DRILLSTRING INSTABILITY PHENOMENA STUDIED BY SUPERIOR ANALYSIS TECHNIQUES, RESONANCE MODELLING

BY

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ABSTRACT

Drillstring instability phenomena leads to damage all parts of the drillstring, wellbore instability and reducing the rate of penetration (ROP). The bottom hole assembly (BHA) configuration is a main factor in optimizing the drilling operations. Therefore, should be designed to minimize the vibration levels in the lateral, axial and torsional directions. This can be done, by avoiding the rotation of the drillstring at the natural frequency which called the resonance.

In this thesis the vibration of drillstring was studied under the impact of weight on bit and rotation drillstring. Thus, the lateral vibration has been chosen as the most important and centered element, because it is increased dramatically with the variation of the rotary drilling speed. The design of current bottom hole assembly (BHAs) components need utilizing of sophisticated analytical methods that can solve the complex and time-consuming equations.

The Finite Element Analysis (FEA) is the most common way that used to evaluate the behavior of the drillstring vibration by means of mesh discretization of a continuous body into small components. Two softwares were employed for a superior analysis techniques *ANSYS* and *LANDMARK*.ANSYS software has been used to investigate the lateral vibration of drillstring in a vertical well, and to determine the critical speeds of the drillstring that should be avoided. consequently, the resonance can be prevented and be away from severe downhole vibration which lead to drillstring damage. The Simulation was first carried out by benchmark model before proceeding to deal with the actual case studies by implementing the parametric study (drill string length, weight on bit, range of frequencies).

The analysis by ANSYS was applied in two stages. First stage of *modal analysis* was performed to determine the natural frequencies of the drillstrings for three sections of well ZB-202 (17 ½", 12 ¼" and 8 ½") .The second stage of *harmonic analysis* was executed to obtain the frequency response at a varying bottom hole assemblies (BHAs) for well ZB-202.The critical rotary speeds that should be avoided were obtained from the aforementioned analysis can be listed as following, for the drillstring section 17 ½" resonance occurs at frequency 3.9 Hz and rotary speed of 234 revolution per minute (RPM), for the drillstring section 12 ¼" the resonance occurs at frequency of 5.08 Hz and rotary speed 304.8 RPM and for the drillstring section 8 ½" the resonance occurs at frequency of 2.58 Hz while rotary speed was 171 RPM .The study focused on 12 ¼" hole section of well ZB-202 with the entire details because it is the longest and most problematic section such as wellbore instability and lost mud circulation

The second software was *LANDMARK* used to determine the torque, effective tension and weight on bit (WOB) which directly influence the lateral vibration.

Keywords: Superior analysis, Resonance and Lateral vibration.

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NOMENCLATURE

Symbol	Description
Cr	Damping Coefficient of Stick/Slip Model
E	Young's Modulus
e_0	Eccentricity of Center of Mass in the Whirling Model
F_{ss}	Friction Parameter in the Stick/Slip Model
L_0	Maximum Axial Elevation in the Bit-Bounce Model
L_y	Displacement in the Whirling Model
L_z	Displacement in the Whirling Model
$L_\varnothing$	Angular Displacement for Continuous and Stick/Slip Model
Ω	Rotary Table Speed of the Stick/Slip Model
ξ	Damping Ratio Used in the Stick/Slip Model
ω	Natural Frequency of the Stick/Slip Model
V_0	Velocity Parameter in the Stick/Slip Model
T	Time
ε	Equation of Motion Term in the Whirling Model
u	Lateral Displacement in the Continuous Lateral Vibration Model
ρ	Density
G	Shear modulus
F_y	Tangential Force
Fs	Friction Parameter in the Stick/Slip Model
I_z	Cross Sectional Area Moment of Inertia in the FE Lateral Vibration Model
K	Torsional Stiffness in the Stick/Slip Mod

CHAPTER ONE

INTRODUCTON

1.1 Background of study

One of the important steps in the oil and gas industry is the wells drilled through the reservoir to output hydrocarbons with economic feasibility. Drill bits are the main parts of the drillstring that are utilized to excavate these oil and gas wells. The drill bits are run by means of top drive or rotary table throughout a chain of hollow pipes which famous as drillstring, that may extend for thousands of meters. In order to rotate the drill bit, there are two ways, first one is the entire drillstring should be rotated from the rig floor by using top drive or Kelly. The Kelly used with old fashion of drilling rigs, nowadays, most of modern rigs are using top drive to rotate the drillstring. In the second way, downhole motors can be used above the drilling bit to rotate it while the drillstring remains in stationary status.

The drillstring is suspended by hoisting system through top drive which leads to the fact that the upper part of the drill pipe section is in a state of variable tension while the lower section of the bottom hole assembly (BHA) is beneath compressing due to directly contact with the rock formation.. The hollow drillstring works as a channel passes through it the drilling mud that is pumped by the mud pump that reaches the annular space through the bit nozzles. The main function of the drilling mud is to prevent formation fluids from entering the well, suspending and transfer the rock cutting to the surface, cooling and lubricating drilling bits and clean during drilling operation. Below is a description of the main components are given.

Consequently, vibrations of the drillstring is usually categorized into three types lateral, axial, and torsional. The axial vibrations can lead to bit bounce that may cause significant harmful to bearings and cutters of drill bit. While, torsional vibrations may lead to irregular rotation at down of the wellbore. Whereas, stick slip is always obvious during drilling and is a serious generate of torsional oscillations of the drillstring in which the drill bit remains constant for some time. As the torsional vibration becomes more stressful, the time of the sticking period increases, whereas the rotational accelerations raise dramatically as the bit releases. Torsional fluctuations may cause fatigue of drill collar connections and in consequence can damage the bit.

As results of vibration, the Resonance occurs when the frequency of forcing is equal to the natural frequency of the system and this is called resonance. Self-excited vibration happens when the natural frequency of the system close to the frequency of the input force. This disturbance is long-lasting unlike free vibration, and unlike forced vibration, the disturbance is constant rather than regular, and varies around its natural frequency. One good example provided by Schmitz is the sound made in a violin by a bow and a string, depending on the speed at which the bow moves across the string, the friction between the string and the bow generates vibrations which create different sounds. when the resonance occurs, it will damage the drillstring and can generate highly energetic and sustained lateral impact with wellbore. It can cause fatigue in the connection of the drillstring

1.1.1 Rotary system

The rotary system run the drillstring and therefore the rotating passes to the drill bit. The important components that are necessary to achieve rotation include, the top drive system (TDS) which located at top of the drillstring and it is capable of to rotating the drillstring. TDS contain one or more motors (electric or hydraulic) linked to a small part of the pipe named a quill with suitable gear, that can be screwed inside a saver sub or the drillstring itself. The top drive system is hanged on the hook, so the rotating mechanism is free to travel the derrick up and down.

This vary drastically from the more traditional rotary table and kelly technique of rotating the drillstring because TDS facilitates the drilling operations with three joints in stands rather than single pipe joints. It also allows the driller to catch the pumps or the rotary quickly while trip in or trip out the pipe, which can't be done easily with the Kelly system. Although, the modern top drives are a breakthrough improvement in the technology of drilling rigs and a major contributor to the capacity to drill more complex extended-reach wellbores (ERD). Additionally, the top drive allows drillers to minimize both frequency and cost per stuck pipe incident. (Rabia 2002). The main functions of top drive are listed:

- Suspension of the drillstring.
- Rotating the drillstring.
- Allowing to pump the drilling mud while the drillstring is in rotation.

Figure 1. 1 **.** top drive (courtesy of canring).

1.1.2 Drillstring

Drillstring describes the tubulars and accessories on which the drill bit runs to the borehole bottom. The drillstring consists of drill pipe (DP), heavy weight drill pipe (HWDP), drill collars (DCs) as well as other equipments such as stabilizers, reamers, that are included in the drillstring just above the drill bit as illustrated in Figure1.2. The configuration of the drillstring with the exception of the drill pipe is commonly referred to the Bottom Hole Assembly (Aadnoy et al. 2009)

The drillstring main functions are

- To hang the drill bit.
- To transfer rotation from the top drive system or rotary table to the drill bit.
- To supply a conduit for the circulation of drilling fluids to the drill bit.
- Take weight on bit; as a compressive force required to break the rocks.

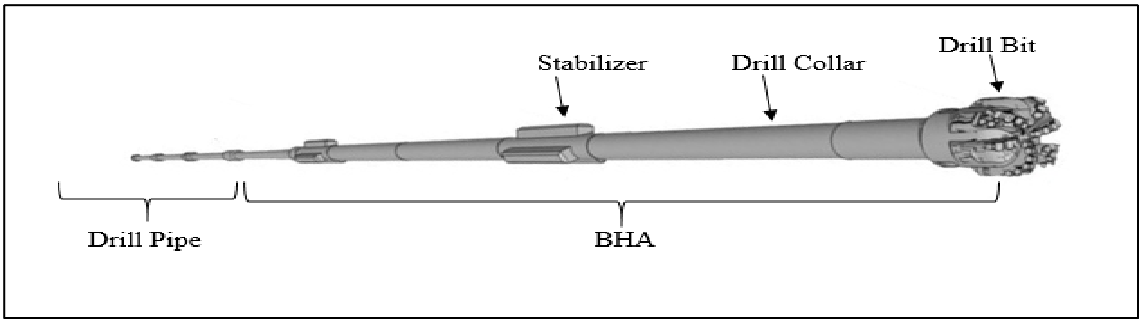


Figure 1. 2. Schematic of drillstring (Upside Energy Services, 2010).

1.1.3 Drill pipe (DP)

DP is a tubular steel pipe, having an outside diameter in the range of 2 3/8” to 6 5/8” with weights from 10 to 40 kg/m, adjusted with particular threaded finishing called tool joints. The drill pipes connect the rig floor equipments with the bottom hole assembly, and pump drilling fluids to the bit and to be able to elevate, lower and rotate the BHA. Other than the drill pipes, most of tubulars in oil field industry are one used, therefore potential wear and corrosion may occur to drill pipes. Moreover, the average length for a single pipe is 9.5 m. The API laid down guidelines for the classification of pipes in API RP7G (Aadnoy et al. 2009)

The main Classes of drill pipes are:

- New: No damage, ever used.
- Premium: regular wear and a minimum 80 % new pipe wall thickness.
- Class 2: D.P with a less 65 % wall thickness with all damage on one end as Longitude as the cross-sectional area is similar to the prime level.
- Class 3: 55 % minimum wall thickness drilling pipe with all wear on one side (T. Bourgoyne et al. 1986).

1.1.4 Heavy weight drill pipes (HWDP)

HWDP is special kind of drill pipes whose walls are densest and tool-joints are longer than classic drill pipes. In the vertical drilling industry, heavy weight drill pipe is usually run between the drill collars and the drill pipe to prevent the drill pipe fatigue. In the horizontal directional drilling (HDD) industry, heavy weight drill pipe is also utilized for extra strength in high stress situations to avoid pipe collapse, pipe stretch and buckling. For the transition between the drill collars and the drill pipe, heavy weight drill pipe may be used, for that reason the HWDP function is to ensure a flexible transition among the drill collars and the drill pipe. (F. Mitchell and Z. Miska 2018)

The main Features of Heavy weight drill pipes are:

A. High dimensional and shape accuracy.

B. Strong resistance to low temperature.

C. Excellent integral mechanical properties.

D. High force of connection and seal ability.

E. Big diameter within the tool joint.

F. Strong drag resistance.

G. Strong tiredness and long-term exhaustion.

1.1.5 Drill collars (DC)

DC is heavy, thick-walled steel pipe placed between the heavy weight drill pipes and the bit to put weight upon drill bit. The range of drill collars 11” weight is up to 445 kef/m). In some cases, spiral drill collars can be utilized to avoid pipe sticking problems or slick collars in normal situations. Furthermore, the average length is usually around 9.5 m and threaded connections pin at one end and box at the other. This enable double collars to be screwed with each other along down hole tools to compose the bottom hole assembly

The main functions of drill collars are:

- To supply enough weight on bit for active drilling.
- Keeping the drillstring under tension, thus reducing bending stress and failures
- To provide for directional control stiffness in the BHA (Mitchell 1995).

1.1.6 Stabilizers

Stabilizer is a short piece of pipe (1-1.5 m) with steel spiral blades of the same diameter of the bit or slightly smaller as depicted in Figure 1.3. It is added to drillstring in order to keep the borehole in vertical profile. The placement of stabilizers in drillstring depends on the design of the wellbore trajectory. Therefore, there are two types: near bit and string stabilizers. In addition, they are also help in deviation control, extreme dogleg and avoid differential pipe sticking. They manage these functions through centralization and extra rigidity of BHA. Additionally, they might increase the bit performance(F. Mitchell and Z. Miska 2018).

There are two types of stabilizers basically:

• Rotatable Stabilizers.

• Non rotatable Stabilizers.

Rotating stabilizers include integral blade Stabilizer, sleeve stabilizer, and welded blade. Stabilizer are machined from high quality solid parts such as artificial diamond and Tungsten carbide. The faces of the blade are coated with Inserts of carbide sintered from tungsten. The blades could be either straight or spiral. On the other hand, rubber sleeve and a mandrel are included within the non-rotating stabilizers design. The sleeve has been Predicted to stay constant whilst rotating the mandrel and drill string. This form is used during drilling activity to avoid reaming of the hole walls and to protect the drill collars from damage due to contact with wellbore wall (Etal 1966).

The main functions of stabilizers are:

- Reduces drill collar buckling and bending stress.

- Allow higher weight on bit.
- Avoid sticking of drillstring.
- Increase service life by reducing vibrations.

1.1.7 Drilling Jar

Jars provide a way of creating the shock with effective for releasing stuck drillstring up or downwards. The jar is a mandrel that slips inside a sleeve. The two ends of the mandrel is molded in the form of a hammer to act strikingly against the anvil 's face. There are two basic types of jar depending on the type of tripping mechanism.

1. Mechanical jar: own a presetting load causing the jar to move when the knocker attack the anvil. It is also sensitive to the load being used; this kind of jars is time independent therefore any time delay will not affect the jar action.
2. Hydraulic jar: to control the release of the jar, a hydraulic fluid is used, so that the drilling operator can apply the load on the drillstring to maximize jarring effect. This control the action (delay) that is supplied by Fluid pressured through a small ports or series of jets. Hydraulic jar firing delay is dependent upon the combination of load and time. Hence hydraulic jars are adjustable according to downhole overpull (W. Evans 1993).

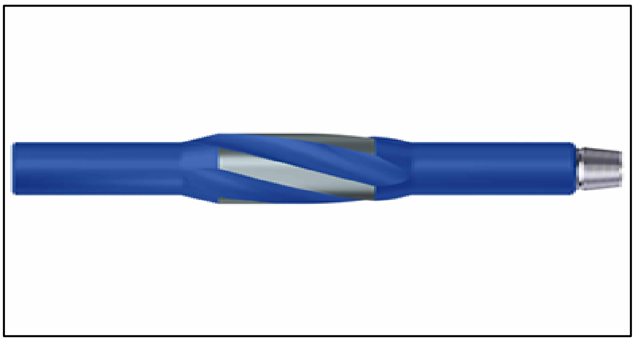


Figure 1. 3 drillstring stabilizer (courtesy of schlumberger).

1.1.8 Drill bit

A drill bit is the cutter tool that is existed at the end of the drillstring. The bits penetrate the formation by scratching, chipping, or grinding the rock at the bottom of the borehole. The drill bit is continuously got rid of cuttings throughout the mud circulation at the bottom of the wellbore, otherwise bit balling may develop. Drill bits can be classified into two main categories:

1-Roller Cone Bits: It is obvious from the name; the roller cone bits are usually composed of three cones of equal size and three identical legs connected by a pin. Each cone is attached to bearings that act on a pin forming an integral part of the leg of the bit. Welding and connecting the three legs together form a cylindrical section attached with threaded neck to produce a pin link. The pin link is the linking point between the cutter portion and the drillstring. Each leg has a channel for fluid circulation. The size of this channel can be controlled by using nozzles of different sizes. As shown in figure 1.4 a.(Chen and C. Sui 2008).

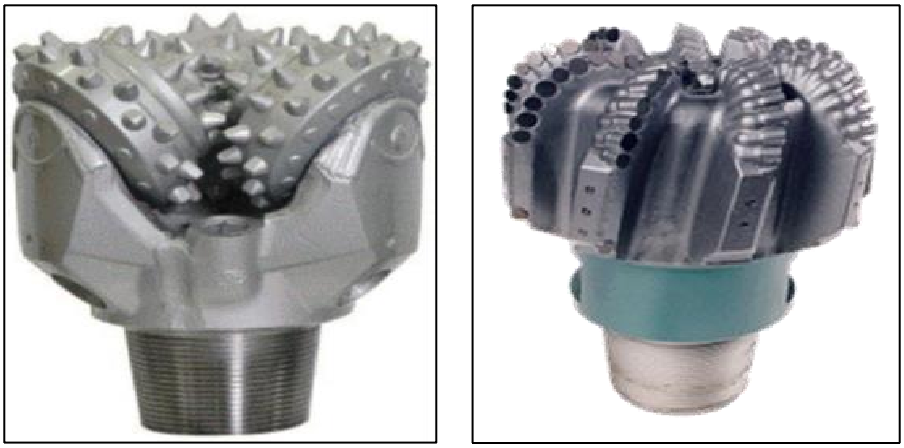
Roller cone bits can be divided into:

A. Milled Tooth Bits: The cutting frame of the cone is made of grinding steel.
B. Insert Bits: -The cutting structure is a set of pressed inserts into the cones.

