Dynamic Analysis of High Frequency Vibro-Impact Drilling

Prepared By:

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Dissertation submitted in partial fulfilment of
the requirement for the
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
Univrtsiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL)

Approved by,

____

(DR. Setyamartana Parman)

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CERTIFICATION OF ORGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein has not been undertaken or done by unspecified sources or persons.

(PRATHAB A/L MUNIANDY)

ABSTRACT

Vibro-impact drilling system modelling is a research and results of the selected models which is more complex model known as three mass model. As we know that this model is invented to prove the dynamic relationship between the drilled formation and drill bit. The static force, excitation frequency and the excitation amplitude is the main three main control parameters. The investigation ensures that rate of progression is varied by the three main parameters. Higher the static force and excitation amplitude, the best progression rate can be achieved. Thus, in this case, the static force is linear with excitation of amplitude. However, the lower value of excitation and increases in excitation of frequency with the decrease in static force, the result shows zero progression rate. Thus, this concludes the zero progression rate at higher excitation frequency for this models. As based on analysis, the model uses the resonance enhanced drilling (RED) technique for forming resonance state by using the adjustable high dynamic stress to improve the rate of progression. The simulation for the vibro-impact drilling motion is obtained by solving the equation of motion using MATLAB software.

ACKNOWLEDGEMENT

Firstly, I am grateful to do and complete my Final Year Project (FYP) II semester. It is my great opportunity to work on this project and I am glad to extend my highest appreciation to my FYP supervisor, Dr Setyamartana Parman, who have sincerely guiding and coaching me throughout these two semesters. I would grab this chance to direct my thankfulness to my superior for giving me the opportunity and also contribute to my self-development with his constant motivation until the end of the project.

I would like to extend my gratefulness to my examiner, Dr. Tamiru Alemu on behalf of giving proper comments to improve my project and give idea to make sure my project is complete and verified in both Final Year Project 1 and 2. I appreciate their concern on my development and all the information gain is worth-full.

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DEFINITION OF VARIABLES

$K_{1,2,3}$	Spring stiffness, N/m
$M_{1,2,3}$	Model mass, kg
C_1	Coefficient of damping of rock, Ns^2/m
$C_{2,3}$	Coefficient of damping, Ns^2/m
P_r	Resistive force, N
X_t	Surface of rock, m
X_b	Displacement of slider, m
P_c	Contact force, N
G	Initial gap, m
LVDT	An acronym for Linear Variable Differential Transformer
t	Time (seconds)
Ω_0	Natural Frequency
Φ	Initial Phase (rad)
F_0	Excitation force amplitude, N

CHAPTER 1: INTRODUCTION

1. 1 BACKGROUND STUDY

The cutting method that uses drill bits to cut or increase a hole about round cross-section in hard tools is known as drilling. The equipment for drilling is the rotary cutting tools that comes with different technologies and its often multipoint. The drill bits which also known as the rotary cutting tool is pushed alongside the rock block and spins at the rate of hundreds to thousands of revolution per minute. This process causes the forces to cut effective against the rock block to form a hole while it's been drilled.

There are many types of drilling in order to extract oil and gas through the layer of rocks and it can be done in onshore and offshore. They are spot drilling, center drilling, deep hole drilling, gun drilling, trepanning, micro-drilling and finally vibration drilling. In the 1950s, the first study of vibration drilling has begun. In generating the axial vibrations is the main standard to feed the drive of the drill to break the chips apart. Thus, it can be removed easily from the cutting zone.

The techniques involving the function of a vibrator to induce oscillations of the drilling tool is vibration drilling. The depth of 20-30m in soft rock is carried out through the vibration drilling process without rotating the cutting tool. As the depth is deeper than 30 meter, the rotary cutting tools and vibration on the hard rock works simultaneously. Usually the vibrator of directly-acting mechanical is placed above the cutting tool. The mounted shock absorber above the vibrator are used to shield the drill pipes from harmful damage from the effect of vibration during deep drilling.

Vibration drilling increases the bit life without any adverse effect on the other performance indexes in deep holes for percussion rotary drilling. The construction of reliable vibrators is the main problem with regard to further improvement of drilling. Vibration drilling is used in geological surveys, in the construction of deep-set supports and also in drilling for oil and gas.

Moreover, there are two main technologies for vibration drilling. The technology are the self-maintained vibration systems and forced vibration system. In the case of self-maintained vibration drilling, the frequency by mas-spring system which have included in the tool holder. It allows high frequency for small magnitude. They only suitable for drilling small holes. By mechanical system, vibration can be generated. However, through revolution speed and the oscillation number per rotation, the frequency can be analyzed. On the other hand, the vibration drilling is meant for situation such as deep hole drilling, stack drilling of multi-material and dry drilling which is without lubricant. This is can generally provide an improved reliability and greater control of drilling operation. For the forced vibration system, it is produced due to the rotation of the rotary cutting tool. These vibrations have high frequency of excitation and caused due to high speed of rotary tools.

As facing the real situation, the vibratory drill head produces high frequency resonant vibration from the drill string until the drill bit. In this case, the operator plays an important role to control these frequencies according to the specific condition of the rock. The drill head could also generate vibration and it can vary by the operator.

The amplitude of the drill bit is magnified by the resonance. As the soil particles is fluidized at the bit head, there will be fast and easy penetration through the layer of soils. The vibrational forces from the rest of the drill rig is isolated by the internal spring system.

There is more to explore in vibration drilling such the vibro-impact system. The system had known to layman and children before they were considered by the science world. The excited vibration that combines with the weight, impact and also friction in the woodpecker toy. It has the dynamic which was analyzed with one-dimensional of Poincare's map.

In facts, the system forms the jumps in state of space that involves multiple interaction. Due the impact caused, there enormous waste of energy and in terms of coefficient of restitution, the degree of energy also dissipates. Vibro-impact is measured before in contact with the rock, during the impact take place with no progression and finally the contact with progression. The time scale of natural frequency is greater than the time scale was involved.

