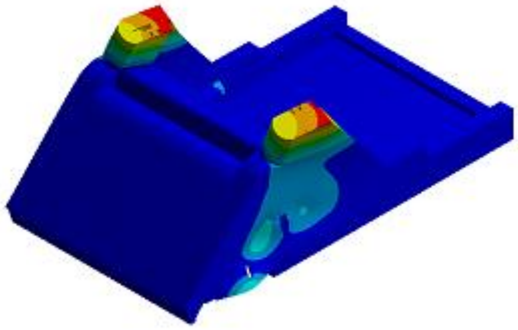
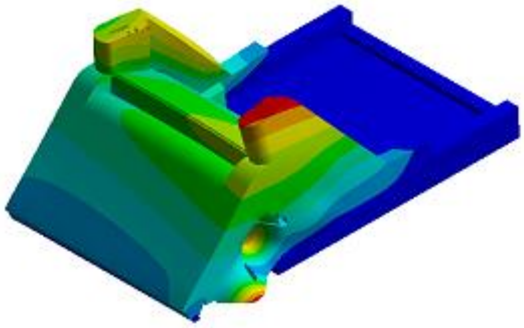
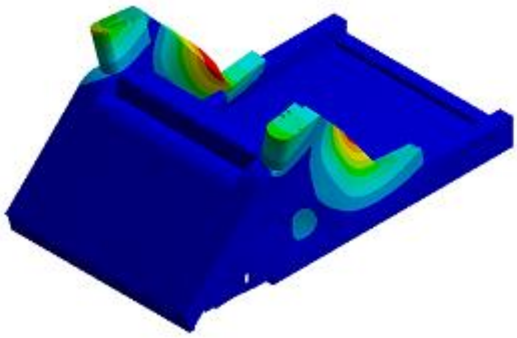
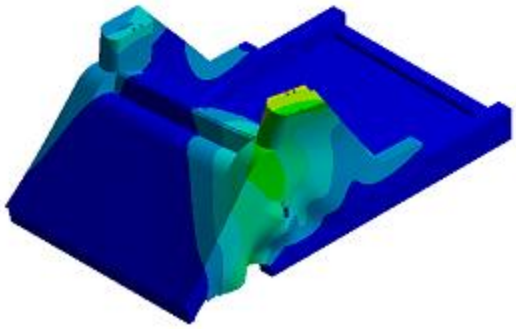
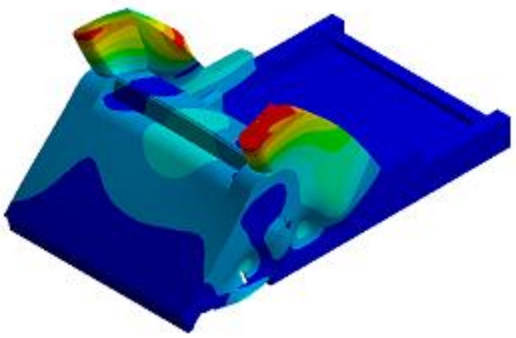
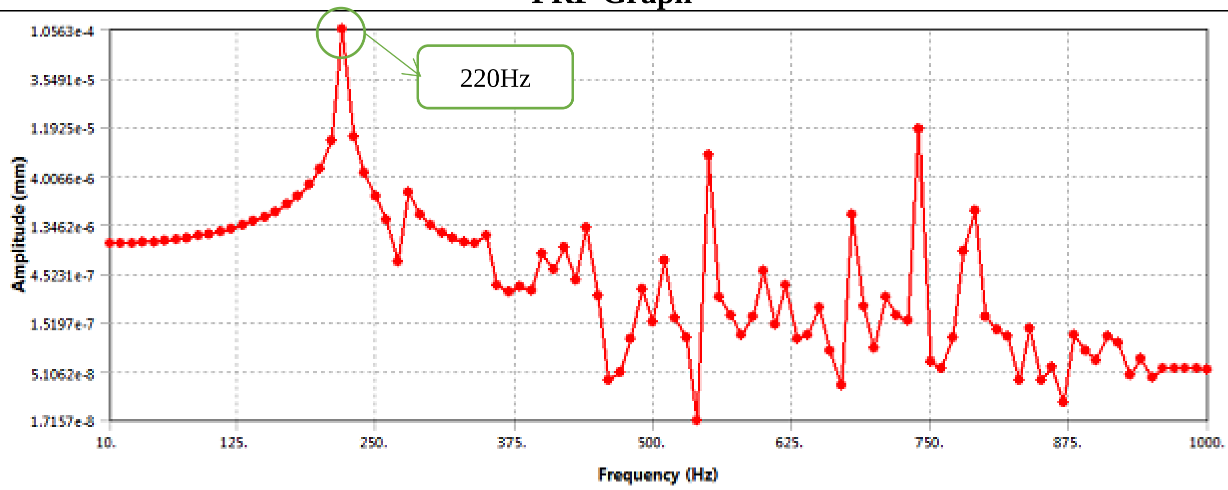
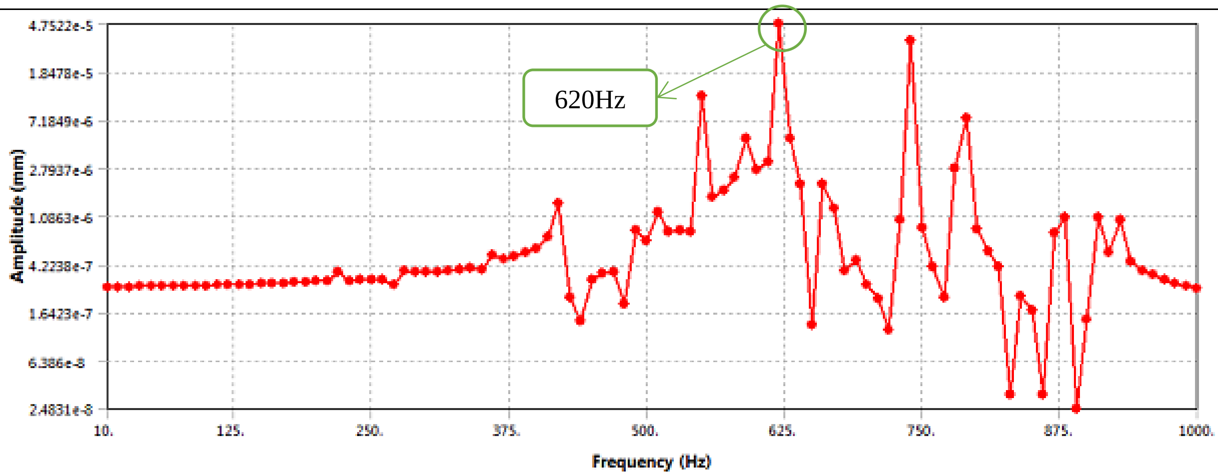
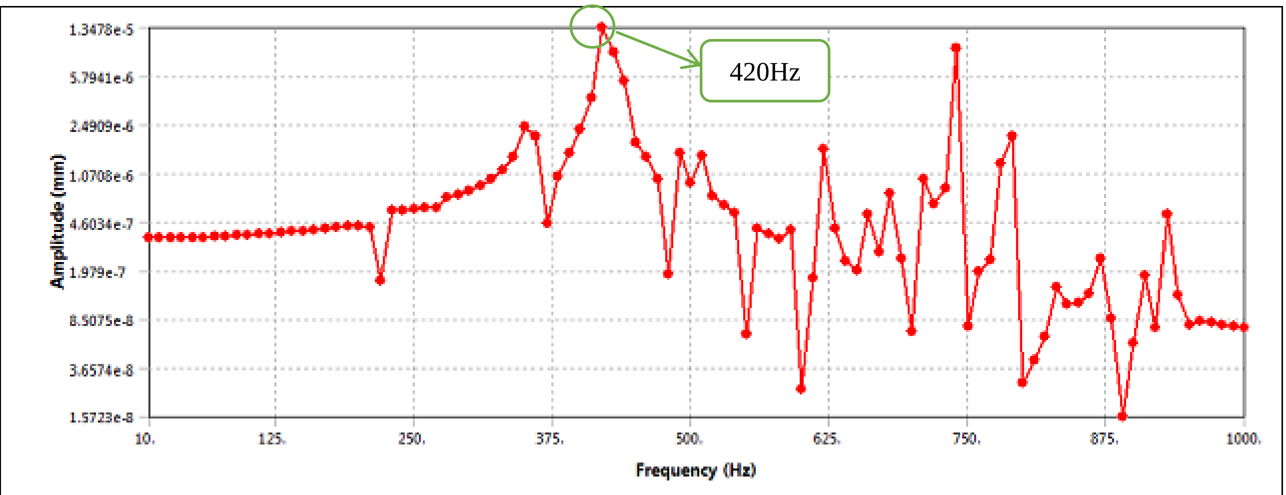
4		397.83 Hz	3.9 mm
5		424.18 Hz	1.4 mm
8		484.64 Hz	3.8 mm
11		593.2 Hz	3.2 mm
17		705.61 Hz	2.5 mm