2-Fixed Cutter Bits: There are no moving parts (i.e. there are no bearings) in the polycrystalline diamond compact (PDC) bit as clarified in figure 1.4 b and are designed to drill rocks in shear not in compression as in the case of the roller cone bit. Breaking the rocks by shear requires much less energy than in compression. Here we can use less weight on bits, resulting in less tearing and wearing on the drilling rig and the drillstring (Yahiaoui et al. 2013).

There are three types of fixed cutter bits

- Natural Diamond Bits.
- Synthetic Diamond Bits (PDC Bits, TSP Bits, Impregnated Bits).
- Drag bits.



(a) (b)

Figure 1. 4. Roller cone bit (Courtesy of Baker Hughes). B. Fixed cutter bit, PDC bit (courtesy of Smith).

1.2 Problem statement

As the drillstring travels down a hole, undergoing various of subsurface condition including vibration tension, compression, torsion, friction, formation pressure and circulated fluid pressure. All of them can lead to drillstring failure if they are not properly controlled. In particular, these vibrations can disturb the accuracy of the drilling operations and can cause fatigue-related harm. Drillstring vibrations are highly complicated because of the random nature of a multitude of agents such as bit and formation interaction, drillstring and wellbore interaction. Therefore, it is important to conduct vibration research, to understand its consequences and to find ways to avoid it. Through this thesis, Finite Element Analysis (FEA) was applied to investigate the vibration of three real cases of drillstring with different configurations and diameters that subjected to lateral vibration.

1.3 Objective and scope of thesis

The main goals of this thesis are:

- Modeling of a drillstring using Finite Element Analysis softwares like

  ANSYS and LANDMARK.
- Include the drillstring components in the model and carry out *modal* and *harmonic* analysis.
- Conduct modal analysis on the aforementioned model to determine the first three critical frequencies, critical velocities and mode shapes.

- Harmonious study of the critical component in order to understand the frequency response to lateral displacement.
- determine the frequencies where resonance occurs to avoid working in these parameters.

1.4 Thesis Structure

The study consists of the introduction, which include explanation of the thesis background, a description of the rotation system, definition of the drillstring with satisfied introduction of each component and the function of every single part of the drillstring. In addition, a demonstration of the problem statement, identify the objectives and scope of the thesis. The literature review was exploited to explain the effects of drillstring vibrations, supply an overview about past researches in drillstring vibration and concluding remarks.

Through the review, the methodology which include the importance of lateral vibration, display the most important equations in mathematical analysis, drillstring lateral vibration, natural frequency, definition of resonance and its impact on the drillstring during drilling operations. Furthermore, there is a brief overview of the Landmark software with the most important applications that are needed in the calculations part of this thesis. The Finite Element Analysis (FEA) has been described briefly. Thus, clarification of Modal and harmonic analysis of the drillstring was implemented after obtaining the results from the software and the outcomes were discussed deeply. The ANSYS program was employed to determine the frequency of the drillstring that used to drill of a vertical well in Zubair field and compare the results with Burges Model who used the mathematical equations to calculate the frequency of drillstring. The software was utilized as well to determine the areas where resonance occurs to avoid working in this region. On the other side, the LANDMARK program has been invested to study the effective tension, weight on bit and buckling. The previous three parameters have direct contact with the lateral vibration. Eventually, it was concluded that the frequency which may cause the maximum vibration was 5.08 Hz, that vibration might lead to drillstring damage. Therefore, it is highly recommended to work in the range of reasonable vibration.

Chapter Two

LITERATURE REVIEW

2.1 Effects of drillstring vibrations

According to (Schlumberger 2010) Drillstring vibrations are also split into three lateral, axial, and torsional forms, as shown in Figure 2.1. The axial vibrations can produce bit bounce which can cause serious damage to bearings and drill bit cutters. While torsional (stick slip) vibrations can lead to random rotation down the hole. Stick slip is still evident during drilling and is a severe form of drill string torsional oscillations in which the drill bit stays steady for a while. The length of the stuck time rises as the stick slip becomes more extreme, while the rotational accelerations grow dramatically as the bit releases. Torsional fluctuations may cause fatigue of drill collar connections and in consequence can damage the bit.

Lateral vibration is the most disruptive form of vibration which cause great shocks as the bottom hole assembly impact the wall of the wellbore. Sometimes the interaction between BHA and drillstring results in reverse whirl, which is a serious type of vibration, causing a wide range of frequencies and huge buckling moment fluctuation. Accordingly, the drillstring components become under high fatigue level. There are a wide variety of possible causes of excitation including drillstring instability, deformation and trouble or twists, drill bit cutters action, blades of stabilizer, mud motors, and the coefficient of friction between borehole and drillstring.

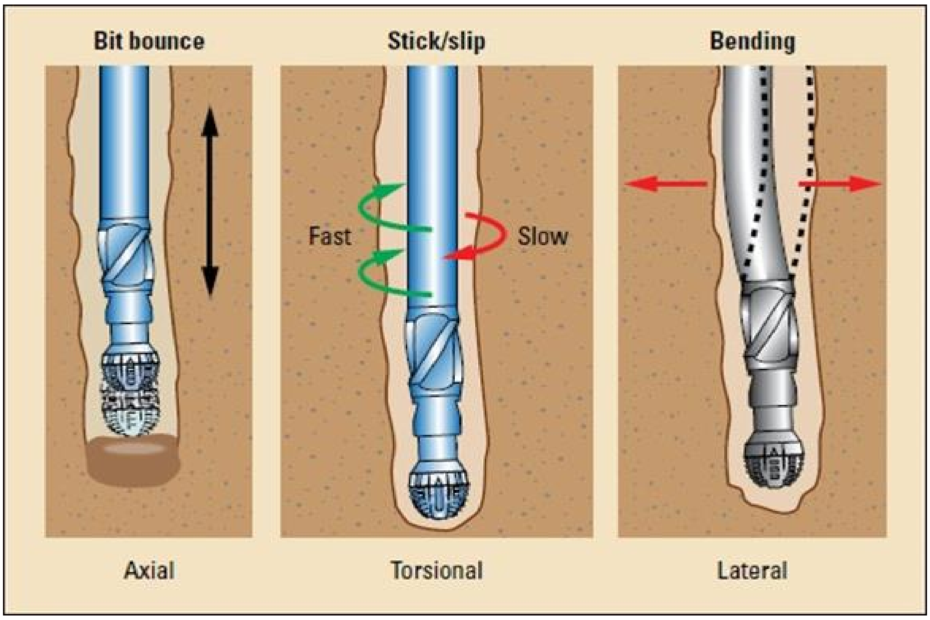


Figure 2. 1 types of drillstring vibrations (www.slb.com/drillingop).

2.2 Literature review survey

Wide studies are that carried out in the last fourty years on the drillstring vibration. The current literature on the vibration can be mainly categorized into publications based on axial, torsional and lateral vibrations. The latest literature surveys will provide an overview of publications related to the drillstring lateral vibrations. Although torsional, axial and lateral vibration are interacted with each other, mainly publications about lateral vibrations will be studied. Because the lateral vibration is the extreme harmful kind of vibration to the drillstring as mentioned the previous section.

Lubinski (1950): A comprehensive and systematic study has been presented in the vertical wells for the elastic stability of the drillstring. A solid foundation was established for the study of mechanics of the drillstring, and the theory provided anisotropy of formation in the drilling process. Critical conditions sites were also investigated. The points were located when the buckled pipe was Just in touch with the hole wall. The strength to which the wall was connected was determined (Lubinski 1950).

Bailey and Finnie (1960): At first analyses axial and torsional drillstring vibrations in vertical well through using equipment to calculate parameters of physical drilling, and then determine natural frequencies using the trial-and - error method. This paper provides a new knowledge of the causes and influence of the vibration of drillstrings and presents the result in terms of formulas that can be implemented directly by the drilling designer and users of tri cone bits. This paper was builder on these assumptions made in the analysis are as follows:

- The drillstring is uniform and continuous rods in each Segment.
- The drill bit is a roller cone bit.
- the system is an undammed forced vibration.
- Hole inclination and curvature do not affect drillstring vibrations.
- There is no distance or speed of slip between borehole and drill bit.
- The teeth which touch the bottom hole share the weight of bit (Jiang Han 1960)

Mitchell and Allen (1987): By using finite element harmonic analysis to verify that in 8 cases studies involving real BHA failure critical rotation speeds that can be accurately Linked to the terms of operation at the time of failure. The model takes into account the impact of the drilling mud mass that was overlooked in previous studies. Additionally, the reversing stress measured for the critical working speeds exceeded the connections' durability limits and happened at the BHA's positions where failures were observed. These comparisons to field data are the first steps in creating model reliability, so it can be used as a tool for selecting operating speeds or evaluating BHA designs with confidence (Mitchell and Allen 1987).

Skaugen (1987): Investigates the effect of semi-random vibrations bit on drillstring attitudes. The quasi-random vibrations are produced by the roughness of formation strength, random rock breakage, and amplification of effects by coupling of the vibration mode. It through the resonance peaks and smooths them out. In fact, these raised vibration models predict severe amplitudes when rotary velocity in the drillstring Is certain resonance frequencies subharmonic. The current model here shows how these resonance peaks are severely reduced and smoothed by considering the observed quasi-random existence of the drill bit vibrations the model findings are correlated with the vibrations of the drill string experienced while drilling and while using an exciter downhole(Skaugen 1987)

Vandlver et al. (1989): Describe two sources whirling motion and bending vibration of BHA, i.e. Drill collar whirling and linear coupling of Weight to Bit (WOB) variations and lateral displacement of the curvature of BHA.Downhole bending moment measurements are proved useful in the detection and identification of bending vibration events. Downhole data taken from a Shell field test of a downhole vibration measuring Device is used to illustrate cases of vertical bending, forward and reverse whirl and bit bounce (Vandiver and Shya 1989)

Brakel and Azar (1989): Present a 3D dynamic model of BHA idealization by finite-element algorithm in a horizontal well. This model is composed of inertia properties that predicted the BHA 's transient dynamic behavior during drilling. To solve the motion equation for this model, the Wilson-based Form of numerical analysis and a Gussian exclusion algorithm are used. They suggest that the bit and rock interaction should be considered to accurately predict the BHA's inclination and azimuth behavior, because bit and rock interaction is an important part of BHA behavior. They develop two models of bit and rock interaction, i.e., roller-cone bit and polycrystalline-diamond-compact (PDC) bit, to ensure the proper boundary conditions at the bit and rock interface. Radial clearance is the distance between the well-bore and the drill string. Influence on BHA behavior is a significant factor. But rotary velocity does not mainly affect the BHA's azimuth response.(Brakel and Azar 1989).

Paslay (1992): An analytical model is explained in detail which predicts the oscillatory movements and forces at the top of a drill string due to forward whirl of the bottom hole assembly at a lateral BHA resonance. Geometry and amplitude structure of the BHA mode are used in a scheme that converts the lateral movements into sinusoidally shifting axial forces and tangential impulses that work on the BHA. Then, the whole string is evaluated for the waves propagating axial forces and torsional impulses. In this way the complex axial and torsional reaction at the top of the drill string can be used for determining BHA forward whirls at each of the lateral BHA resonances. The model was incorporated for practical analyzes in a computer program (Paslay et al. 1992).

Kriesels et al. (1999): Propose an integrated approach that decreases BHA and drill pipe vibration, increases drilling efficiency, such as penetration rate and bit life, and saves costs due to reduced well days and tool failure prevention. It consists of applying a soft torque rotary system to eliminate BHA and bit vibration, vibration analysis software for BHA design, cost-effective deployment of vibration monitoring tools, and frequent inspection of components of drillstrings. Kriesels integrated approach consists of the following elements:

- Applying a smooth Torque rotary mechanism (electric and mechanical rotary drives) for eliminating BHA and bit slip stick vibration.
- Use vibration analysis software to design a BHA to avoid buckling and to recognize stable running rotary speed windows.
- The cost-effective implementation of vibration monitoring instruments.
- Standard inspection of components in drill string (Kriesels et al. 1999).

Heisig and Neubert (2000): He derived and provided an empirical solution for the natural frequencies. They compare three separate models, linear analytical model, linear finite element model and non-linear finite element model, in continuous contact with the wellbore on the lower side of the hole for lateral drillstring vibrations. Animated simulations of this model on a time domain offer a greater insight into the complex behavior of the drill string. The Conclusions on improved drilling practices in extended-reach applications are drawn from the theoretical results-especially with regard to hole cleaning problems (Heisig and Neubert 2000).

Richard et al. (2002): Describe a model that takes the axial, torsional, and axial-torsional vibrations coupled together. The laws governing bit-rock contact generate axial-torsional, coupled vibration. These interaction laws account for frictional contact, the cutting step of the bit-rock interface and potential loss of frictional contact between wear-flats and rock. In such conditions the occurrence of self-excited movements happens by the delayed and coupled nature of bit-rock touch and transition to stick-slip. Ground measurements agree with the characteristics of the torsional motions expected by this model. The vibration induced by drilling assembly while drilling with PDC bit increases bit wear and may lead to sudden fatigue failure of the string or breakage of the bit itself. According to a study conducted by (Henry Henneuse 1992) the occurrence of stick-slip corresponds to about 50 % of the drilling time at the bottom .(Richard et al. 2002)

Abdollahi and Skalle (2003): Use a case study to describe the challenge during the drilling situation and identify that the most probable factor to induce drill string failure in the potential risk formation is drill string vibration in a torsional mode (Abdollahi and Skalle 2003).

Chen et al., (2003): This paper presents a recently established 'intelligent' approach for resonance reduction and vibration minimization. The platform incorporates real-time BHA dynamics software and real-time hole vibration data to provide precise modelling results and data analysis. Unlike standard BHA dynamics applications running for well-planning or post-run analysis, this device uses real-time data (e.g. WOB inclination, DLS) to generate real-time alerts of critical rotary speeds. Updates are then expressed along with rotational speed to indicate whether the rotary is too close to one of the crucial rotational speeds predicted. Furthermore, to validate the actual downhole state, the simulation outcome can be correlated with real-time vibration data from a hole. Field results shows that the new method is successful in recognizing the vibration pathways and preventing harmful vibration (Chen, Smith, and LaPierre 2003).

Hemphill and Ravi (2005): Investigate the effect of rotation of drill strings on axial flow from a fluid dynamics perspective. They use the rheological model Herschel-Bulkley to calculate the characterization of the shear rate throughout the annulus, coupled with pure laminar flow and rotation. In normal drilling and circulating conditions, it is better to understand annular flow behavior when the effect of drill string rotation on axial velocity is mathematically characterized (Hemphill and Ravi 2005).

Chi et al., (2006): This study examined the combined influence of torsional and axial vibration on drillstring damage. A computerized model for simulating axial and torsional vibration loads was built. An analytical method was created to predict the tiredness of drill string life. The way uses the computerized model output. Engineering charts for typical drilling conditions were also created. These charts have been adjusted in the song Liao basin, China, drill string damage control program (Chi et al. 2006).

Aslaksen et al. (2006): Create a Finite Element Method (FEM) program to solve four-dimensional, time-based simulations of the entire drilling cycle on Unix platform. Their method partners with drilling tool cutting mechanisms and BHA's and drill pipe actions to forecast the efficiency of the drilling process reliably. They take into consideration the actual bit size, rock properties, drilling conditions, the capabilities of the BHA and drill shaft, and the interaction of those forces. They analyze the effect of WOB and rotary velocity on the BHA and drill pipe axial vibration, lateral vibration, torsional vibration, and buckling. This simulation software can be used by operators to determine the overall drilling performance based on drilling design and configure drilling parameters to avoid extreme vibrations (Aslaksen et al. 2006).

Hakimi and Moradi (2010): They used the technique of differential quadrature (DQM) to evaluate the vibrations in a near-vertical hole of the drill string. Next, a nonlinear static analysis is conducted to determine the effective duration on the borehole wall of the string it lies in. The precise form of the curvature of the beam can be used for string design. The system is modelled by a series of springs mounted along its length to represent the contact between the different sections of the drill string and the wall of the borehole. Then the DQM is extended to the nonlinear differential equations of the drill string parts and to those defining the edge and interface boundary conditions. The Newton-Raphson algorithm is used to solve the nonlinear equation system. Next is done a free vibration study to determine the normal frequencies of the drill line. Free vibration analysis is conducted using the effective length derived from static analysis to determine the natural lateral frequencies of the drill string, while the maximum length of the string is used to measure its natural frequencies, axial as well as torsional (Hakimi and Moradi 2009).