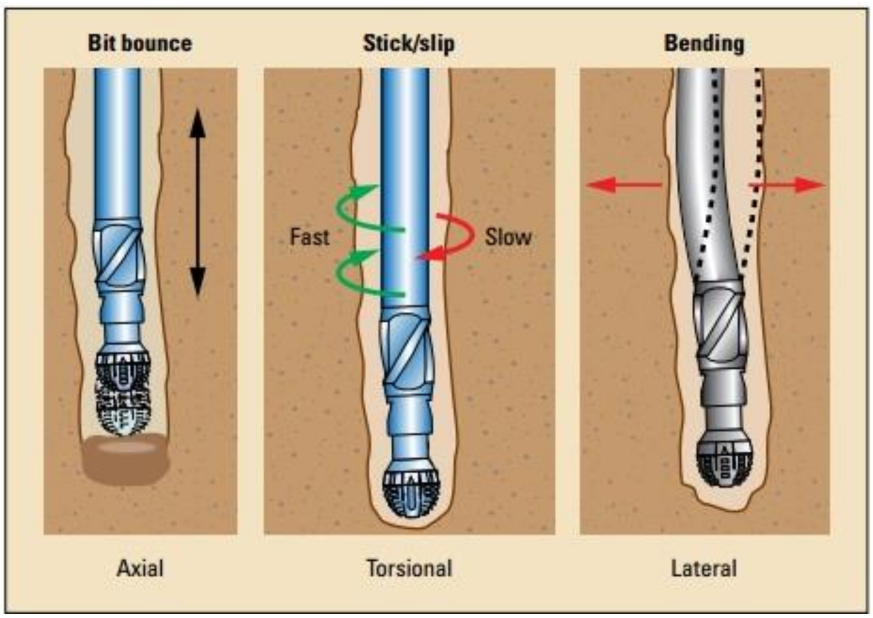


Figure 1.1: Type of Vibration

According to **Figure 1.1**, there are many type of vibration and it can be divided by three types, or modes such as axial, torsional and lateral. In terms of drilling, the destruction nature of each vibration type is different. For Axial vibration, it can cause the bit to bounce which could damage the bit head and the bearings. On the other side, the torsional vibration will cause downward hole rotation irregularly. In this case, the stick/slip effect will occur during drilling and form the drill string torsional oscillation. It causes the bits to become stationary for a period. If the severity of stick/slip hikes, the length of the stuck period increases and also does the rotational acceleration as the bits breaks free. In terms of lateral vibration, it is the most destructive type of vibration compared to others. It can create the enormous shock as the bottom hole-assembly impacts the wall. As the bottom hole-assembly could interact with drill string and can drive the system into backward whirl which can cause one sided wear of components.

During rotary drilling, all the three types of vibration may occur. In the situation as the induced axial vibrations at the bit can cause lateral vibration on the bottom hole-assembly (BHA). The displacement and the bending moments introduced by lateral vibration can increase the ratio hole size to bottom hole-assembly collar size increases as the axial and lateral vibration is at vertical or low-angle wells.

1.2 PROBLEM STATEMENT

The invention of vibration drilling has been a vital study to research on for upstream field. This study has been undertaken to come up with different condition of modelling for the vibration drilling systems in term of impact such as three masses model. However, this model work according to system response analysis such as optimal loading parameters and control parameters.

Therefore, in terms of these parameters, the investigation and research need to be done in order to confirm the progression rate of drilling system in the model chosen. From the completion of these investigation, we should be able to develop mathematical models in terms of equation of motion.

1.3 OBJECTIVES

The objective of analyzing the dynamic of high frequency vibro-impact drilling as follows: -

- To study and derive mathematical model of Vibro-Impact System.
- To develop computer code using MABLAB for Vibro-Impact system.
- To stimulate and analyze the dynamic behavior of Vibro-Impact drilling.

1.4 SCOPE OF STUDY

This investigation includes the study of vibration towards drilling, background research and analyzing the mathematical models according to the equation of motion and use this principle to apply on high frequency vibro-impact drilling. Then, the outcome will be able to prove the possibility of solving this problem eventually with mathematical formulation in dynamic of drilling and get familiarize with MATLAB. Finally, create the coding from the formulated derivation and start the stimulation accordingly.

CHAPTER 2: LITERATURE REVIEW

When a quantity of tools was established known as down-hole hammer, percussive hammers and percussive drills was reported as earliest of 1949 where the impression of utilizing the energy of impact to drill rock geology that was tested by the engineering society. However, it was developed after the first well was completed using a cable tool percussive in 1859 by Colonel F.L (Samuel, 1996). The mechanism of transferring the potential energy to kinetic energy is the similar principle that compressed air operates the piston with an impact upon the drilling rod to drill bit (Rabia, 1985). As the drill-string penetrate through the rock, the rock is crushed and chipped together with the drill bit. According to motion of percussive drill bit, the rotary action has the super-imposed to further enhance the penetration rates. The cuttings are being efficiently removed as the rock surface area given to the drill bit for the drilling field.

In the laboratory or field, the performance of percussive hammers has been considered comprehensively (Samuel, 1996). The rotary percussive drilling usage technique to drill as close to four-kilometer-deep well was the first reports that was presented. The consideration of weight of bit effect and rotary speed play an important role in the tool performance in various formation and behavior of different drill-bits during the percussive drilling were also studied. Comparing with rotary drilling, the substantial development in penetration rate were achieved. The range from 5 to 17 Hz on granite blocks is the frequency effects of percussive drilling was investigated in the laboratory as the experiment is conducted by (Topanelian, 1958). A research was investigated by conducting the evaluation on the effect of percussion to develop the fluid- operated hammer drill to accelerate the penetration rate of hard rock by obtaining the different design characteristics and the possibilities of percussive is determined by low range frequency (Samuel, 1996).

With proper equipment of hydraulic lifting rotary table, the experiment of the drill bit was placed in still state and the experiment was done to rotate and force upwards the block. Using the percussive action more compared to the double penetration rate which will be generated by the static weight of bits that was conducted for the experiment. The field results of percussive air drilling was presented by Bates in the year of 1964 (Bates, 1964). The results show to the pressure to function the percussive tool which is the only aspect affecting the progress and choice of bits was vital for the whole process. On the other part of the outcomes were presented by (Smith & Kopczynksi, 1961)whom also interpreted that the air-rotary percussive drilling is an important tool in the industry and it needs additional improvement and optimization (Smith & Kopczynksi, 1961).

The chances of improving the utilization the energy to the drill rock by the down-hole operation that will be subjected as the geometrical limitation as each rock configures less favorable in loading geometry compared to differential ones (Simon, Energy balance in rock drilling , 1963). However, the effectiveness of stress energy change into exertion ended by the bit through the rock and the required energy in the stress energy is generated by the drill steel bit that impacts the striker with the energy needed (Simon, Tranfer of stress wave energy in the drill steel of a percussive drill to the rock, 1964). The combination of harmonic and static force in ground molding percussion drilling with ultrasonic machines, will result the cutting element to penetrate faster at rate when compared to the traditional drilling method (Ajibose , Wiercigroch, Karolyi , Pavlovskaia, & Akisanya, 2012).

Thus, the effect of contact geometries and the force-displacement of governing force is shown when the deformation experienced as linear spring and damper with nonlinear spring was replaced upon impact as a threshold force was exceeded (Ajibose , Wiercigroch, Karolyi , Pavlovskaia, & Akisanya, 2012). The investigation of the new model of progression phase of drifting impact oscillation was penetrated using the impactor into elasto-plastic solid. To formulate the force-penetration relationship, the contact phase and impactor geometry should be considered. The development of the new drifting oscillation is suitable for percussive drilling. The calculation of dynamic analysis of the system is for the mass of impactor geometry's contact surface. The dynamic analysis for non-linear was carried out and found that at about 75 percent of harmonic force amplitude have maximized the progression results as the periodic motion and static weight is exhibited in the system. This concludes that the invention of vibro-impact system could be efficient to increase the performance with the influence of geometry system impactor (Ajibose , Wiercigroch, Karolyi , Pavlovskaia, & Akisanya, 2012).