Table 4.3 shows the FRF of the spillway in X,Y and Z axes direction. The highest natural frequencies of X, Y and Z direction occurred at 220 Hz, 620 Hz and 420 Hz, respectively with the maximum deflection value of 1.056 x 10^{-4} mm, 4.75 x 10^{-5} mm and 1.35 x 10^{-5} mm . The most significant vibration occurred in X axis direction which at 220 Hz of natural frequency with the highest deflection of 1.056 x 10^{-4} mm.

Table 4.3 FRF graph of spillway in X, Y and Z direction

Direction	FRF Graph
x	
y	

z	

4.3 ODS of the spillway model during water spilling

Two way FSI study was performed for the scale 1:20 scale of spillway model using ANSYS software. This study was carried out to determine the deflection shape of the dam when there is external force or vibration induced. The results that obtained from FSI simulation is in time-domain form. Using the Fast Fourier Transform (FFT) method in Microsoft Excel, the time-domain data from the simulation was converted into frequency-domain. Moreover, this study conducted for the purpose of finding the effect of water spilling of the spillway. The detail results of ODS will be discussed in Section 4.3.1 below.

4.3.1 Comparison between MA and ODS of the spillway model

From the modal analysis result, any vibration or external force frequency that occurred at 220.87 Hz have to 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 4.4, the ODS result shows that the deformation amplitude value of 0.003mm 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