Ghasemloonia et al., (2013): Examine the simultaneous axial transverse displacement of the drill string under the rotary drilling effect aided by the displacement. They build a complex finite element system model with a particular BHA and this model includes the effects of mud damping, moving torque, dual contact and temporarily axial load shift. In this thesis, the dynamic mathematical model defines two different types of friction forces, i.e., kinetic friction and fluid friction, in the horizontal wells. The kinetic friction is the force between the BHA and wellbore, and the effect of drilling fluid into the BHA is the fluid friction. This model can be used to investigate the effects of the axial vibration parameter on the drilling. Oil or gas companies use this model to predict the axial vibration depending on the workplace conditions and adjust the drilling parameter automatically to control the axial vibration (Ghasemloonia, Geoff Rideout, and Butt 2013).

Majeed (2013): By applying an unqualified drill bit model. The methods used for the system were black box. Results of the simulations were obtained with residual 0.05 %. Two major causes aggravated the vibrations in rotary drilling: borehole friction and critical speed of operation. This research developed an autonomous tuning Adaptive controller that might effectively mitigate the aggravating causes of vibration and Improve drilling efficiency overall. The controller automatically switches to practical application. Detected vibrations, mitigated the aggravating causes of the vibrations and resumed normal drilling in less than 10 seconds. The controller action was experimentally proven in two cases: (1) when borehole friction was affected, and (2) when an unbalanced drill bit was present. The experimental data validate all experiments and control techniques applied in this thesis (Majeed 2013).

Pan (2014): Due to different loads, vibrations occur axial loads such as a hook load and drill string weight, final torque applied by surface motor and restricted at the bit, fluid drag force, and contact force between the well wall and the drill string. To describe the stable state of the drill string, a mathematical model was assumed to represent a mixture of fixed and variable loads that affect drill string behavior. The analytical method and the Riley Ritz method obtain the first critical values for these loads, and the corresponding position shape. COMSOL and ABAQUS are used without analytical solutions to verify numerical results of the cases. Here with Results, we see that the Rayleigh-Ritz method gives precise results and predicts drilling system instability (Pan 2014).

Al Dushaishi (2015): One of the factors that influence the drilling string vibration is the drilling environment and design decisions. Examples are; Bottom hole assembly configurations, operational parameters, nature of lithology. Vibration modelling, vibration data analysis, and specialized vibration reduction tools. Using a non-linear stress that combines all types of vibration, the model has two new tools to reduce vibration, developed. The obtained motion equation was compiled using MATLAB digitally solved finite element analysis. Sensitivity analyses the Euler-Bernoulli and Timoshenko models both revealed that the Euler-Bernoulli assumption was adequate when modeling the vibrations of the drill string under normal drilling conditions (Fayez and Dushaishi 2015).

Greenwood (2016): This research aims at discovering the root causes and means of vibration elimination. Three vibration modes exist: axial, torsional and lateral, and six degrees of freedom. We use this to define the different vibration processes. Like stick / slide, bit jump, bit whirl, BHA whirl back and forth together, torsional ripple, bit chatter, conditional pairing and side shocks. The real cause is defined and improved by the capacity to summary the distribution of vibration levels by operating and graph analysis, and the ability to filter around depth and time scales, and further filtering depending on the operation codes of the drilling site, through surface indicators and wellbore observations. There are many factors influencing the vibration of the drill string, like WOB and TRQ force inputs, bit, BHA geometry and stability, type of lithology, geological formations, boring geological contact, size of the borehole and size of the BHA, route hole, rotating from the stabilizers blades, extension of the pit, electrical system of the rig, and on naval floating ships. (Greenwood 2016).

Kudaibergenov (2017): They focus on the topic of highly nonlinear of the resonance regimes of a drill string under the control of changing compressive axial force. The drill string is simulated as an isotropic, elastic rotary rod with hinged ends. Deformations of the drill string are called finite. Using Galerkin 's approach to a statistical analysis of lateral vibrations in the drill string reduces the generalized time function to an ordinary differential equation which is nonlinear. The magnitude-frequency characteristics of the resonances are computed by adding the frequency domain procedure on base and higher frequencies. As a result of numerical study of the influence of dynamic system variables on the resonance curves, significant nonlinear effects of the amplitude-frequency properties of the drill string vibrations are reported. Recommendations for choosing optimum constructive and competitive properties of drill strings (Kudaibergenov, Kudaibergenov, and Khajiyeva 2017).

Chacin (2017): Two distinct findings have been discussed in this study. The first study compares six different cases to a simpler range of the bottom hole assembly and suggests that when one vibration mode is added, the vibration response is greater than if all three vibration modes were put into the device. The second study extended, with four different materials compared. As the previous study, it was also inferred from this analysis that the vibration response behavior is predictable according to established analytical models when one vibration mode is implemented, but when both modes are present in the device, the behavior varies greatly**.** (Chacin 2017).

2.3 Concluding Remarks

The literature review was performed to explain and examine the scope of the studies and draw the researches goal. Because of the wide range of research areas within the drillstring vibration, the researches were classified into categories to simplify the review. The conclusions in the observed and analyzed major categories are described in the following sections:

- **Drillstring vibrations and their causes.**
- **Mathematical models of rotary drilling describing the dynamic of drillstring.**
- **Bit whirl causes: Bend drillstring, and Bit bounce.**
- **The drillstring vibration minimizing solutions.**
- **Analysis of drillstring vibration by using different softwares like ANSYS, COMSOL and ABAQUS.**

The previous researches investigated most cases of the drillstring instability as mentioned above. Therefore, this study aimed to apply some of previous studies by taking real data represented by three BHAs of sections size 17 ½'' ,12 ¼'' and 8 ½'' from one vertical well (Zb-202). Commercial softwares ANSYS and LANDMARK have been invested to obtain natural frequency and resonant vibrations of the drillstring. Hence, that might help for using the suitable drilling parameters to minimize drillstring vibration, deformation and improve drilling performance.

CHAPTER THREE

METHODOLOGY

3.1 Importance of the lateral vibration

Lateral vibration is described as a non-centered rotation of the bit and/or bottom hole assembly (BHA), which causes lateral effects with the wellbore sides. The mass component relates the system's forces and acceleration (Newton's 2^{nd} law). The motion of this mass is what generates the potential energy of the system. Whereas, the stiffness of the drillstring components are related to the system's forces and displacement as per Hook's law. This motion is produced and sustained by the Drillstring rotation. The drillstring rotation results in a complicated imbalance, which causes lateral, torsional and axial vibrations. There are three forms of lateral vibration as listed below:

A. Bit whirl: defined as bit rotating around axes which is not compatible with the drillstring axes. This kind of vibrations is popular with PDC bits.
B. Forward BHA whirl known as off-center BHA rotating, with rotation in the middle line The same rotational orientation for the drillstring.
C. Backward BHA whirl happens where the friction between the borehole wall and drillstring attempt to obstruct the drillstring rotation in forward direction.

The lateral vibration could be decreased or increased by several factors:

- Kind of bit.
- Lithology.
- Stability and centralization of BHA.
- Hole profile with new bit (tapered hole).

Because lateral mode does not move to the surface immediately, the effects of the lateral vibration remain unrecognized for a period of time. With the measurement while drilling (MWD) technology, vibration is recognized more easily than conventional drilling technology. Lateral vibration can cause serious damage to the wall of the borehole and affect the direction of the drilling. The BHA whirling is most important type of the lateral vibration phenomenon. Whirling is a state in which the immediate center of rotation shifts around the bit face as the bit rotates which can be forward, backward, or chaotic (Brett, Warren, and Behr 1990). The vibration amplitude resulting from bit whirl increases with the formation strength for both PDC and tri-cone bit. The frequency of the bit and bottom hole assembly in the range of 5 to 100 Hz as illustrated in the Figure 3.1 depending on the rotation speed and the number of bit cutter (Esmaeili et al. 2012).

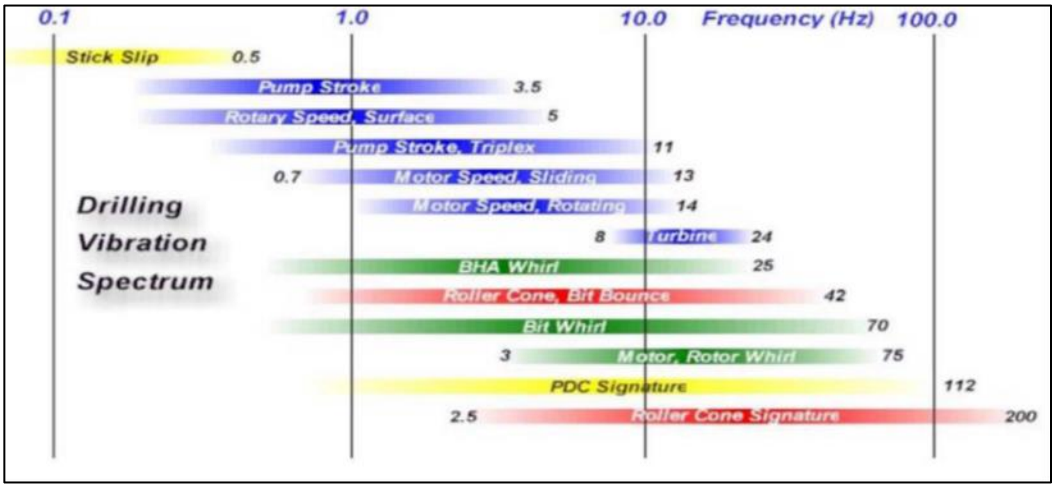


Figure 3. 1 drilling vibration spectrum of frequency ranges (Macpherson et al 1993).

Most of the BHA components are under compression while drilling where buckling and whirling can occur. On the rig floor high whirling can be observed the horizontal movement of the moving block and the whipping of the line. What is more, reverse whirl is the most common type of lateral vibration. If the pressure between the stabilizers and the borehole exceeds the powers of structural and hydrodynamic damping, there can be lateral vibration.

Lateral Side effect including backward and forward whirling occur, when the rotary speed increases, this ultimately affects the borehole wall and parametric instability (Yigit and Christoforou 1998). Additionally, it is diagnosed that if a rotating drill bit abruptly stopped, the drillstring will rapidly whirl. Consequently, this leads to a disastrous drillstring collision with borehole wall based on the energy change in motion (Tucker and Wang 1999).

3.2 Mathematical Analysis of drillstring lateral vibration.

The model was developed by Spanos in 1992, using a single degree of drillstring freedom description in which a massless the torsional vibration occurs. k stiffness models the total drilling bottom hole assembly length. The rotary table drives the drillstring at a constant velocity Ω on the surface, which makes the motion equation in the form of:(Spanos and Payne 1992)

$$I\ddot{L}_{\emptyset} + C_r L_{\emptyset} + F(L_{\emptyset}) + kL_{\emptyset} = k\Omega t \qquad 3.1$$

Where $L_{\emptyset}$ is the angular displacement of the BHA, C_r is the viscous damping coefficient, k stands for the tensile rigidity of the drillstring, I is the mass moment of inertia with respect to the rotation axis, and F(ϕ) is the friction induced forces. In fact, by normalizing the previous equation (3.1) at the moment of inertia, and by obtaining the following equations

$$\ddot{\emptyset} + 2\xi\omega_0\dot{\phi} + f(\dot{\phi}) + \omega_0^2\Omega t \tag{3.2}$$

Where

$$\omega_0 = \sqrt{\frac{k}{I}} \text{and} \xi = \frac{c_r}{2\sqrt{KI}} \tag{3.3}$$

And $f(\emptyset)$is in the form of

$$f(\dot{\phi}) = \begin{cases} F_S - \frac{F_S - F_{SS}}{V_0}\dot{\phi}, & 0 \le \dot{\emptyset} < V_0 \\ F_{SS}, & V_0 \le \dot{\emptyset} \end{cases} \tag{3.4}$$

In the above equation the parameters F_S, F_{SS}, and V_0 depend on the drilling assembly's physical characteristics. These fundamental formulas take into account the friction factor when the system is switching from a static to a kinetic state. The continuous lateral vibration model was developed with previous fundamental equation. Furthermore, the principle of the Euler-Bernoulli beam is considered, and the assumption of the low slopes is adopted. The Euler-Bernoulli equation consists of:

$$\rho\frac{\partial^2 u}{\partial t^2} + \frac{\partial^2}{\partial x^2}(EI_z\frac{\partial^2 u}{\partial x^2}) = g(x,t) \tag{3.5}$$

Where u (x, t) is the lateral displacement, ρ is the mass density, E is the elasticity module, and I_Z is the related moment of inertia of the beam's cross section, and finally, g (x, t) is the external load. Therefore, if consideration is given to the axial force the equation will become:

$$\rho\frac{\partial^2 u}{\partial t^2} + \frac{\partial^2}{\partial x^2}(EI_z\frac{\partial^2 u}{\partial x^2}) - F_P\frac{\partial^2 u}{\partial x^2} = g(x,t) \tag{3.6}$$

Where the FP stands for axial force.

Whirling is the most important phenomenon in lateral vibrations. Several studies have addressed this phenomenon in two-dimensional assembly. Single lumped mass is demonstrated by the equations of motion with a constant rotary speed at equal distance between two stabilizers (Vandiver and Shya 1989)

$$m\ddot{y} + C_w L_y + k_w L_y = me_0\Omega^2\cos(\Omega t) \tag{3.7}$$

$$m\ddot{z} + C_w L_z + k_w L_z = me_0\Omega^2\cos(\Omega t) \tag{3.8}$$

Where Ly and Lz are the lateral coordinates, m is the collars equivalent mass, C_W is the damping coefficient, kw is the collar's equivalent lateral stiffness, e_0 is the center of mass's eccentricity, and Ω is the drilling assembly's rotational speed(Saldivar Márquez et al. 2015).

3.3 Natural frequencies

Natural frequencies are frequencies at which the system tends for moving and vibrating. Every natural frequency has an associated mode form as presented by Figure 3.2. In this figure the top portion refers to the lateral displacement in the borehole of a restricted pendulum bottom hole assembly. In addition, the natural frequency depends only on the system properties, such as mass, shape, material, etc. The initial conditions do not influence the natural frequency of the system. On the other side, the static analysis is utilized to identify contact points of the bottom hole assembly (BHA) which are used in the lower section of the figure to measure the natural frequencies and mode shapes of the system (Schlumberger 2010).

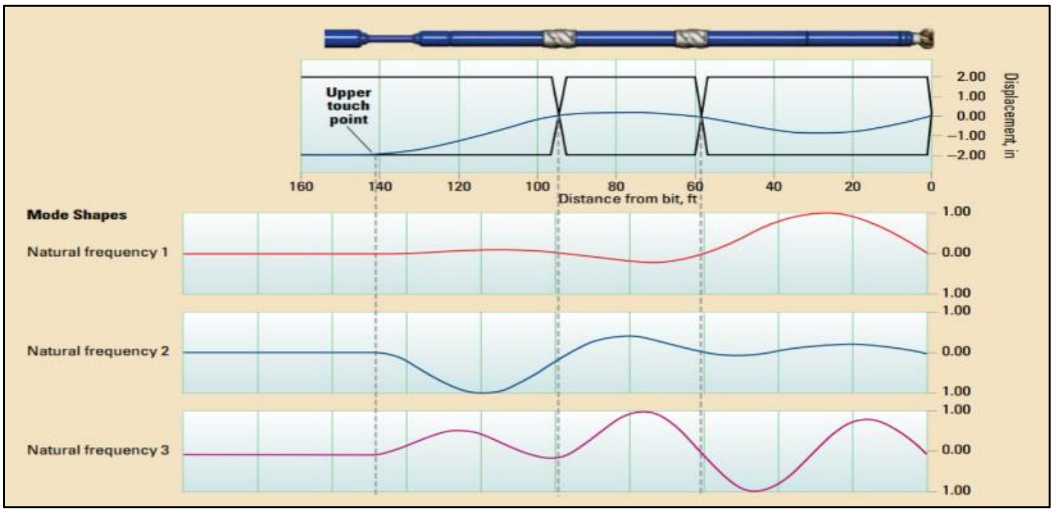


Figure 3. 2 first three natural frequencies. (schlumberger 2010).

3.4 Importance of Resonance

The Resonance occurred when the driving frequency is equal to the system's natural frequency and this is called resonance. Self-excited vibration occurs when the system's natural frequency is similar to the input force intensity. Unlike free vibration, this disturbance is long-lasting, and unlike forced vibration, the disturbance is continuous rather than regular, and varies across its natural frequency. A good example given by Schmitz and Smith (2012) is the sound created by a bow and a string in a violin, depending on the speed at which the bow travels across the string, the friction between the string and the bow creates vibrations that generate different sounds. Figure 3.3 shows the resonance curve, when the resonance occurs, it will damage the drillstring and can create highly energetic and sustained lateral impact with wellbore. It can cause fatigue in the connection of the drillstring .(Schmitz and Smith 2012).