According to (Franca & Weber , Experimental and numerical study of a new resonance hammer drilling model with drift, 2004), to gather the information of rock properties, bits conditions and drilling effectiveness, he have done the model of rotary-percussive drilling that connects the phenomena of bit rocks was designed in-house series of experiment of rotary-percussive drilling rig. Conducting numerical studies and experiments on the drift of resonance hammer drilling model which illustrates that the system behavior can fluctuate considerably from normal periodic systems to chaos by (Franca, A bit-rock interaction model for rotary-percussive drilling, 2011). On the other hand, the studies of ultrasonic percussive drilling with diamond-shaped tools on the rock were conducted in the laboratory (Wiercigroch , Wojewoda , & Krivtsov, 2005). The research has aimed to widen the understanding of down-hole drilling and the development support of mathematical models that can show the main phenomena during drilling process.

To advance the Resonance Enhanced Drilling (RED) technique, the University of Aberdeen have done extensive research for the past few years. The paper has shown that the modelling of the mathematical and its analysis from the task. The key point for this project is to relate the adaptable high frequency dynamic stress which will be created from the axial oscillation. As the penetration rate enhanced, it is influenced by this high frequency dynamic stress with the rotary action that creates resonance environment between drilled formation and drill bits. Considering the factor of adjusting the frequency and amplitude to generate the adaptable spreading fracture zone that will be effective as resonance is well maintained during drilling the hard rock.

In order to widen the idea, an experimental of rig was manufactured to collect data in condition of vertical oscillation of drill bit created by PEX magneto-strictive device and also bit's static weight. As the bits provided by hydraulic cylinder, it will be separated from specimen's rotary motion that will be supplied by the vertical latte and rotary table. This is to maintain the combined rotary percussive action applied on the rock or drill bit by the arrangement mention previously that allow the simplification of rig instrumentation.

Finally, this modelling actually focusses on the main model which are three masses model. It was formed to show the dynamic relationship between the drilled formation and drill bits (Pavloskaia, Wiercigroch, & Grebogi, 2001). The main purpose would be finding the degree of complexity of the model that to include parameters like the additional degree of freedom and control parameters. There will be parameters for external force as well on the system to show the typical behavior of examined system.

CHAPTER 3: METHODOLOGY/PROJECT WORK

3.1 MATLAB®

MATLAB® is known as the advanced language and an easy-to-use environment used by universities student, engineers and researchers globally. Signal and image processing, communication and control system are the disciplines that can be explored and the visualizing the collaborated idea by MATLAB® software. The MATLAB® version R2015a will be used to run the project simulation.

Figure 3.1: Logo of MATLAB® Software

3.2 RESEARCH METHODOLOGY

For Final Year Project 1 (FYP 1), there will be more on the understanding the concept of vibro-impact drilling and its parameters. Not to forget, the calculation is also required to derive the mathematical modelling prior to the project title. Thus, modelling the equation of motion including all parameters or condition will be done with the guidance of research papers. According to the equation, there will be sequence of motion following the phases such as progression once the slider and mass are in contact, contact without progression, no contact and how the progressions are influenced by the control parameters. Once the computer simulation is done, the calculation results will be compared to prove the research of this project and followed by its interpretation of results accordingly.

During the Final Year Project 2 (FYP 2), the familiarization in software will be done by practice using MATLAB software. The result will be produced according to the "key milestone' table mentioned below. Thus, the steps will be taken to produce the results using the software.

3.3 KEY MILESTONE

The main key of this project to obtain the objective as stated above. In order to complete the task according to the time frame, a key milestone table is constructed as below.

Table 3.1: Key Milestone

PROGRESS	DATE OF COMPLETION
CONFIRMATION OF RESEARCH TOPIC	30 SEPTEMBER 2015
PROBLEM IDENTIFICATION, LITERATURE REVIEW AND PROPOSAL PREPARATION	30 OCTOBER 2015
PROPOSAL DEFENCE	19 NOVEMBER 2015
UNDERSTANDING MATLAB MATHEMAICAL CODING	25 DECEMBER 2015
DERIVATION ON EQAUTION OF MOTION FOR THREE MASS MODEL (Preliminary Equation)	28 DECEMBER 2015
SUBMISSION OF INTERIM REPORT	31 DECEMBER 2015
DERIVATION OF MATHEMATICAL MODEL FOR VIBRO-IMPACT DRILLING	FEBUARY 2016
MODELLING/ STIMULATION ON VIBRO-IMPACT DRILLING MODEL	1-20 MARCH 2016
IMPLEMENTATION OF SIMULATION RESULT	6 APRIL 2016
COMPLETION OF FINAL REPORT AND VIVA	8-11 APRIL 2016

3.4 FLOW CHART

This is the flow chart of the future planning of the research study.

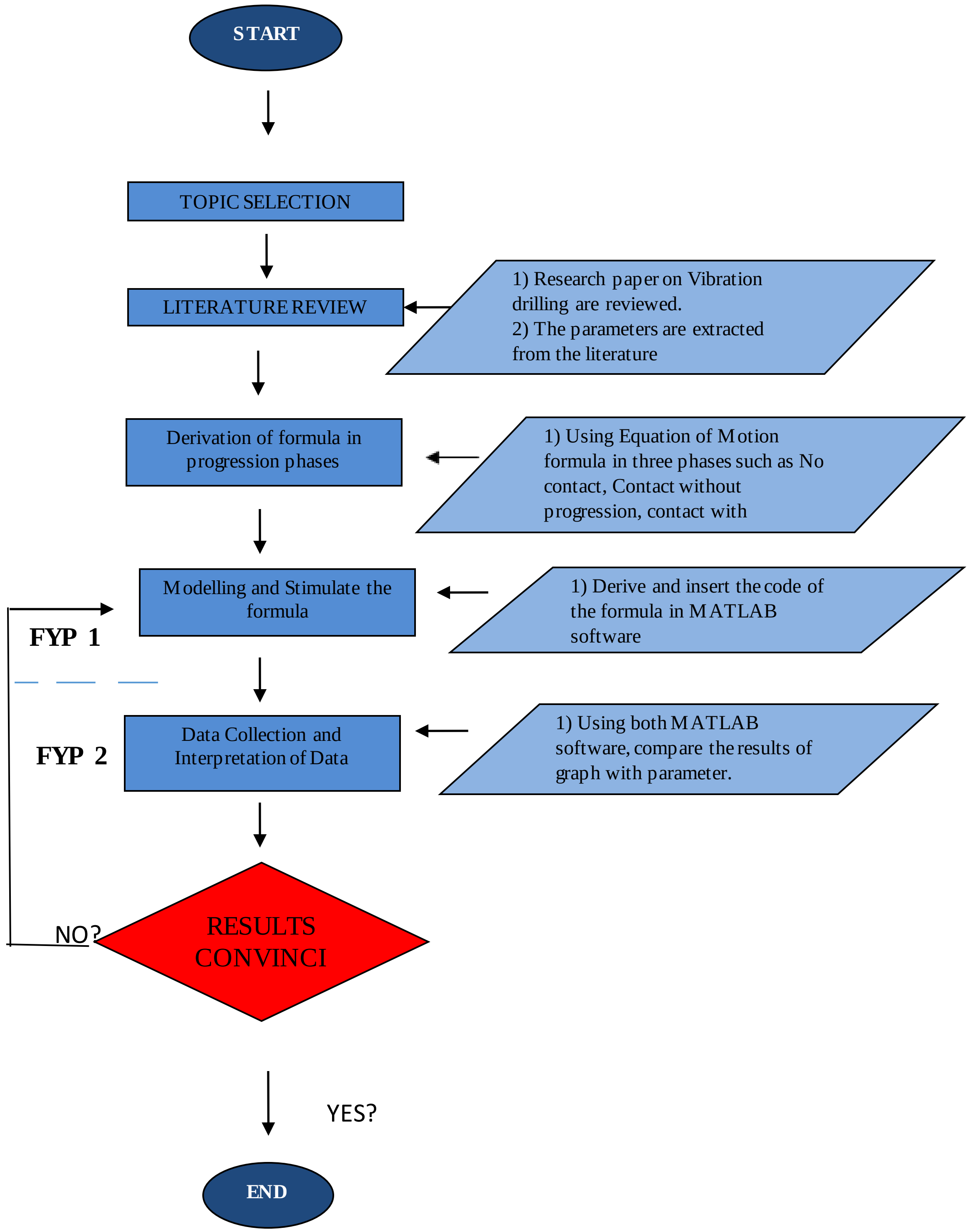


Figure 3.2: The Flow Chart of Research Study

As mentioned in **Figure 3.2**, in order to successfully complete the tasks and achieve the project objectives within the time period given, an organized procedure has to be produced. The flow of this project is as stated below: -

I. Project Topic Confirmation

The beginning of this project by selecting the project topic. Topics where given to students to choose their preferable one for the list of topic. Upon selection of topic, the first meeting with the respective supervisor will be scheduled.

II. Consultation with Supervisor

Appointment and consultation with supervisor is done once have selected the topic and confirmed by the coordinator. This is to make sure that to get a clearer view and understanding about the project is faster as follow ups with the project supervisor are set every now and then in order to update the progress and the clarification when problem arise.

III. Problem Identification

Identifying the problem will be the next point of multi-phase of undertaking. This is will an important part of the whole project as incorrect problem identification of problem can lead to altered final outcome of the project.

IV. Project Objectives and Scope of Study

Based on the project identified, the project objectives are set and the scope of work will be more specific in order to accommodate the constraints that can hinder the probability of completing this project. The scope cannot be too extensive or detailed the real-world application project in order to complete the project within the cost and time frame.

V. Literature Review on High Frequency Vibro-Impact Drilling

Intense research on Vibro-impact drilling have been carried out to produce the computer coding that will be able to stimulate the drilling dynamic characteristics as close and precise as its real-world behaviors

VI. Computer Code Development and Stimulation

The development of the computer code in MATLAB software is started soon as the project supervisor validates and verifies the derivation of the equation of motion. Once done with validation, the stimulation is done afterwards and the stimulation graph is generated as results of this project.

VII. Data Collection and Interpretation of Data

As the steps are taken, the critical analysis and study from the data collection of results of this project. Thus, the interpretation of data is also done to comes up with the proper understanding and it is discussed further in the discussion of this project.

3.5 GANTT CHART

For this research project, the table below shows the overall work progress of Gantt chart for FYP 1 and FYP 2.

Table 3.2: Gantt chart for FYP 1 Research Project

No	Project Activity	FINAL YEAR PROJECT I													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Introductory Lecture with the FYP Coordinator														
2	Title Selection														
3	Confirmation of Project Topic			*											
4	First meeting with Supervisor														
5	Preliminary Research Work														
6	Submission of Extended Proposal														
7	Proposal Defence									*					
8	Project Work Starts														
9	Understanding MATLAB Mathematical Coding										*	*	*	*	*
10	Derivation On Equation Of Motion										*	*	*	*	*
11	Submission of Interim Draft Report to Supervisor												*		
12	Submission of Final Interim Report													*	*
13	Submission of Marks by Supervisor														

Table 3.3: Gantt chart for FYP 2 Research Project

No	Project Activity	FINAL YEAR PROJECT II													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Derivation Of Mathematical Model For Vibro-Impact Drilling	*	*	*											
2	Modelling/ Stimulation On Vibro-Impact Drilling Model				*	*	*								
3	Progress Report														
4	Preparation for Pre-SEDEX														
5	Technical Paper														
6	Implementation Of Simulation Result										*	*	*		
7	Submission of Final Draft (Dissertation)										*	*	*		
8	Viva													*	*

Process   * Key Milestone

CHAPTER 4: RESULTS AND DISCUSSION

4.1 THREE MASS MODEL MATHEMATICAL MODELLING

For the three mass system model which shown in **Figure 4.1** below explains the number of elements including exciter providing the dynamic external force. There are two spring involved with the back mass to ensure the vibration is in control within the system and the drill-bit. To drive the system downwards, the hydraulic cylinder is used to apply the static force as the rock is cracked and the progression occurs. The Resonance Enhanced drilling (RED) technique is the system used using axial oscillation in combination with rotary action with an adjustable high dynamic stress to increase the rates of penetration by forming resonance condition between drill-bit and the drill formation.

The simple differential equation of the Multi-Degree-Of – Freedom- System and also known as equation of motion with force response is written as: -

$$M\ddot{X} + C\dot{X} + KX = F_s \qquad \textbf{(1)}$$

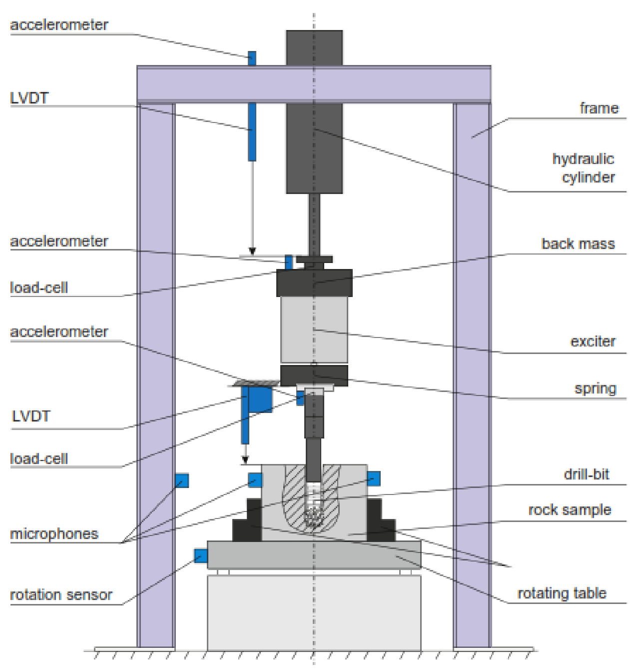


Figure. 4.1: Schematic of the experimental rig.