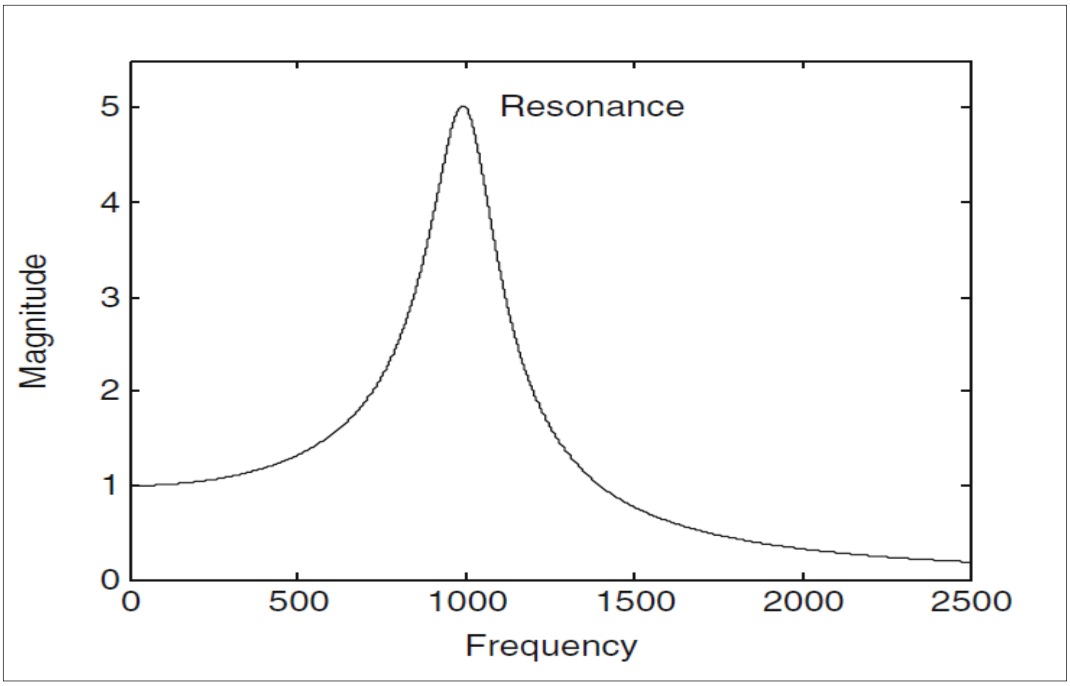


Figure 3. 3 The Resonance curve (Schmitz and Smith 2011).

3.5 Landmark software Analysis

The landmark software considered one of the most famous programs used in the oil industry, it was developed by Halliburton. The software has been used by oil companies for more than 25 years for well design in safe and cost-effective manner. Landmark is able to solve the complicated well-string operations involves thorough research in order to determine the main aspects of each pipe-related operation within the wellbore. The last version of the landmark resolves powerful and accurate engineering algorithms with significant improvements in ease of use and data visualization. Additionally, it allows the engineers to conduct better analyzes more quickly. WellPlan software offers the oil industry most extensive well-engineering tool kit and it is designated to minimize the cost throughout the lifecycle of well. Landmark is dedicated to do the following:

Optimize the Right techniques for any job: WellPlan software can help drill a wide variety of well styles from onshore, offshore, deep water, high-pressure high-temperature (HPHT), 3D spatial profiles, horizontal and extended reach (ERD) in choosing the right suitable rig and equipment, string components and fluids. Also, Landmark technologies can help predict threats and drill faster without losing operational protection.

Graphical visualization: The software is capable to construct the design requirement in 1D, 2D and three-dimensional figures, which simplify the interpretation of well design.

Hyperlinks the input data: perform faster and more accurate analyzes to support better decisions.

Sensitivity Analysis: Landmark software offers an efficient tool for general sensitivity analysis, rather than manual experiments or multiple analyzes running one at a time. Users may specify a set of values for the quantitative variables they like and execute the analysis simultaneously. In addition, detailed graphic representations allow for a fast analysis of the different alternatives (www.halliburton.com).

3.6 Finite element analysis of drillstring

The finite element analysis (FEA) is a well-known and commonly used analysis for numerically solving mathematical and engineering problems. Use of this technique begun in structural engineering with Hrennikoff 's research as early as 1941. The Finite Element analysis applications to the nonlinear drillstring vibrations was successfully achieved by Millheim in 1978 and the analysis was executed on the drillstring. In their design as demonstrated in Figure 3.4 by using beam components and a uniform grid of basic beam supports, they simplified the problem and found four different combinations of stabilizers placement (Millheim, Jordan, and Ritter 1978).

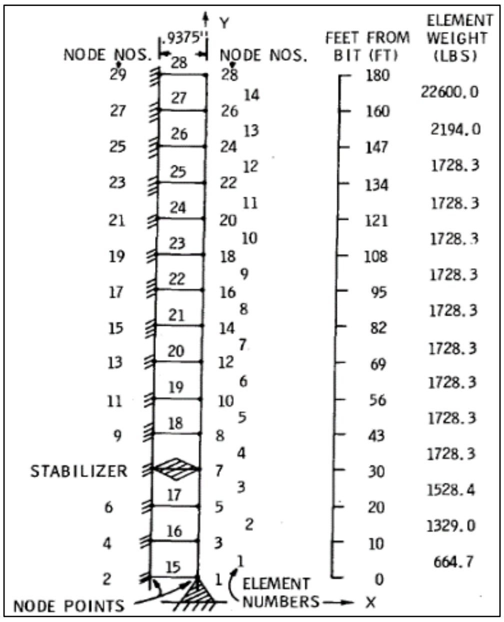


Figure 3. 4 drillstring simplification for FEA (Millheim 1978).

Since important development was already made about how this methodology can be extended to different engineering fields. This technique can tackle a wide range of problems including, but not exclusively: structural design, heat transfer, fluid flow, mass transportation and potential electromagnetic problems. The finite element analysis is very desired because of its implementation in a system of algebraic equations, rather than requiring differential equation systems to be solved. This technique works by fragmenting the structure at hand into small components which are linked through vertices called nodal points or simply nodes. Then, instead of trying to solve the physical and mathematical problem for the entire system in one step, the system is solved algebraically to combine and integrate the overall result for each node and element (Logan 2012).

The thesis presents a finite element analysis (FEA) using software ANSYS to investigate the lateral vibration of drillstring in a vertical well. ANSYS is a finite-element simulation software for static, dynamic structural analysis, heat transfer, fluid dynamics, acoustics and electromagnetic problem computing solutions. Modal analysis was used in this thesis to assess the vibration characteristics of the drillstring, using harmonic analysis. The typical structure of the modelling process using ANSYS is depicted in Figure 3.5.

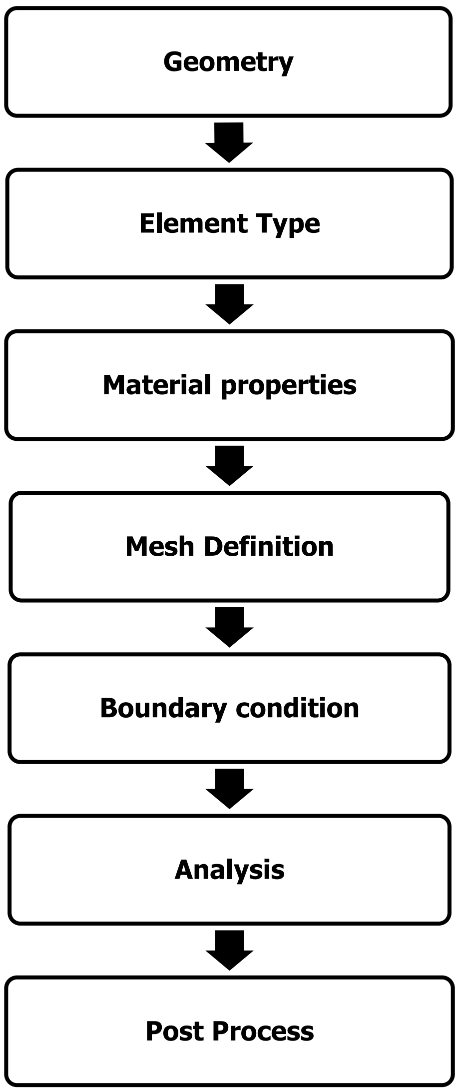


Figure 3. 5 Modeling with ANSYS

3.7 Drillstring modelling

In 1987 Burgess used a drillstring of certain specification for his vibration research. The information for this drillstring was collected from a field study that had been subjected to resonance failure. The drillstring effective length was about 213 m as shown by the Table 3.1. Approximately 3-3.4 Hz was found at the first critical frequency. Burgess performed a finite element analysis for the drillstring arrangement and observed by static analysis that the curves of the mode shape tend to be zero at 34.4 m. This means that the lateral vibration affects only 34.4 m of drillstring length which is taken as the cutoff point.

Therefore, in this study, the drillstrings is modeled up to 165 m, 319 m and 277 m. Nevertheless, the wellbore impact is taken into account by means of the boundary conditions that will be later defined (Burgess, McDaniel, and Das 1987).

Table 3. 1 Configuration of BHA used in study of Burgess

Description	OD (Inch)	Part length (m)	Prog. Length (m)
BIT	6.25	0.99	0.99
Stabilizer	4.75	1.95	2.94
DC	4.75	9.39	12.33
Stabilizer	4.75	2	14.33
DC	4.75	161.3	175.63
HWDP	3.5	37.9	213.53

3.7.1 Geometric modelling

In order to identify the influence of various lengths and weights on the drillstring vibration, the drillstring configurations are presented in the following tables.

Table 3. 2 Drill string configuration of section 17 ½"

Description	OD (inch)	Part length(m)	Prog. Length(m)
Bit	17 1/2	0.43	0.43
NB STB	17 3/8	2.40	2.83

Shock Sub	9 1/2	4.89	7.72
S stabilizer	17 3/8	2.38	10.10
9 ½ DC	9 1/2	9.37	19.47
S stab	17 1/2	2.45	21.92
3*9 ½'' DC	9 1/2	28.12	50.04
XOS	9 1/2	1.09	51.13
8*8 ¼ DC	8 1/4	75.44	126.57
Drilling Jar	8 1/4	9.53	136.1
3*8 ¼ DC	8 1/4	28.25	164.35
XOS	8 1/4	1.23	165.58

Table 3. 3 Drilling mud properties section 17 1/2"

Mud type	Mud Density(gm/cm^3)	Mud viscosity(s/l)	Mud Plastic viscosity(cp)	Mud yield point (gm/100 cm^2)
PHB	1.12	47	14	26

Table 3. 4 Drillstring configuration section 12 ¼"

Description	OD (Inch)	Part length (m)	Prog. Length (m)
PDC BIT	12-1/4	0.33	0.33
N.B. Stab.	12 1/4	2.26	2.59
8 1/4 DC	8 1/4	9.44	12.03
Str. Stab.	12-1/8	2.06	14.09
8 1/4 DC	8 1/4	9.45	23.54
Str. Stab.	12 1/8	1.95	25.49
12 x 8 1/4 DC	8 1/4	113.16	138.65
Jars	7 15/16	9.70	148.35
3 x 8 1/4 DC	8 1/4	28.00	176.60
X/O	8 1/4	1.23	177.83

15 x HWDP	5	141.27	319.10

Table 3. 5 Mud properties 8 ½"

Mud type	Mud Density(gm/cm^3)	Mud viscosity(s/l)	Mud Plastic viscosity(cp)	Mud yield point (gm/100 cm^2)
KCL Polymer	1.2	48	15	21

Table 3. 6 Drillstring configuration section 8 ½"

Description	OD (inch)	Part length(m)	Prog. Length(m)
bit	8 1/2	0.34	0.34
bit sub	6 5/8	1.23	1.57
MWD-GR	6 3/4	9.45	11.02
UPA sub	6 3/4	1.54	12.56
string stab	8 1/8	2.18	14.74
DC	6 3/4	9.45	24.19
string stab	8 1/8	2.26	26.45
12 x DC	6 3/4	113.19	139.64
jar	6 5/8	6.07	145.71
2 x DC	6 3/4	18.88	164.59
12 x HWDP	5	112.98	277.57

Table 3. 7 drilling mud properties section 8 ½"

Mud type	Mud Density(gm/cm^3)	Mud viscosity(s/l)	Mud Plastic viscosity(cp)	Mud yield point (gm/100 cm2)
WB	1.65	55	33	23

With the ANSYS software, the user can build up the drillstring with the bit, stabilizers, drill collars, heavy weight drill pipe and rotary table sequentially as follow

- Select mechanical model which will open onto a new window. On this window, geometry is selected that will allow geometric modelling.
- From the primitive's menu, cylinders can be created with proper dimensions.

The solid cylinder represents the equivalent of bit without its complex design. Similarly, the stabilizers with its specific outside and inside diameters are created. The drill collar, Heavy weight drill pipe and rotary table are all designed in a similar fashion as well. The following figure presented the geometry of the drillstring design (without scaling) applied for simulations.

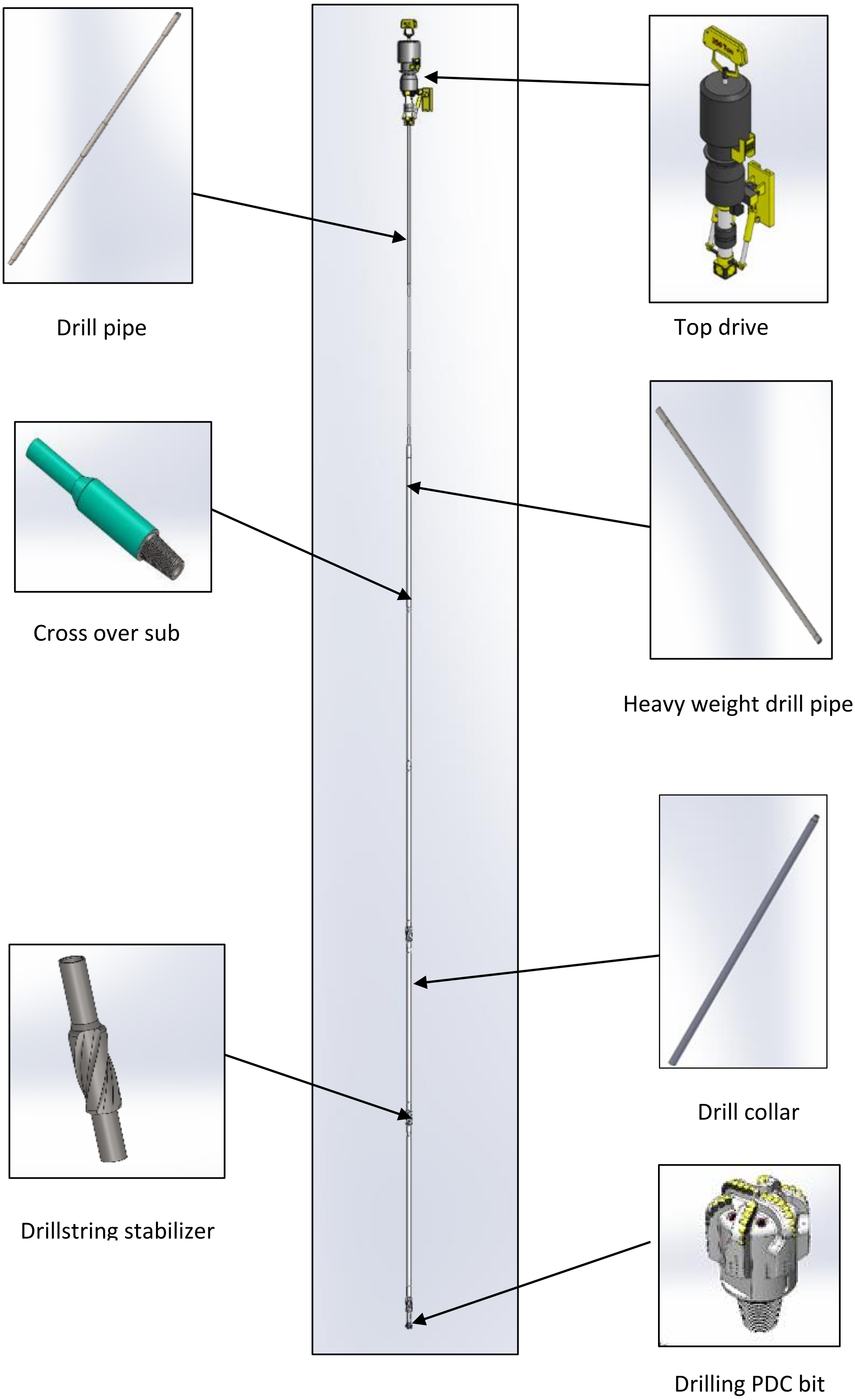


Figure 3. 6 drillstring design.