From **Figure 4.2**, it can be seen that the simple drawing of three mass model in Multi-Degree of Freedom. The drill-bits is modelled by a mass M_1, which is located at a distance of G from the surface of the rock. From the small contact forces, the spring stiffness, K_1 and the damping coefficient for damper, C_1 shows elastic-behavior of the rock. The force acting on the slider can exceed P_r. As the drill bit head and rock block are not in contact, the contact force, P_c and velocity is zero. During the free motion process, the surface rock, X_t in the forces of the spring, K_1 and the damper C_1. The value of initial gap, G will be evaluated when the drill head is in touch with the rock, the displacement of X_1. The top mass, M_3 is modelled on the equivalent frame oscillating mass and comparing with the connected the mass of exciter, M_2 by a spring of constant K_3 and coefficient of damping, C_3.

By direct application of Newton's second law and from **Figure 4.3**, it can be verified by the equation of motion as shown below:

$$M_3\ddot{X}_3 + C_3(\dot{X}_3 - \dot{X}_2) + K_3(X_3 - X_2) = 0 \quad \textbf{(2)}$$

The mass of exciter, M_2 is connected to the drill-bits via spring constant, K_2 and the damping coefficient of C_2.

$$M_2\ddot{X}_2 + C_3(\dot{X}_2 - \dot{X}_3) + C_2(\dot{X}_2 - \dot{X}_1) + K_3(X_2 - X_3) + K_2(X_2 - X_1) = F_s \quad \textbf{(3)}$$

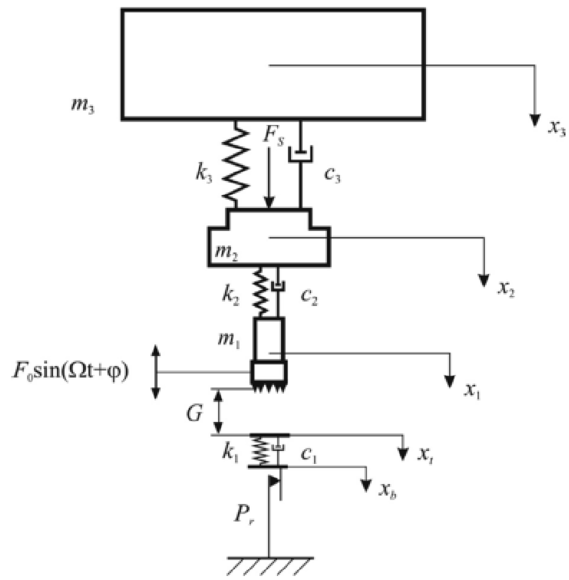


Figure 4.2: Simple drawing MDOF system.

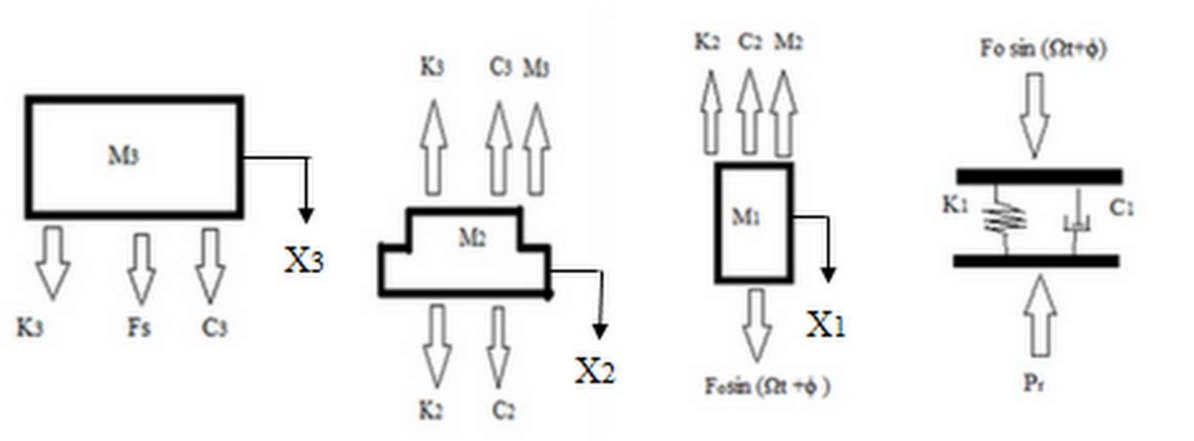


Figure 4.3: Free Body Diagram of Mass, Spring and Damping

However, the bottom mass, M_1 is the drill bit and its three dissimilar phases of operation dependent on its point with respect to the rock surface, X_t. The different phases condition and modelling the equation is stated below: -

I. No contact phase,

$$X_1 < X_t + G. \quad \textbf{(4)}$$

This is the first stage where the drill bits reach the slider at $X_1 = X_t + G$.

. At this stage, the contact force is: -

$$P_c = K_1 (X_t - X_b) + C_1 (\dot{X}_t - \dot{X}_b) = 0 \quad \textbf{(5)}$$

The mass, the rock surface and the slider move according to the equation of motion

$$M_1\ddot{X}_1 + C_2 (\dot{X}_1 - \dot{X}_2) + K_2 (X_1 - X_2) = F_0 \cos (\Omega t + \phi), \quad \textbf{(6)}$$

$$\dot{X}_t = -\frac{K1}{C1} (X_t - X_b), \quad \textbf{(7)}$$

$$\dot{X}_b = 0.$$

In matrix form, we obtain:

$$\begin{bmatrix} M1 & 0 & 0 \\ 0 & M2 & 0 \\ 0 & 0 & M3 \end{bmatrix} \begin{bmatrix} \ddot{X}1 \\ \ddot{X}2 \\ \ddot{X}3 \end{bmatrix} + \begin{bmatrix} C2 & -C2 & 0 \\ -C2 & (C2 + C3) & -C3 \\ 0 & -C3 & C3 \end{bmatrix} \begin{bmatrix} \dot{X}1 \\ \dot{X}2 \\ \dot{X}3 \end{bmatrix} + \begin{bmatrix} K2 & -K2 & 0 \\ -K2 & (K2 + K3) & -K3 \\ 0 & -K3 & K3 \end{bmatrix} \begin{bmatrix} X1 \\ X2 \\ X3 \end{bmatrix} = \begin{bmatrix} Fo\ (\Omega t + \varphi \\ Fs \\ 0 \end{bmatrix}$$

II. Contact without progression phase,

$$X_1 \geq X_t + G,\ \dot{X}_1 > 0,\ 0 < K_1 (X_t - X_b) + C_1 (\dot{X}_t - \dot{X}_b) < P_r \quad \textbf{(8)}$$