Since the mud effect will be considered in the analysis, the mechanical properties of drill string and mud are as the following table:

Table 3. 8 Drillstring material Properties

Drillstring	**Modulus of elasticity(kg/m^3)**	$69.5*10^9$
	Density (kg/m3)	7831.6
	Poisson ratio	0.23

3.8 The Numerical Analysis

The Finite Element Analysis (FEA) is now commonly used for the engineering and science in a number of fields. Taking advantage of the rapid development of high memory capacity digital computers and fast computing. Due to its capabilities which include complex geometrical boundaries and nonlinear material properties, FEA is recognized as one of the most effective numerical methods. Throughout this study, Finite Element Analysis has been used as a numerical method with the help of ANSYS Workbench 18.2 software to demonstrate the effect of fatigue performance on a structural feature to assess the behavior of total deformation due to natural frequency. By using ANSYS the general analysis includes three distinct stages which:

- Constructing model geometry.
- Apply the load limiting conditions and obtain the solution.
- Check the results.

3.8.1 Building up the geometry

The ultimate aim of study with finite elements is to mathematically re-create the behavior of an actual engineering system. In other words, the analysis of a physical prototype must be a precise mathematical model. The model comprises, in the broadest sense, all the nodes, components, material properties, real constants, boundary conditions, and other features used to reflect the physical system. The model was created using two different methods:

1-Modeling solid

2-Straight generation.

With solid modeling, the geometric boundaries will automatically determine the model, with defined controls on the size and desired shape of the components. Contrary to the direct generation process, node, scale, shape and connectivity of each entity can be identified by the position before defining those entities in the model. Solid modeling is generally more effective and flexible than direct generation and it is the preferred method for generating models, as an alternative to creating solid models. The model can be created via CAD system, and after finishing all the information in the model, the export option makes the work between the CAD system and the ANSYS group so easy. ANSYS Workbench 18.2 primarily deals with ACIS. (sat), Mechanical Desktop (dwg), Solid Works. (SLDPRT, SLDASM) ... and so on.

Consequently, the model's extension for solid work of software is SLDPRT and then export another copy to ANSYS Parasolid(*.x_t) simulation with extension framework for exporting operation. Afterword, according to its extension. (sat), the layout can be imported from the CAD framework into ANSYS Workbench 18.2.

3.8.2 Defining element types

The drillstring was modelled by the SOLID73 partion, which will be used to simulate the solid structures in three-dimensional models. This element is characterized as having eight minor nodes at each major node, with six degrees of freedom. The more the number of nodes is the more resolution in X-Y-Z directions and rotations across the orientation of X, Y and Z. This dimension is better suited to modelling solid structures and takes less time for solution. The elements Contact-176 and Target-170 describe the interaction between the elements.as shown in Figure 3.7

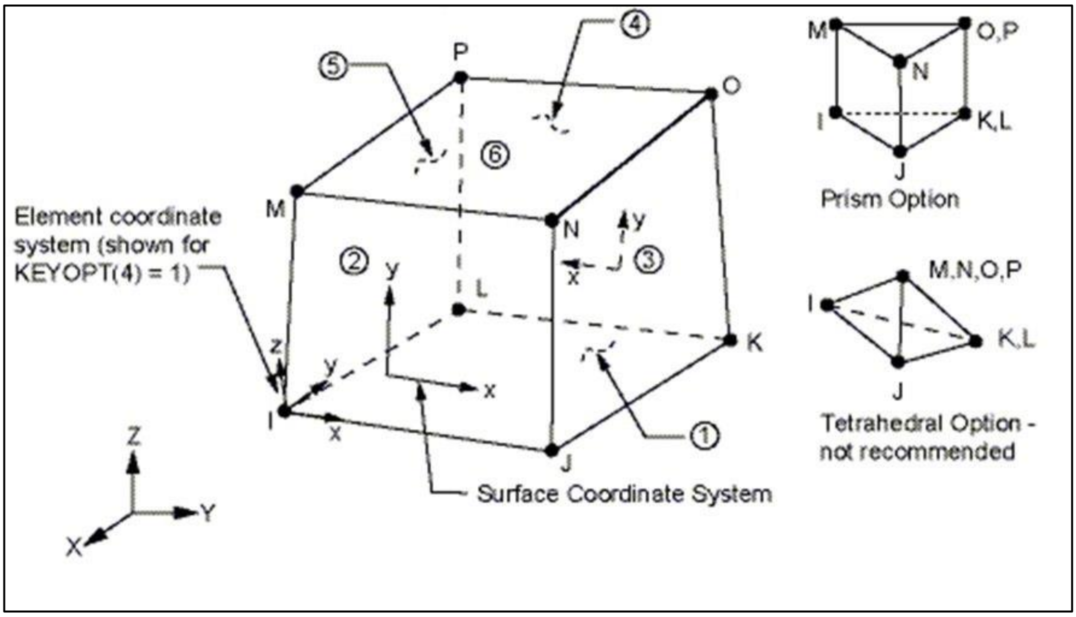


Figure 3. 7 element geometry Solid 73.

3.8.3 Creation of mesh in the drillstring models:

The meshing process was done by selecting the number, and then selecting the shape of the element as tetrahedron (Automatic meshing), as expressed in Figure 3.8.

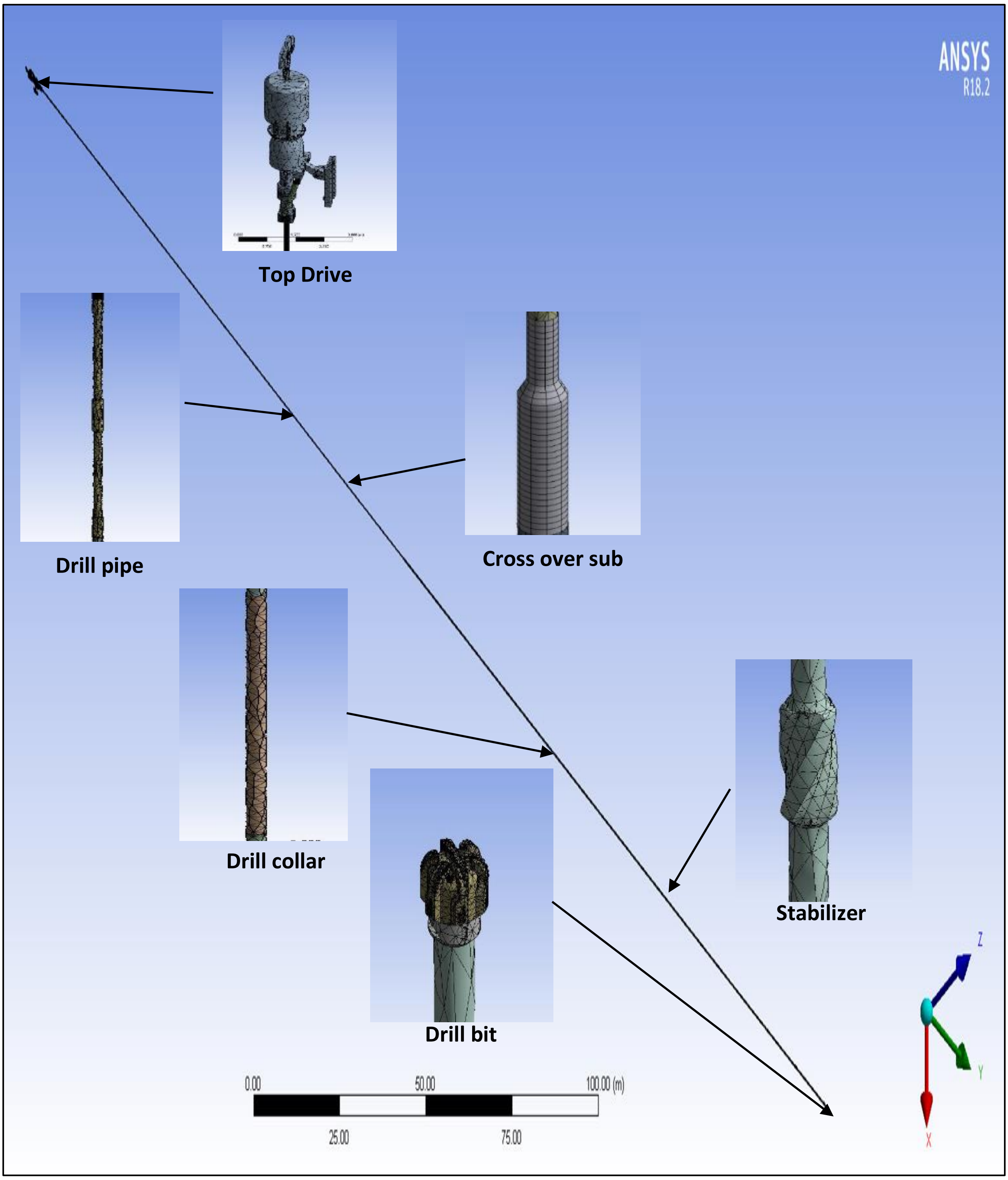


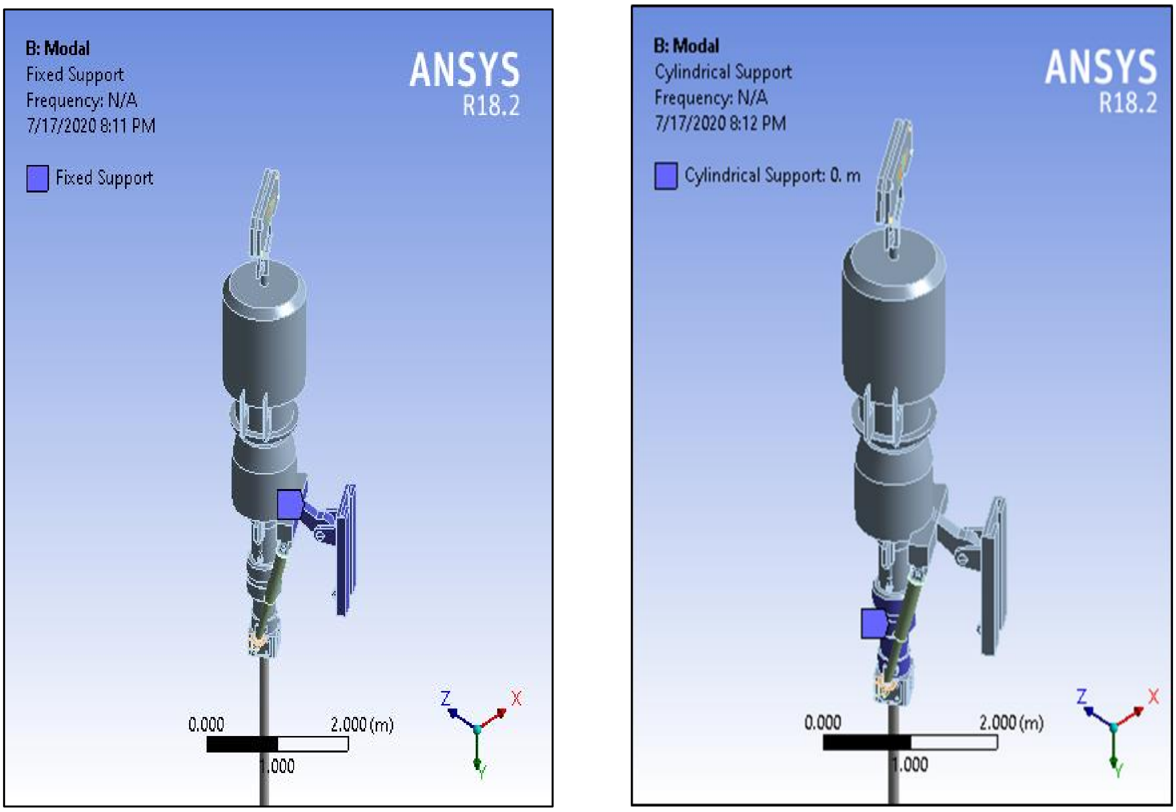
Figure 3. 8 drillstring meshing.

3.9 Boundary conditions

Since this study focus on drillstring lateral vibrations, the boundary conditions are specifically set for observing lateral vibrations. In boundary conditions, only through the allocation of cylindrical supports at the place of the bit, stabilizers and rotary table, the wellbore effect shall be included. The radial supports are the radial deflection and rotation which may be permitted or limited along the drillstring axis. They are classified as listed:

- The drillstring is permited to rotate around its axis and permit displacement in the radial orientation at the bit position.
- Since the stabilizer 's purpose is to restrict the drillstring radial motion; it is radialy restricted from movement but allowed to rotate around its axis.
- At the rotary table position, the radial deflection of the drillstring is restricted but rotating around its axis is permitted.

The figures below indicate the position of supports in the model at the rotary table location, radial deviation of the drillstring is constrained but it is permitted to rotate around its axis the following figures shows the location of supports in the model



(a) (b)

Figure 3. 9 (a) fixed support at Rotary table, (b) cylindrical support at the Rotary table.

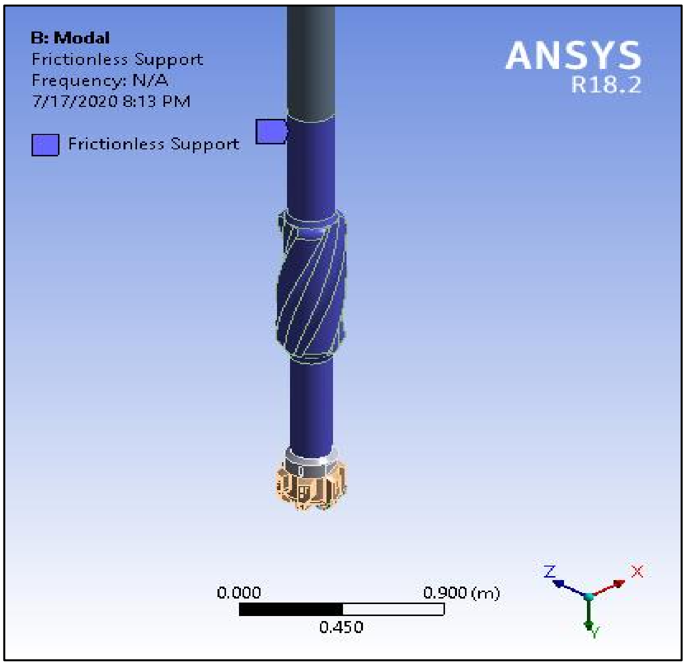


Figure 3. 10 Cylindrical support at stabilizer.

3.10 Modal analysis

Modal analysis has been implemented to identify the vibration characteristics of a structure, natural frequencies and mode types. Since the issues are too complicated to be analytically resolved particularly in the case of mass imbalance, finite element approach was used. The forms of equations that found for diagnosing of modal analysis are used in the Eigen systems. The method for modal analysis of finite elements as following:

1. Geometry and meshing: design geometry is prepared from the drillstring configuration as previously described. Thus, auto meshing is performed to detect aspects of complex mode.

2. Methods for analyzing: it reflects the mode choices available to the user for extraction. This thesis uses the Block Lanczos process. The number of modes to be extracted is provided as three.

3. Loading: restrictions and the loading are carried out as specified in the boundary condition excluding mud effect when analyzing modalities.

4. Solution: by selecting the solution option, the software resolves the geometry-related equation of motion and produces the first three critical frequencies and mode forms.

The Modal has been employed to obtain the final results, after that all the results were compared with results of the experiment to investigate the validity of the outcomes. Hence, reasonable convergence was diagnosed between the analysis of the real data and experimental results The next step is to carry out modal research on various combinations of drillstrings along with their respective lateral vibration.

3.11 Harmonic analysis

Harmonic response analysis was performed to define a linear response of structure in steady-state circumstances when the applied forces vary sinusoidally or harmoniously with time. Thus, it is used to assess if resonance, fatigue and other harmful effects of forced vibrations can be avoided by the structural design. There are basically two ways to execute harmonic analyzes on the drillstring. They can be listed as:

- Full method whereby the harmonic analysis is performed by means of a direct solution of motion equation.
- Superposition mode in which the harmonic solution is extracted for a state of predefined load already solved for modal analysis.

Since the Modal analysis was completed, the use of mode superposition method is beneficial, where the linear combinations of Eigen vectors are already solved from Modal analysis. The procedure for performing harmonic analysis involves the following steps:

Create Analysis System: Modal analysis is a prerequisite for harmonic analysis in which details, the engineering data, geometry and boundary conditions are shared.

Define initial conditions: The number of modes that were taken from Modal analysis is 3, and the average frequency for drillstring was 4.95 Hz. In harmonic analysis, the general rule of thumb for determining the frequency spectrum is 1.5 times the average frequency found in the solution. Therefore, the operating frequency range for the study was between 0 and 7.5 Hz.

Applied Loads and Supports: The loading takes into account the mud weight influence on the drillstring (Buoyancy Factor). Where the weight of drillstring was164 tons in 1.2 gm/cm^3 mud weight.

Buoyancy Factor (B.F) = $(\rho_{stell}-\rho_{mud}) / \rho_{steel}$

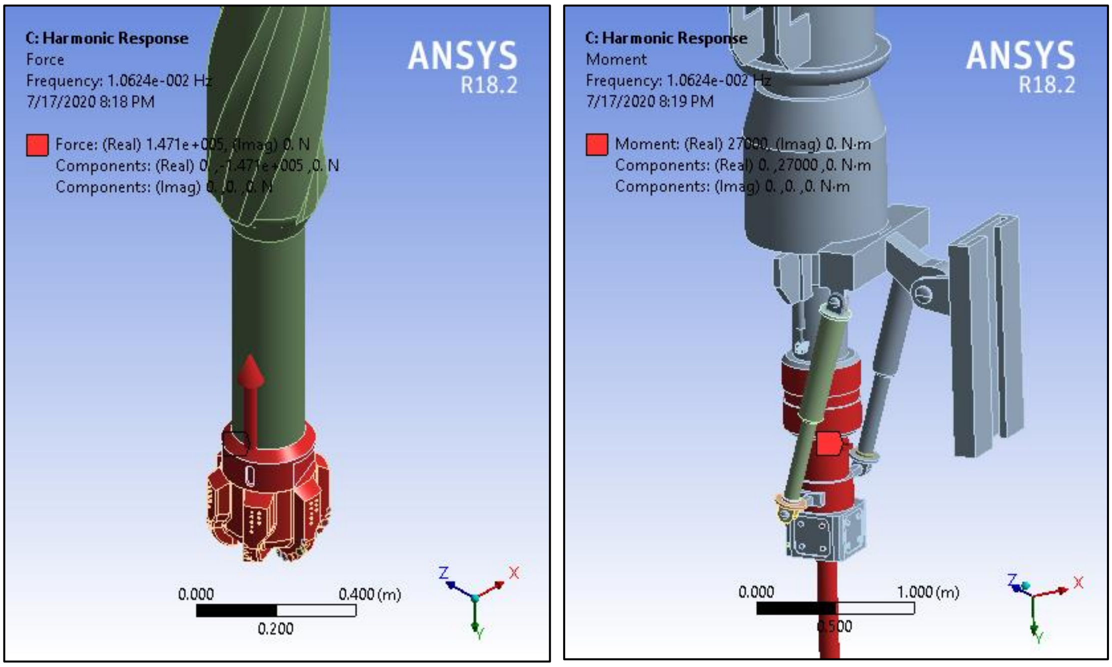
B.F = 0.847

Weight of drillstring in mud = Dry weight of string * B.F

Weight of drillstring in mud = 139 tons (Rabia 2002).

The speed of rotary table (130-140) RPM

25 tons of drillstring works as tensile force. Therefore, according to the model outcomes the heavy weight drill pipe is under the influence of harmonic in the specified operating frequency range, also the rate of penetration 3 m/h and torque at top drive (2-2.7) kg.m were considered.



(a) (b)

Figure 3. 11 (a) harmonic response Force (b) harmonic response Moment.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Case study (Zubair Field well Zb-202)

Zubair field is one of the fully grown oil fields placed 20 km southwest of Basra City in the southern part of IRAQ as shown in Figure 4.1. In 1949 the field was discovered. Zubair consists of four domes from the NW (Al-Hamar, Shuaiba, Rafidyah) to the SE (Safwan), which are in communication with other domes of Zubair Field through aquifer extending beyond the Iraq & Kuwait border.

The field structure includes 4 reservoirs: Mishrif, 3rd Pay, 4th Pay and Yamama. The first three reservoirs have been appraised and produced. These are the Mishrif Carbonate reservoir and Upper & Lower Sandstone reservoirs respectively belong to Middle and Lower Cretaceous. There are also hydrocarbon shows and strong potential in other reservoirs, however, these have not yet been developed. The production of the field started in 1951 and has been driven by natural depletion and low water support from 3rd Pay reservoir. The production has not been continuous because the same has been interrupted most of times due to political and social events. A water injection program was executed from 1999 to 2003 but only in the Upper Sandstone Member.

ZB-202 well is part of Zubair Field Development Plan; its objective is to develop and produce oil from Lower Cretaceous Zubair Sandstone Reservoirs (3rd Pay) and to test the Lower Sandstone Reservoir (4th Pay) and Yamama formation in order to verify the reserve of these reservoirs in the northern part of the field. Zb-202 is an exploration vertical well with total depth of 4005 m (TVD RKB). It was drilled by KCA Deutag Rig (T601) and it was the first exploration well drilled by Zubair Field Operation Division (ZFOD) (Basra oil company and Eni company) in joint venture with Baker Hughes. The main sections of well ZB-202 As following (Field data, Geophysical Support 2013 and 2014 Seismic Horizons Interpretation).

1. 17 ½" hole section

17 1/2" phase was drilled vertically from 663 m to 1886 m TVD RKB (14 m below the top of Sadi formation). The section is going to be drilled using PHB/ Polymer mud (Pre-hydrated bentonite) (MW: 1.10 –1.14 gm/cm^3). The risk of this phase is total or partial losses in Dammam & Hartha formations and Sulphurous Water Influx Umm Er-Radhuma & Tayarat formations and Tight Hole in Shiranish formation, No shallow gas presence.

2. 12 ¼" hole section

This section 12 ¼" was drilled vertically from depth 1886 m to 3505 m TVD RKB. Depth of 9 ⅝" casing shoe depth is at 35 m below top of Ratawi formation. KCL/ PHPA (Partially Hydrolysed Poly Acrylamide) mud system used (Mud Weight: 1.14-1.30 gm/cm^3). The risk of this section formation is hole instability in Tunma, Ahmdi and Nhr Umr, differential stuck pipe may occur in depleted reservoir Mishrif, tight hole in Ahmadi formation and H2S gas in Ratawi formation.

3. 8 ½" hole section

This section was drilled vertically from 3505 m to 4005 m RT (TD). 7" casing shoe depth is 4002 m in Yammama formation. KCL/ PHPA mud system used The MW for drilling through the Yammama was set equal to 1.81 gm/cm^3 and adjusted according to the actual well conditions and hydrocarbon shows. The risk of this section was Well control in Yammama and Ratawi, as well as differential sticking in Yammama (Field data, Master log).

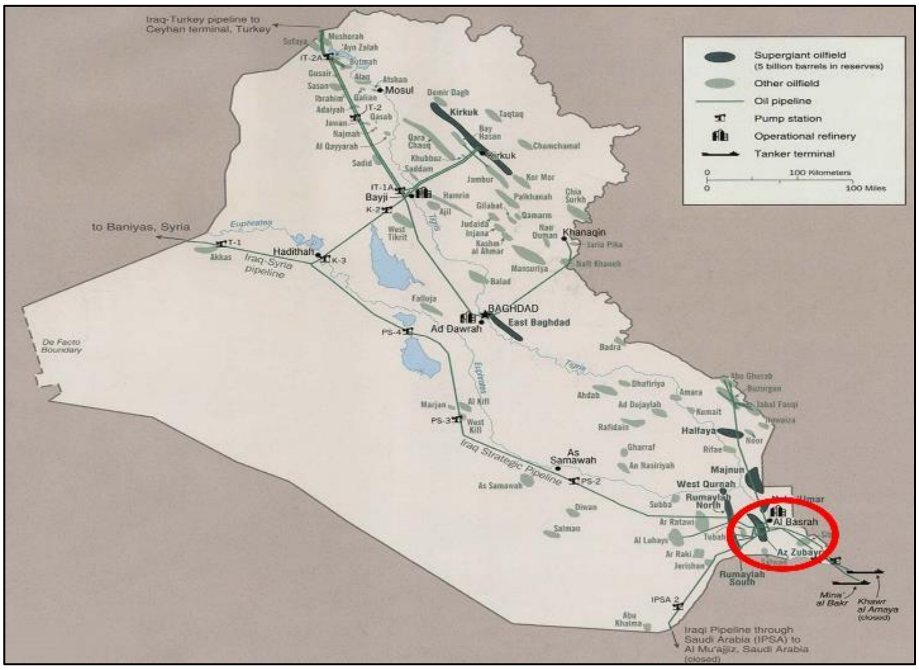


Figure 4. 1 map show the location of Zubair field (Corriere Della Sera).

4.2 Modal analysis

The modal analysis aimed to identify the shapes of the natural frequencies and mode. The simulation comparison between the results that obtained from analysis of Zubair field data with that conducted by (TM Burgess 1987) indicates similarity in the results.

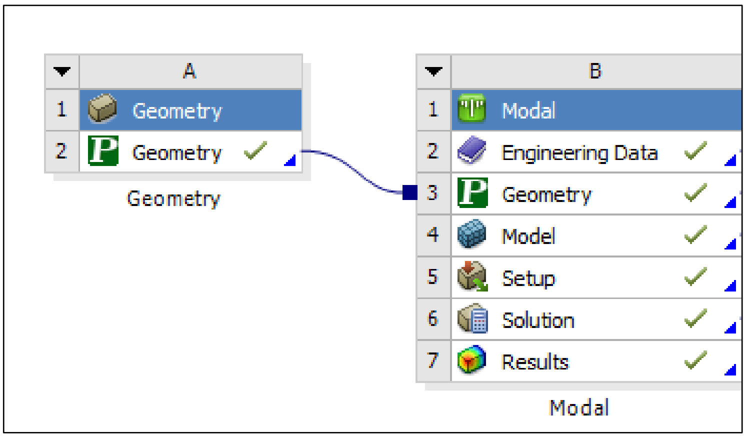


Figure 4. 2 the process to find of ten natural frequencies.

The composition results of first three critical frequencies for the drillstring sections 17 ½", 12 ¼" and 8 1/2" of Zubair field and Burges results are illustrated in table 4.1.

Table 4. 1 Comparison of ANSYS results with Burgess Result

	Length(m)	**1st Natural Frequency (Hz)**	**2nd Natural Frequency (Hz)**	**3rd Natural Frequency (Hz)**
ANSYS Drillstring 17 ½"	165.58	0.495	0.498	1.731
ANSYS Drillstring 12 ¼"	319	1.062	1.139	2.094
ANSYS Drillstring 8 ½"	277.57	1.077	1.0779	3.1078
Burges et al (1987)	34.7	1.43	1.43	4.38

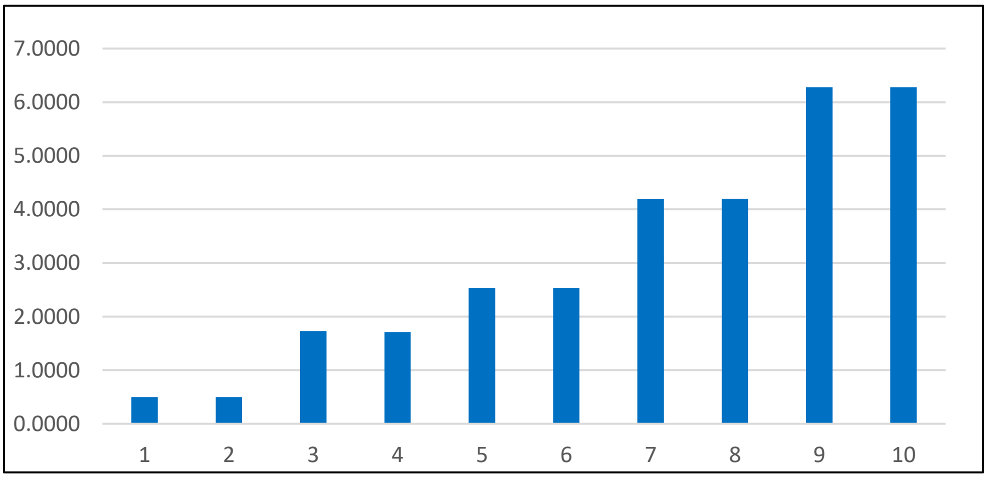


Figure 4. 3 ten mode shapes of natural frequency to the drillstring section 17 1/2".

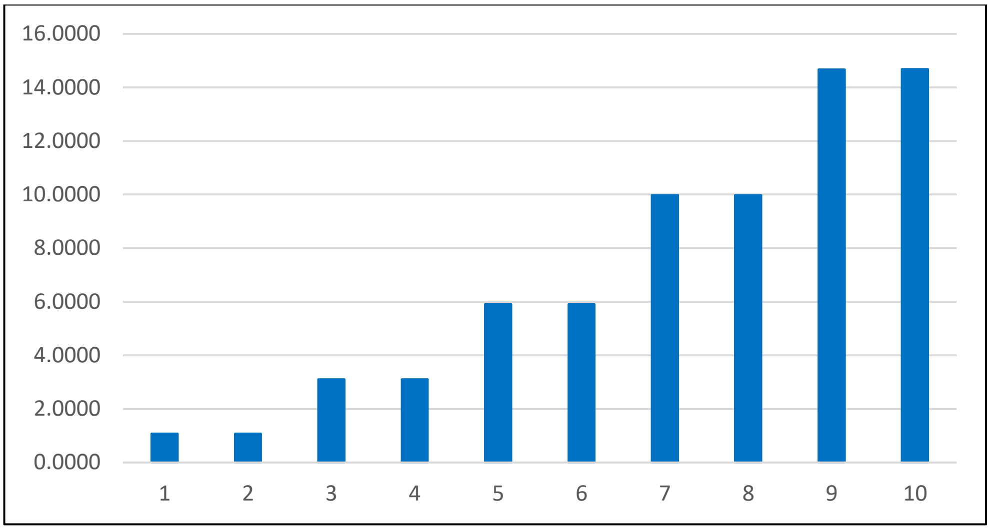


Figure 4. 4 ten mode shapes of natural frequency of the drillstring section 8 1/2".

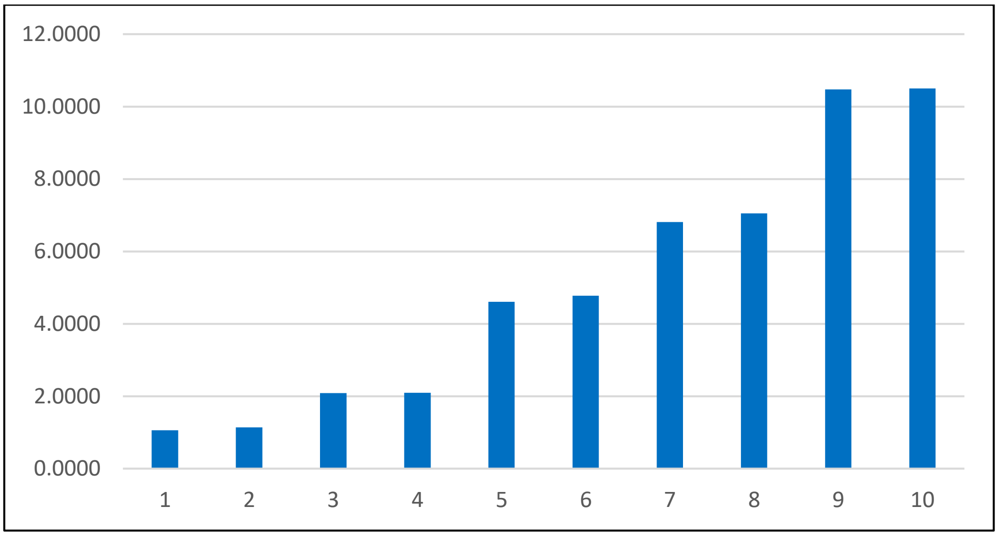


Figure 4. 5 ten mode shapes of natural frequency of the drillstring section 12 1/4".

The cause why the natural frequency 1^{st} and 2^{nd} are equals is due to the symmetrical geometry that applied in simulation, in which case the curvature hardness around the powerful and weak axis is the same. Whether the applied frequency or rotary velocity matches this natural frequency, resonance occurs, and the amplitude of lateral vibration greatly exceeds that. Therefore, the drillstring collides with the wellbore and induces tremendous shocks. The operating speed or frequency must be out of certain critical frequencies to prevent this from occurring.

Since the speed limit of the rotary table at 12 ¼ " hole section of well Zb-202 was about 130-140 revolution per minute (RPM), the normal frequencies of drillstring are in the acceptable range. For different configurations of drillstring it is evident from the Figures 4.10, 4.12, and 4.14 that the drillstring resonance occurs as following:

- The resonance of 17 ½" hole section occurs at frequency of 3.9 Hz and drillstring rotary speed of 234 RPM.
- The resonance of 12 ¼" hole section occurs at frequency of 5.08 Hz and drillstring rotary speed of 304.8 RPM.
- The resonance of 8 ½" hole section occurs at frequency of 2.58 Hz and drillstring rotary speed of 171 RPM.