And the contact force is interpreted as below: -

$$P_c = K_1 (X_t - X_b) + C_1 (\dot{X}_t - \dot{X}_b). \quad \textbf{(9)}$$

The end stage where the contact force P_c exceeds the threshold P_r then followed by the third stage. If the contact force P_c falls less than zero, contacts stop and first step starts. The massless rock surface changes together with drill bits where $X_1=X_t$. Resulting Equation of Motion: -

$$M_1\ddot{X}_1 + C_2(\dot{X}_1 - \dot{X}_2) + C_1\dot{X}_1 + K_2(X_1 - X_2) + K_2(G + X_b) = F_0 \cos(\Omega t + \phi), \quad \textbf{(10)}$$

$$X_t = X_1 - G, \quad \textbf{(11)}$$

$$\dot{X}_b = 0.$$

In matrix form, we obtain:

$$\begin{bmatrix} M1 & 0 & 0 \\ 0 & M2 & 0 \\ 0 & 0 & M3 \end{bmatrix}\begin{bmatrix} \ddot{X}1 \\ \ddot{X}2 \\ \ddot{X}3 \end{bmatrix} + \begin{bmatrix} C1 + C2 & -C2 & 0 \\ -C2 & (C2 + C3) & -C3 \\ 0 & -C3 & C3 \end{bmatrix}\begin{bmatrix} \dot{X}1 \\ \dot{X}2 \\ \dot{X}3 \end{bmatrix} + \begin{bmatrix} K1 & -K2 & 0 \\ -K2 & (K2 + K3) & -K3 \\ 0 & -K3 & K3 \end{bmatrix}\begin{bmatrix} X1 \\ X2 \\ X3 \end{bmatrix} = \begin{bmatrix} Fo\ (\Omega t + \varphi \\ Fs \\ 0 \end{bmatrix}$$

III. Contact with progression phase,

$$X_1 \geq X_t + G,\ \dot{X}_1 > 0,\ K_1(X_t - X_b) + C_1(\dot{X}_t - \dot{X}_b) \geq P_r. \quad \textbf{(12)}$$

The slider moves in the combined force of the opposite force, P_r and the spring between the slider and the rock surface, X_t. As the mass is zero, the contact force, P_c is equal to resistance force, P_r.

$$K_1(X_t - X_b) + C_1(\dot{X}_t - \dot{X}_b) - P_r = 0. \quad \textbf{(13)}$$

Thus, the drill-bit changes together with the rock surface. The equation for the motion for the slider can be expressed as below: -

$$\dot{x}_b = \dot{x}_t + \frac{k_1}{c_1}(x_t - x_b) - \frac{P_r}{c_1}. \quad \textbf{(14)}$$

This stage is the last until the value of $K_1(X_t - X_b) + C_1(\dot{X}_t - \dot{X}_b) - P_r = 0$ falls less than P_r and the stage 2 restarts. Below shown the resulting equation of motion: -

$$M_1\ddot{X}_1 + C_2(\dot{X}_1 - \dot{X}_2) - C_1(\dot{X}_1 - \dot{X}_b) + K_2(X_1 - X_2) + K_1(X_t - X_b) = F_0 \cos(\Omega t + \phi), \quad \textbf{(15)}$$

$$X_t = X_1 - G, \quad \textbf{(16)}$$

$$C_1(\dot{X}_1 - \dot{X}_b) + K_1(X_1 - G - X_b) = P_r. \quad \textbf{(17)}$$

In matrix form, we obtain:

$$\begin{bmatrix} M1 & 0 & 0 \\ 0 & M2 & 0 \\ 0 & 0 & M3 \end{bmatrix} \begin{bmatrix} \ddot{X}1 \\ \ddot{X}2 \\ \ddot{X}3 \end{bmatrix} + \begin{bmatrix} -C2 + C2 & -C2 & 0 \\ -C2 & (C2 + C3) & -C3 \\ 0 & -C3 & C3 \end{bmatrix} \begin{bmatrix} \dot{X}1 \\ \dot{X}2 \\ \dot{X}3 \end{bmatrix} + \begin{bmatrix} K1 & -K2 & 0 \\ -K2 & (K2 + K3) & -K3 \\ 0 & -K3 & K3 \end{bmatrix} \begin{bmatrix} X1 \\ X2 \\ X3 \end{bmatrix} = \begin{bmatrix} Fo\ (\Omega t + \varphi \\ Fs \\ 0 \end{bmatrix}$$

4.2 SIMULATIONS

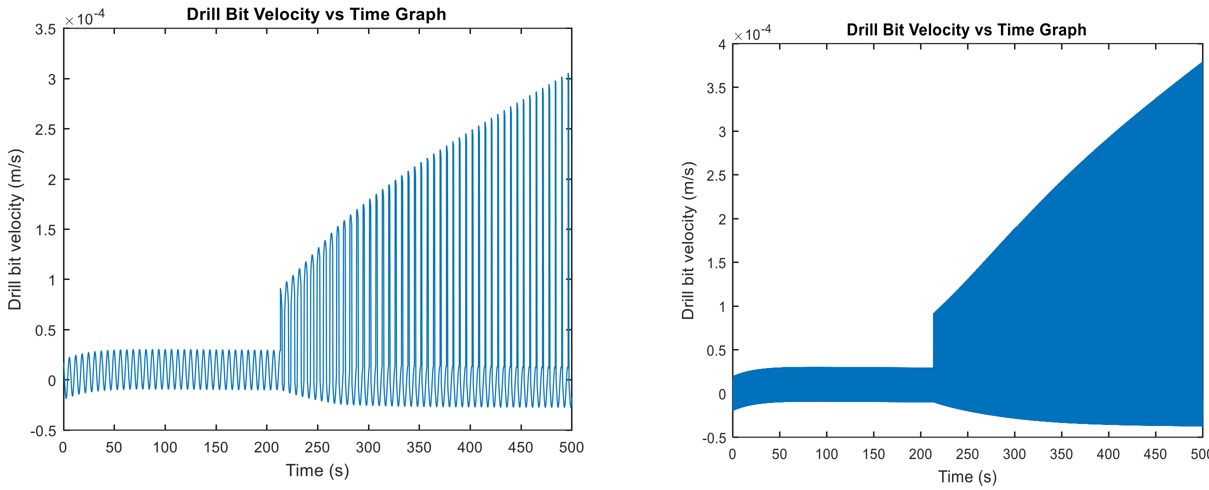
The simulation was done with MATLAB®. According to the equation of motion, the matrix is formed for each variable such as stiffness, damping, external force, time and mass. The simulation of the drilling motion is run according to equation 1 and 2 as basic and equation 3 depends on the different phases of drilling for three mass model.

To start with the project simulation, the familiarization of the software has been done in order to understand its function analysis. For three mass model, the Multi-Degree of Freedom (mdof) will be used accordingly using the transfer function analysis that illustrate how to derive the equation of motion.

In this section, the graph of surge, heave and pitch the excitation amplitude, rock surface and base removal velocity, equivalent frame velocity and the drill bit velocity over time for vibro-impact drilling are presented. So far the graph is obtained for three mass model is under stimulation process. As the results shown above, there will be discussion on the behavior of the model will be carried out to meet the objective.

4.2.1 Graph Plots Results

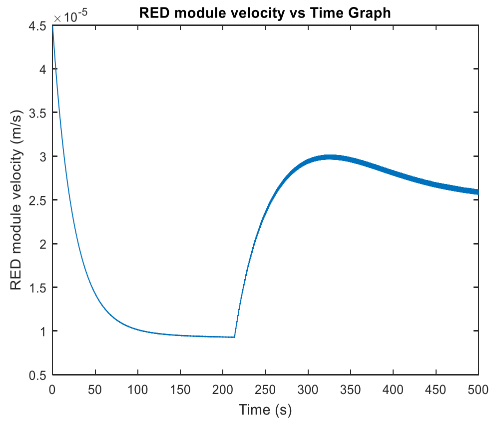
First, the parameters are identified and the high frequency are obtained and compared with the mathematical model as cited from (Jasem & Ahmet, 2014). The study of three mass model's dynamic behavior in order to determine the effect of control parameters such as static force, excitation of frequency and the excitation of amplitude. So all the control parameters of the system with the impact experiment is stimulated. The main parameter values are attached in **APPENDICES**.