The mode shapes of the drillstring in 12 ¼" hole section for the first three deformations, subjected to instability are presented in Figures 4.6, 4.7, and 4.8

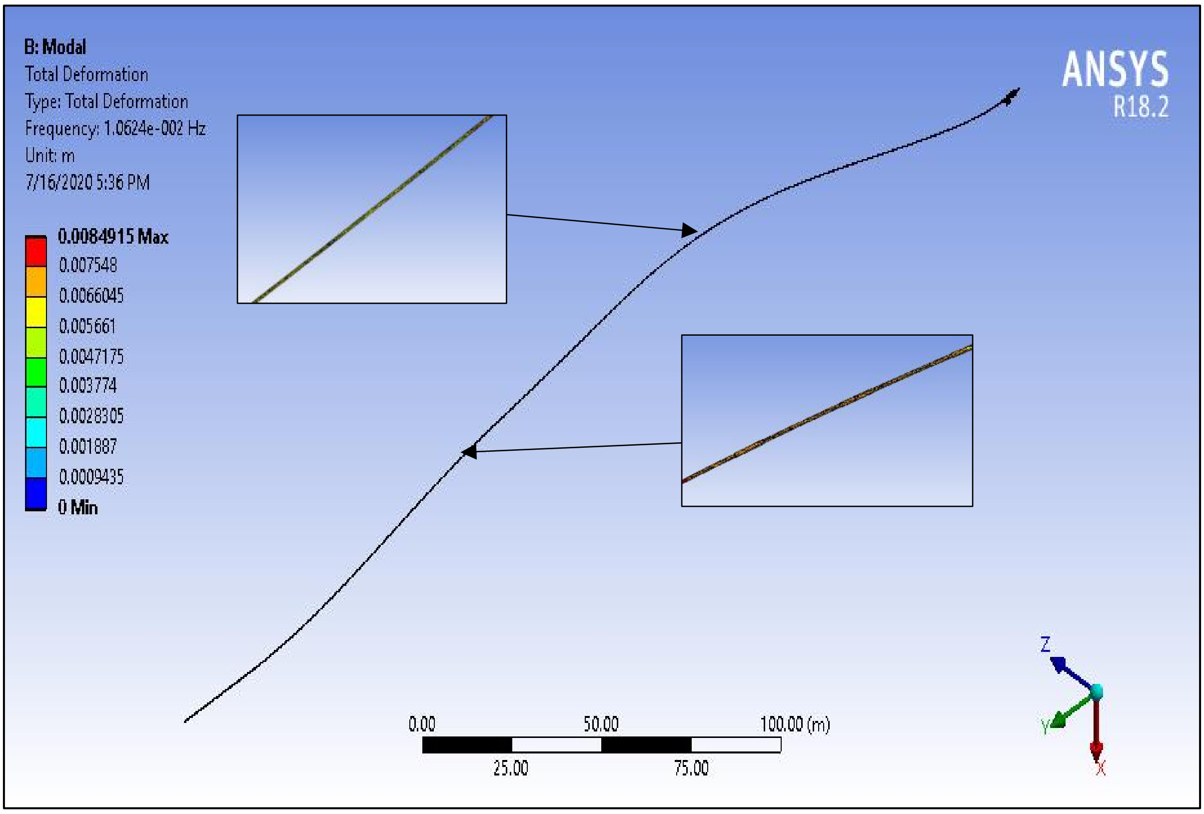


Figure 4. 6 first deformation of drillstring section 12 ¼".

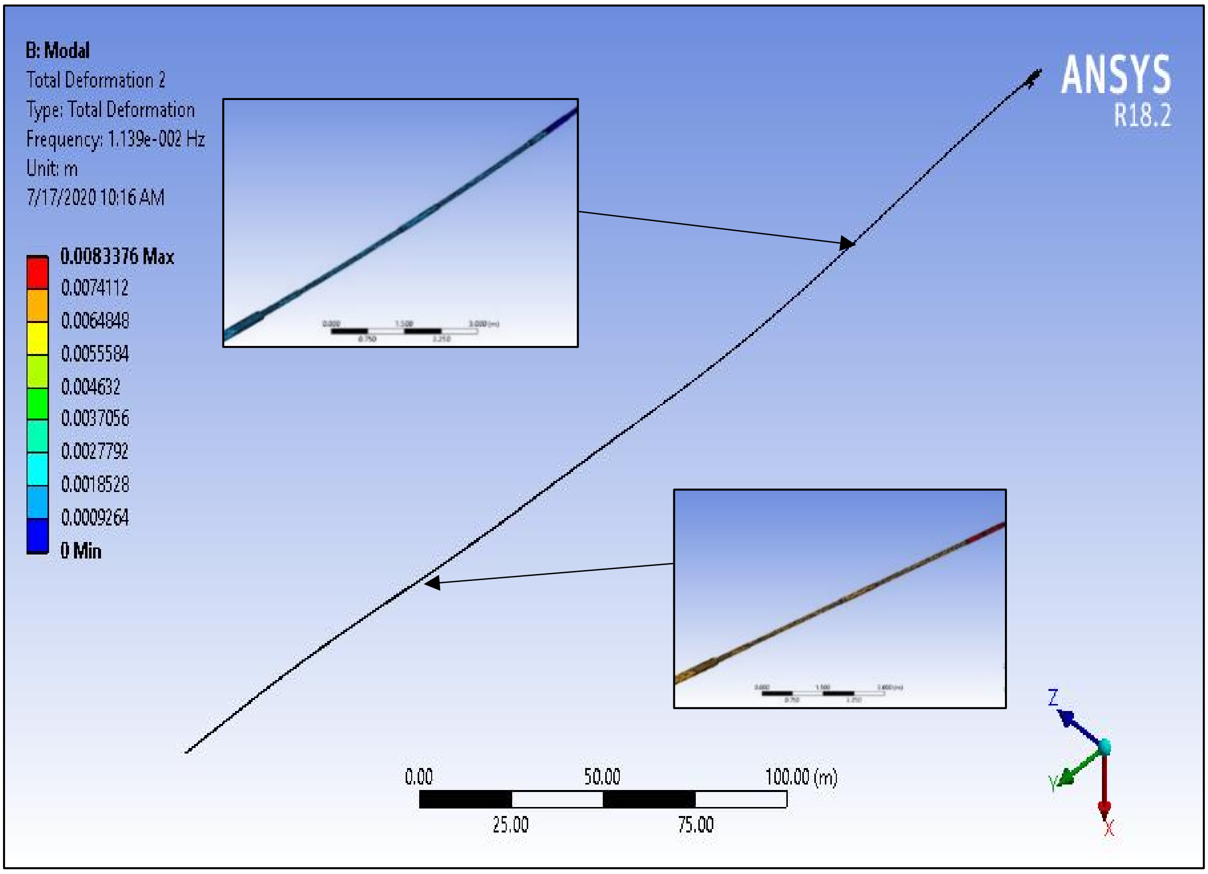


Figure 4. 8 second deformation of drillstring section 12 ¼".

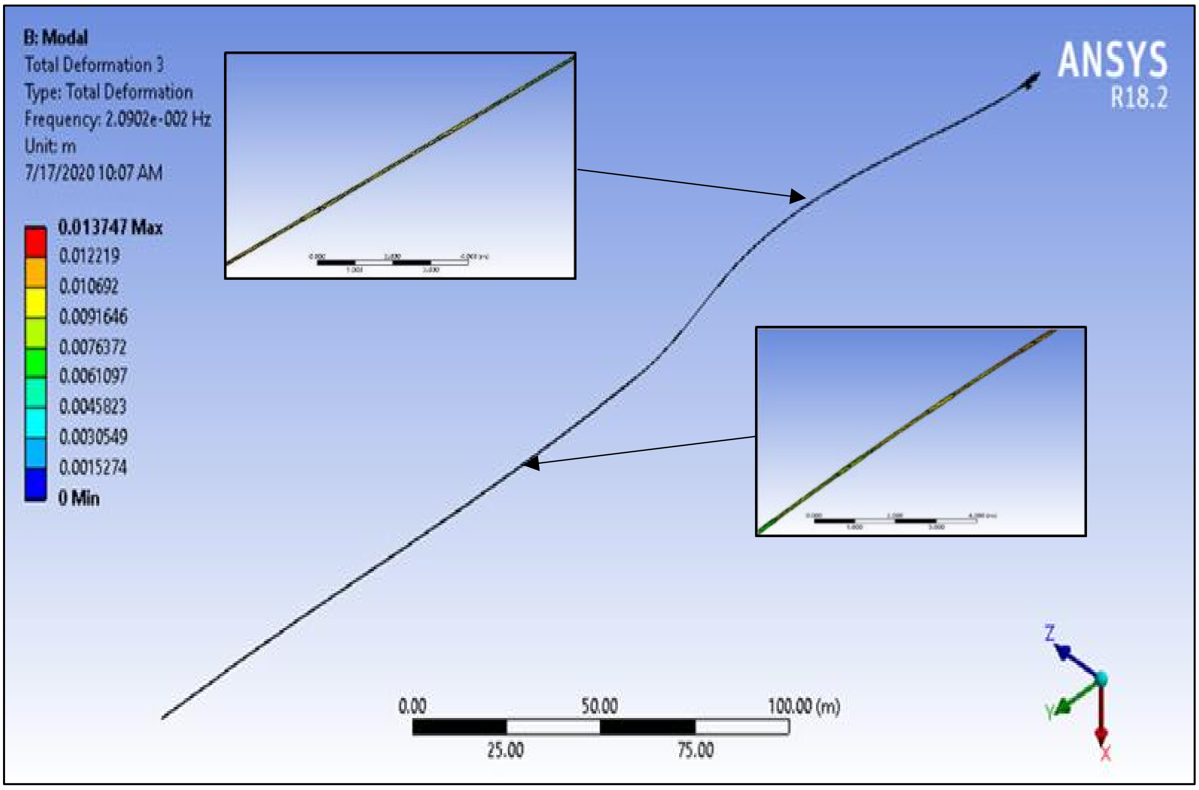


Figure 4. 7 third deformation drillstring section 12 ¼".

It is obvious from the mode shapes which portions of the drillstring are applied to displacements. The lower section of the drillstring which consist of the stabilizers and bit is virtually no subjected to displacement. That is because the stabilizers counteract the effect of movement of the drillstring Just axial rotations, without radial displacements. The largest displacements are located at the site of the heavy weight drill pipe which is just above the third stabilizer. The instability of drillstring can be seen on the previous three figures where in the amplitude of displacements alter within the same configuration.

4.3 Harmonic analysis

Harmonic analysis was performed by ANSYS software as clarified in Figure 4.9 primarily to understand the frequency response of drillstring parts when they are subjected to a sinusoidal load. In this case the critical part of drillstring is the heavy weight drill pipe or drill collar that are under the impact of lateral vibration. The frequency response of the heavy weight drill pipe or drill collar is therefore plotted with respected to lateral deflections in the X direction.

It should be remembered that while the normalized amplitude versus the frequency plot is perceived, the driving force at the bit is uncertain before vibration measurements are available down the hole. The driving force over any part of the bottom hole assembly will not be the same

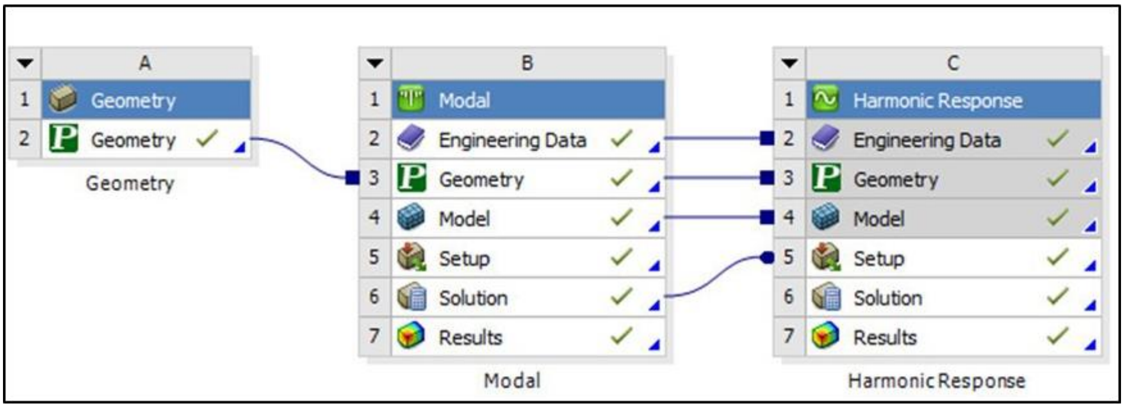


Figure 4. 9 the process to find the harmonic response

The following figures represent the frequency response of the drillstring for 17 ½" &12 ¼" and 8 ½" sections in terms of lateral displacements to investigate at which parameters the resonance will be more effect.

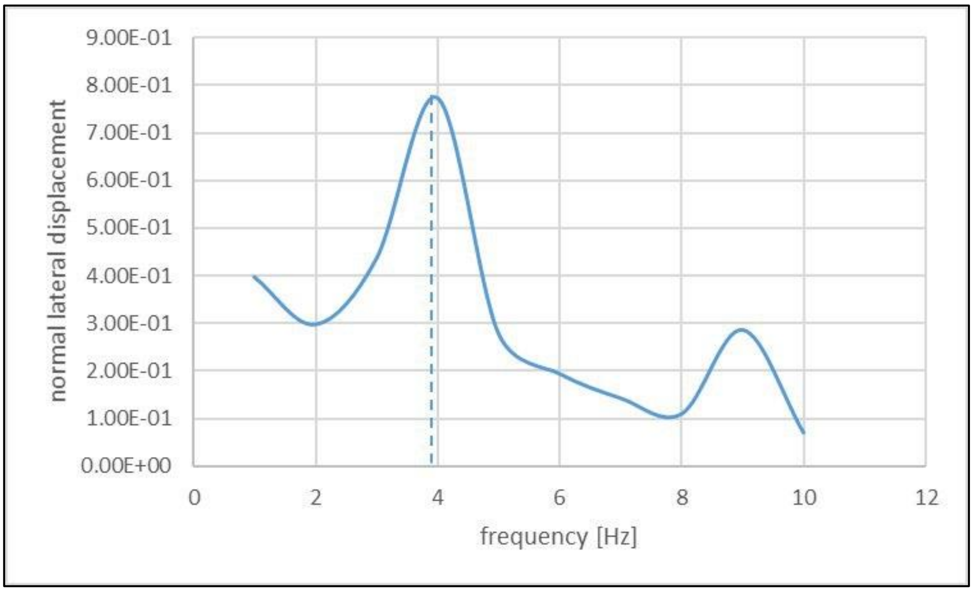


Figure 4. 10 harmonic analysis of 17 ½"drillstring section

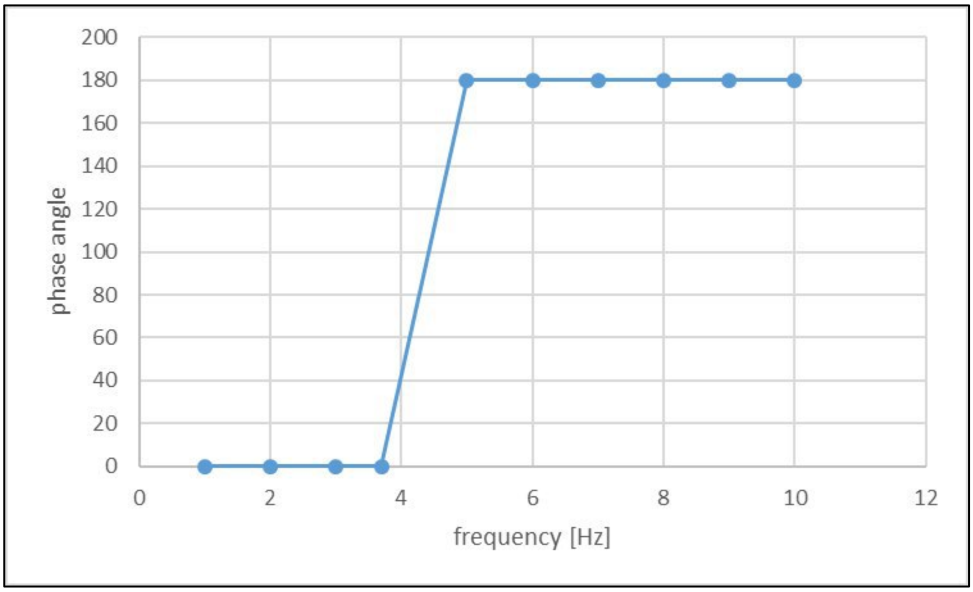


Figure 4. 11 phase angle and frequency of 17 ½'' drillstring.

The resonance initiation is indicated by the peaks in the plot of harmonic responses as shown in Figure 4.10. This plot can be used to describe which parts of the drillstring are subjected to large lateral displacements (lateral vibration). In the case of 17 ½" drillstring the drill collars and bit are subjected to large displacements at 3.9 Hz and rotary speed is 234 revolution per minute. That means the drillstring is under the maximum deflection at 3.9 Hz and rotary speed of 234 RPM.On the other hand, the peak of frequency 1 Hz and rotary speed 60 RPM and the other peak of frequency 9 Hz and rotary speed 540 RPM represent 50 % and

37 % of a maximum deflection. Thus, the driller has a thought of appropriate rotary speed to avert the harmful resonance. Even though, the drillstring experiences resonance at 1 Hz, 9 Hz the deflection of the drillstring is not hard as that happened at 3.9 Hz.