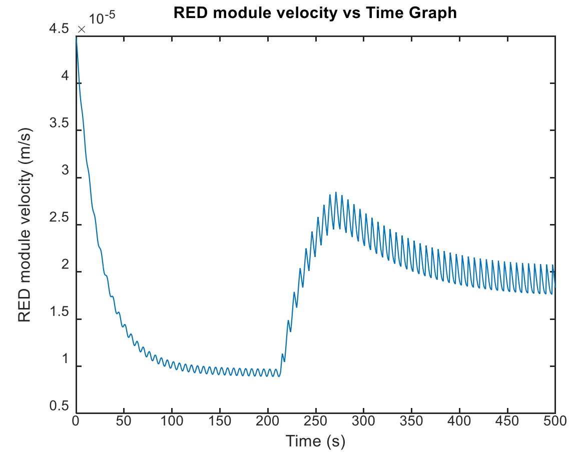


(a) **(b)**

Figure 4.4(a) and (b): Graph of Drill Bit Velocity against time. **(a)** When omega (Ω) is 1 **(b)** When omega (Ω) is 10

The **Figure 4.4(a) and (b)** graph above shows the drill bit velocity against time varied by the difference value of omega (Ω). This is shown from the graph above, as the omega decreases in value, the drill bit velocity of the graph reduces that leads to higher vibration constrains at the drill bit. Thus, decreases the rate of progression. Analyzing the graph shown above, the **Figure 4.4(b)** has higher velocity of drill bit at 500th seconds compared to **Figure 4.4(a)**. This clearly shows that the higher the omega value (Ω), the higher the velocity of the drill bit that results higher rate of progression.



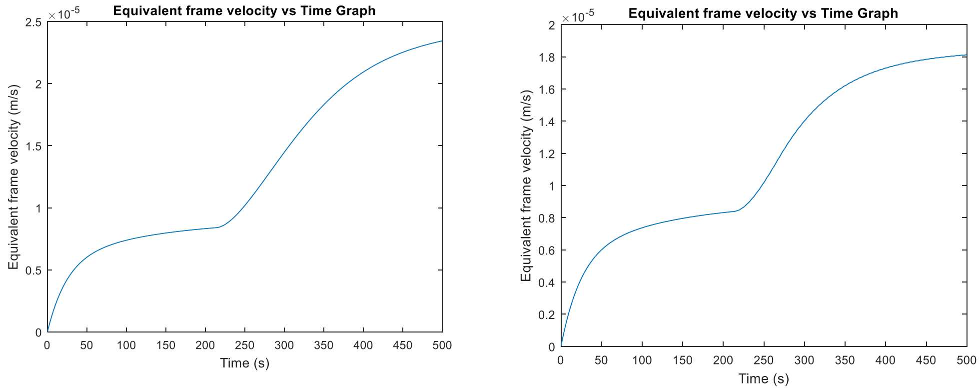


(a) **(b)**

Figure 4.5: Graph of RED module velocity against time. **(a)** When omega (Ω) is 10 **(b)** When omega (Ω) is 1

As for **Figure 4.5**, the RED module velocity graph explains about the resonance enhanced drilling module velocity decrease dramatically in first 210 seconds. However, the velocity of the module still increases dramatically until the velocity reaches the 3m/s and the velocity is drops gradually.

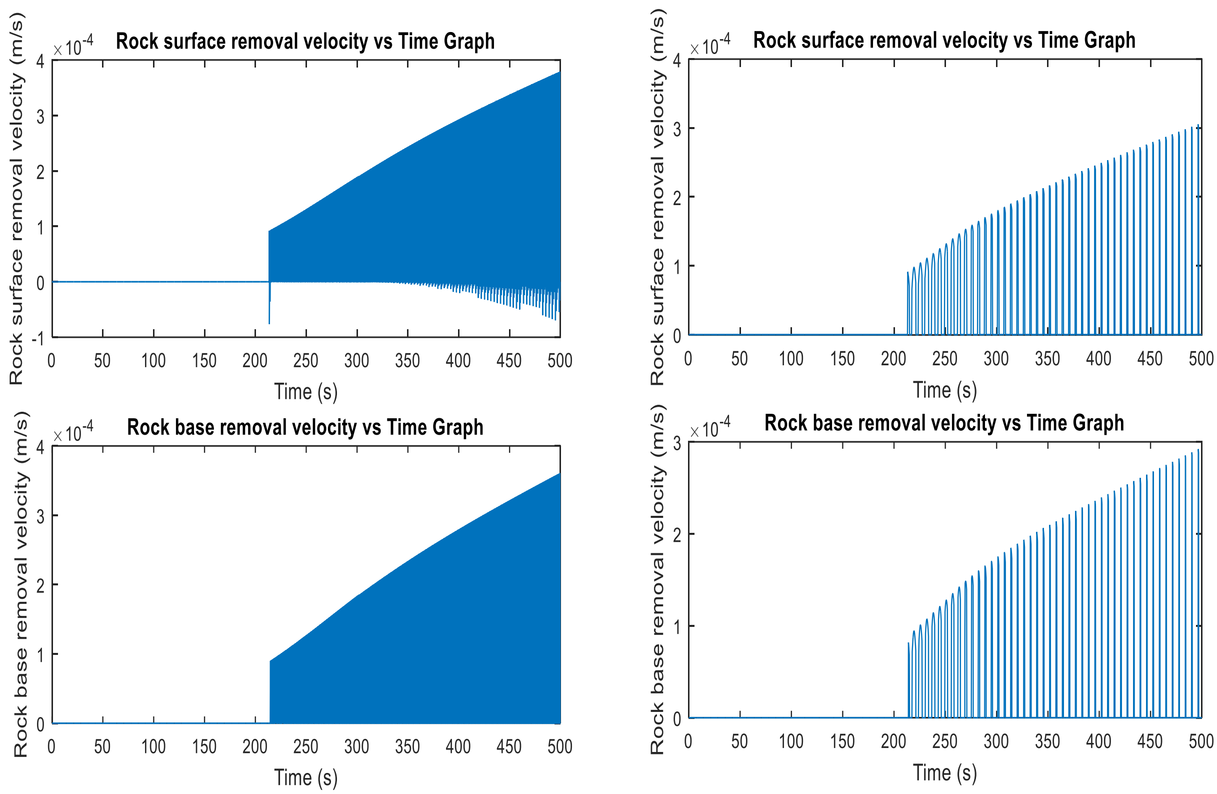
However, there are difference in both graph in terms of overall RED module velocity. **Figure 4.5(a)** show better results compared to **Figure 4.5(b)** and this due to omega difference(Ω). Thus, the higher omega value shows an improved results of progression rate.



(a) **(b)**

Figure 4.6: Graph of Equivalent frame velocity against time. **(a)** When omega (Ω) is 10 **(b)** When omega (Ω) is 1

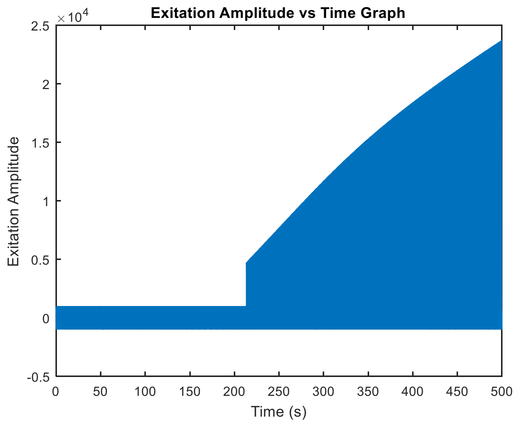
For the equivalent frame velocity against time graph shows the velocity of the equivalent frame increase steadily with time. Thus, this proves the process of drilling is taking place. **Figure 4.6 (a)** has the higher velocity of 2.3 X 10^{-5} m/s compared to 1.8 X 10^{-5} of **Figure 4.6 (b)**. From all other graph observation, the omega value contribute high impact on the results.



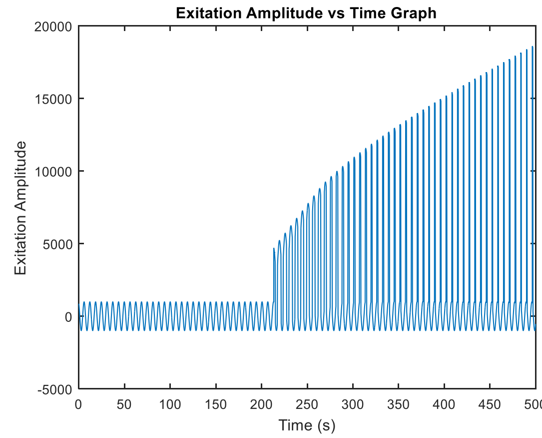
(a) **(b)**

Figure 4.7: Graph of Rock surface and base removal velocity against time. **(a)** When omega (Ω) is 10 **(b)** When omega (Ω) is 1

Based on **Figure 4.7**, there were no sign of velocity reaction at rock surface for the first 20 seconds and the progression of the rock surface removal velocity is observed with time. The same observation has been encounter in the other graph of rock base. This graph also known as the rate of progression. This is because the rock surface velocity, X_t shows the progression rate done on the rock block. However, the rate of progression moves slowly at the pace of 10^{-4} m/s. On the other side, the high value of omega, decreases the excitation frequency gained which eventually boost the progression rate.



(a)



(b)

Figure 4.8: Graph of Excitation amplitude against time. **(a)** When omega (Ω) is 10 **(b)** When omega (Ω) is 1

The increase static force, F_s will eventually increase the excitation amplitude according to the graph above. As proven, the increase in excitation amplitude will contribute better rate of progression.

From the theoretical results, there is velocity variation caused by impact on the surface. When the impact on RED module and the surface, the result graph shows the velocity were very small as it can be noticed in the first 200 seconds.

4.2.2 Dynamic system for Excitation force, F_o variation with Time.

A table was constructed for excitation force against time domain to encounter the variation of results of excitation amplitude obtained from the graph generated using MATLAB software. From the results below, the

Table 4.1- Excitation Force Variation against Time.

CASES	F_o Variation	F_o Variation Value (N)	Excitation Amplitude (N) -At 500 s	Progression Rate ($x10^{-4}$ m/s) -At 500s	Maximum Excitation Amplitude (N) -At 3000 s
1	0.25 F_o	238.75	17000	2.7	94000
2	0.5 F_o	477.5	18500	3.0	89000
3	0.75 F_o	716.25	18000	3.05	86000
4	2 F_o	1910	18000	3.1	90000
5	4 F_o	3820	18000	3.1	94000

Interpreting the table above, case 5 is the best option among the other cases. As the excitation force at its highest force, the excitation amplitude increases gradually until it reaches the peak of 94000N. From the results generated, the progression rate gained is highest and same as case 4.

However, the purpose of this analysis is to obtain the optimal parameters that have maximum impact force that is influenced by excitation force and increase the rate of progression. Despite the high excitation force and the impact can be chaotic situation but as long the main purpose of determining the optimal parameters is obtained.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

For the high frequency vibro-impact drilling, the first objective is achieved by modelling the equation of motion and derived mathematically. The computer coding is done using MATLAB for three mass model. However, proving the dynamic behavior of the three masses model will be shown once the model is stimulated and analyzed in order to accomplish the third objective completely.

According to the objective of this project, several tasks will be done in order to meet the purpose of analyzing the behavior of this model. Thus, those graph results are shown in the Results and Discussion chapter of this paper. Thus, the paper has presented the modelling of high frequency vibro-impact drilling system demonstrating the results for the dynamic behavior of three masses model.

Based on the graphical analysis, while studying the behavior of the three mass model, sweeping the excitation control parameter, have noticed that the lower value for the excitation amplitudes and the increase with excitation of frequency can eventually obtain zero rate of progression. As the omega is also linearly influenced by the excitation of frequency, thus lower the value of omega, the progression rate increases alternatively. This simply shows that the increase excitation amplitudes contribute better progression rate.

5.2 RECOMMENDATION

In order to compare the theoretical value and experimental value, the project should have more resources in conducting the real experiments with the prototype designed according to the requirements of the project. Thus, the validation of the project can be valued. However, the equation of motion must be transformed into the non-dimensional form where further research needed to be done. This is to ensure more variables to be formed.

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APPENDICES I

THE M-FILE USED FOR STIMULATION

The high frequency vibro-impact drilling simulation was written in MATLAB. VibroImpact.m is the main M-file coding that links all other programs command accordingly. The table below shows the list of other programs: -

Table – M-file function description

No.	M-File Name	Description
1	**mass.m**	Using the system mass 3x3 matrix
2	**stiffness.m**	Using the system stiffness 3x3 matrix
3	**damping.m**	Using the system damping 3x3 matrix
4	**force.m**	Calculate the forces during drilling process such as the excitation force and static force.
5	**readtime.m**	To start time and end time for stimulation process

APPENDICES II

THE PARAMETERS FOR STIMULATION

Table –Stimulation Parameter.

Parameters	Symbols	Value	SI
Drill bit mass	M_1	**50142**	**kg**
Exciter mass	M_2	**28054.5**	**kg**
Top mass	M_3	**60790.3**	**kg**
Rock Stiffness	K_1	**3.75*10^6**	**N/m**
Exciter Stiffness	K_2	**701.4*10^3**	**N/m**
Top Stiffness	K_3	**1095*10^3**	**N/m**
Rock damper	C_1	**16697.4**	**N.s/m**
Exciter damper	C_2	**18753**	**N.s/m**
Top damper	C_3	**25800**	**N.s/m**
Gap	**G**	**0.001**	**m**
Exceeded Force	P_r	**95**	**kN**
Static force	F_s	**1260**	**kN**
Excitation force	F_o	**995**	**kN**
Omega	Ω	**1/10**	**rad/s**