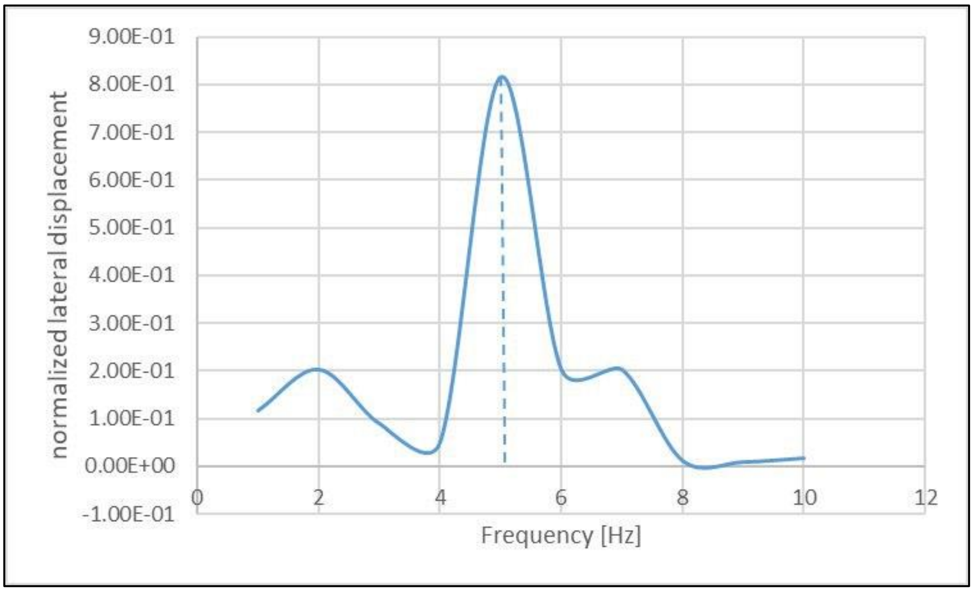


Figure 4. 12 harmonic analysis of 12 1/4"drillstring section

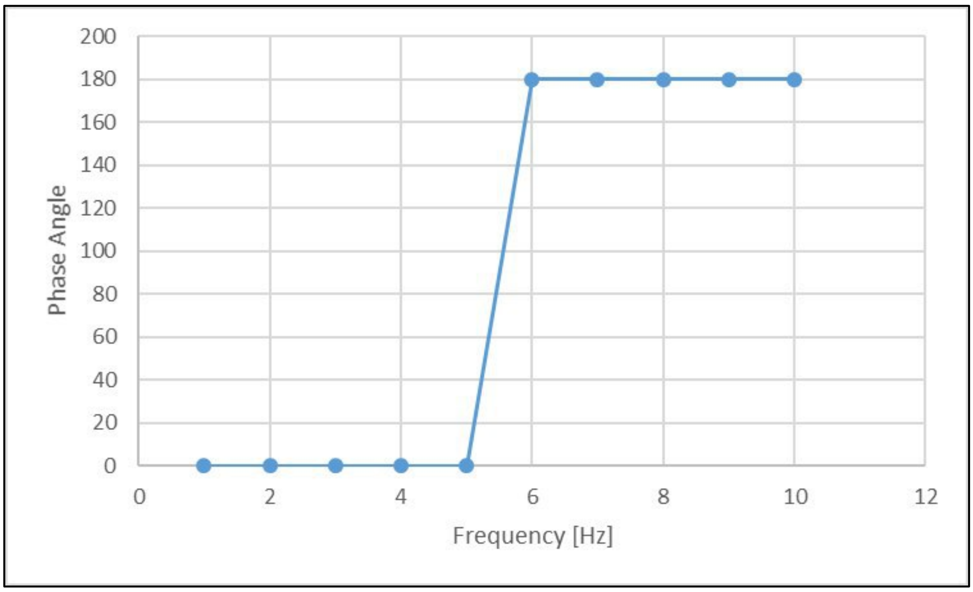


Figure 4. 13 phase angle and frequency of 12 1/4" drillstring

The resonance initiation is indicated by the peaks in the plot of harmonic responses as shown in Figure 4.12. This plot can be used to describe which parts of the drillstring are subjected to large lateral displacements (lateral vibration). In the situation of 12 1/4" drillstring the heavy weight drill pipe is subjected to large displacements at 5.08 Hz and rotary speed is

304 revolution per minute. That means the drillstring is under the maximum deflection at 5.08 Hz and rotary speed of 304 RPM. On the other hand, the peak of frequency 2 Hz and rotary speed 120 RPM and the other peak of frequency 7.1 Hz and rotary speed 426 RPM represent 25 % and 28 % of a maximum deviation. Thus, the driller has a concept of appropriate rotary speed to avert the harmful resonance. Even though, the drillstring experiences resonance at 2 Hz, 7.1 Hz the deflection of the drillstring is not as acute as that happen at 5.08 Hz.

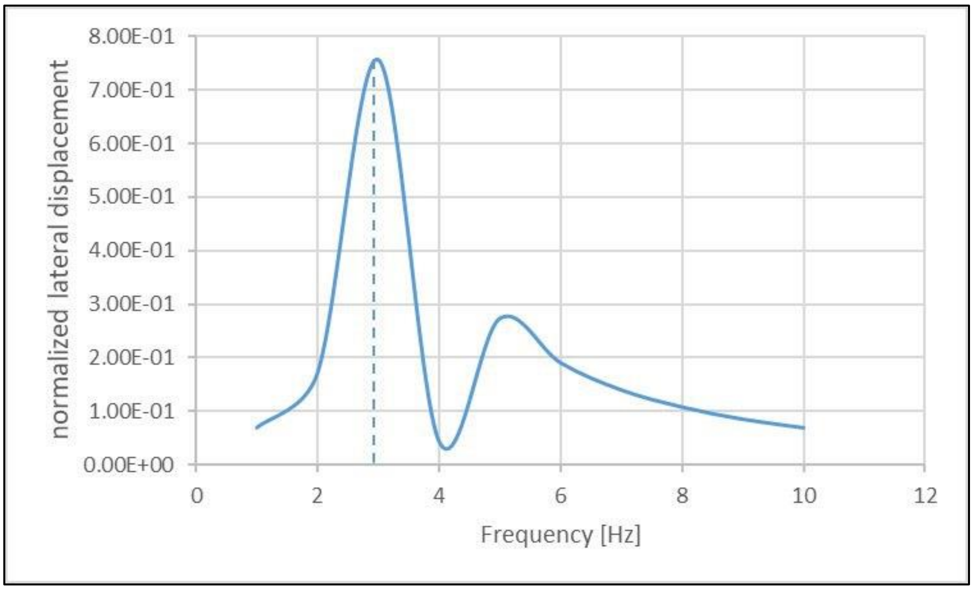


Figure 4. 14 harmonic analysis of 8 1/2" drillstring section

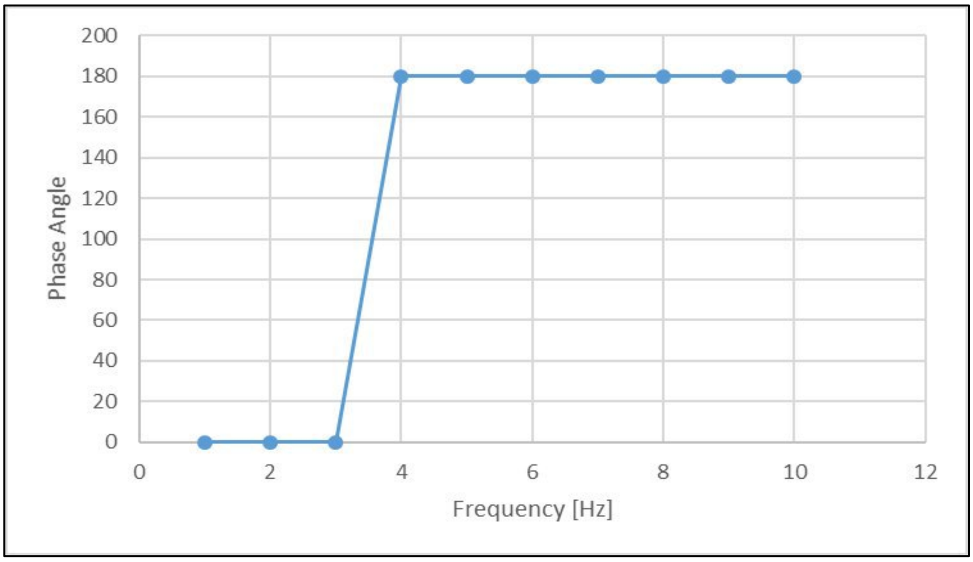


Figure 4. 15 phase angle and frequency 8 ½"drillstring section

8 1/2 " drillstring is subject to a maximum deviation at 2.85 Hz, rotary speed 171 RPM while the peak 5 Hz, 300 RPM represent 37 % of a maximum deviation. Thus, the operator has a thought of appropriate rotary speed to avoid the harmful resonance. Even though, the drillstring experiences resonance at 2.85 Hz, the deflection of the drillstring is not as acute as that happen at 5. Hz.

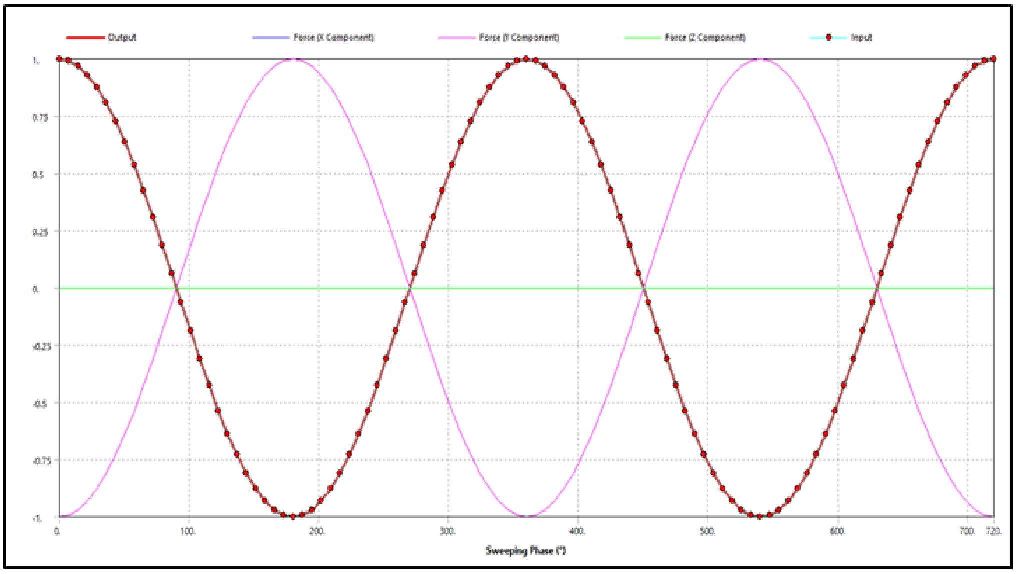


Figure 4. 16 Sweeping phase

4.4 Landmark software Result and discussion:

Landmark software has basically consisted of wellplan, Compass, open well, casing wear, well cat and well cost. Wellplan has been employed for torque modelling in this study.

4.4.1 Wellplan software

Wellplan is an important part of landmark developed by Halliburton. The software can address a range of technological problems like Extended Reached Drilling (ERD), slim hole drilling, deep water drilling and environmentally sensitive drilling areas. It is used for drilling and well-completion during the construction and operation processes. This application helps the operators to recognize possible issues with wellbore construction during the drilling and completion process. Integrated technologies allow the oil companies to research and select optimized BHA scenarios, torque and drag, stuck pipe, well kick, hydraulics, and cementing. The main emphasis for this specific project will be on the Torque and Drug (T&D) analysis. Wellplan torque and drug (T&D) modeling program offers information about expected drilling and casing torque in different loads. Diagnosis of the measured weights and torques that can be predicted during tripping in, tripping out, rotating the drillstring on and off bottom, sliding drilling, and back reaming can be applied. Based on the simulation results, engineers are able to determine if the selected rig has sufficient enough technical characteristics to meet the well design requirements. In this phase, T&D modelling process would be implemented in the following operations sequence:

- Tripping in
- Tripping out
- Rotating on bottom
- Rotating off bottom.

4.4.2 Torque

Torque is defined as the rotating force used to a shaft or other rotary mechanism to cause it to rotate or tend to rotate, and it is measured in length and strength units. The units of the torque depend on the unit of the used system. It can be a newton unit per meter (N.m) in the metric system or pound force per foot (lb. Ft) (Bakke 2012) . While drilling, torque is the force or moment that leads to the drillstring twist off. The torque is produced by the top drive, which is used to counteract the frictional forces that resist the drillstring and bit rotation. The top drive adds torque to the drillstring and the torque transfer through the drillstring until hitting the crush rock portion by drill bit. Additionally, frictional torque is defined as the applied moment by the string weight, the surface torque, must therefore conquer the Rotational friction of the wellbore (Borinb, 2012). It is also true to state that the surface torque is divided into three kinds as follows:

- The torques at bit
- Torque over wellbore
- The mechanical torque

Torque at surface is a combination of bit torque, torque over the wellbore and Mechanical torque. Bottom hole assembly failure which includes drillstring and drill bit damage or fatigue failure causes the most prevalent drilling problems. During normal operation the PDC bit generates an increased reactive torque that acts in the opposite direction of the driving rotation to achieve penetration that cannot be met by the drilling motor power section. This rapid rise in reactive torque is transmitted as torsional 'stick-slip' vibration through the drillstring, which is often considered to be one of the most destructive vibrational modes.

4.4.3 Torque plot of 12 ¼" drillstring

Figure 4.17 represent torque of tripping in, tripping out, rotating on the bottom, rotating off the bottom and back reaming operations in all parts of the drillstring. Obviously, the surface torque when the drillstring is on bottom will be greater than that torque when drillstring is off bottom due to the rotational friction forces. Torque at the surface begins to decrease with depth until reaching the minimum value at the bit which known as torque on bit (TOB). Fundamentally, if there is no rotation in the drillstring, the torque values are equal to zero during the tripping in and out operations. Since all the torque curves shown during different operating modes do not exceed the torque limit, the tool joints of the drillstring cannot exceed or break the torque.

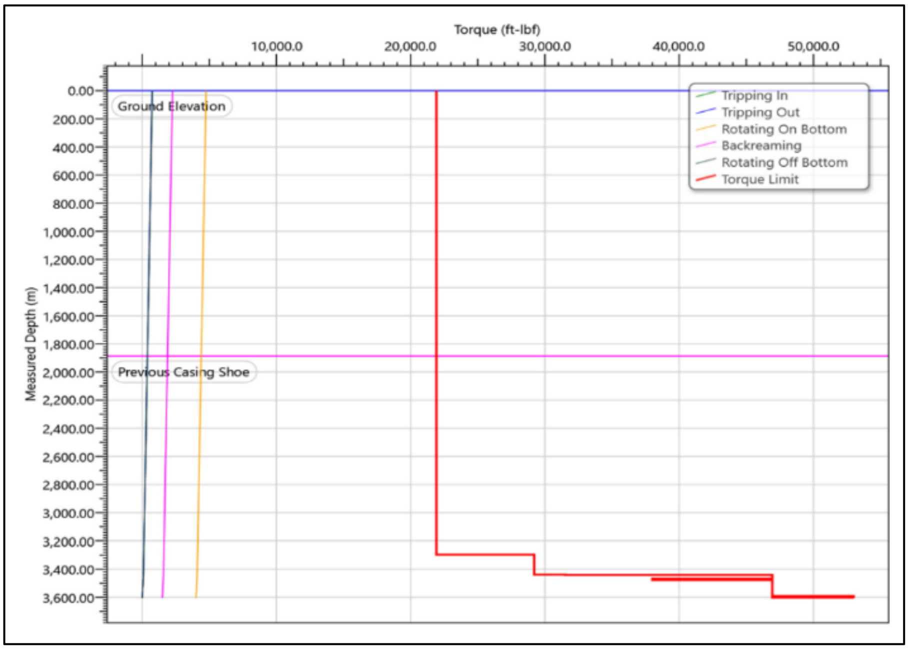


Figure 4. 17 torque plot of 12 1/4"drillstring

4.4.4 Effective tension plot of 12 1/4" drillstring

The plot of effective tension should be used to evaluate the protentional buckling that may happen while drilling. Buckling phenomenon is related to vibration, when the buckling increases the lateral vibration increased. With respect to Figure 3.18, as load paths do not intersect the buckling load lines at any depth along the well, there's no possibility of buckling whether sinusoidal or helical, along the entire length of the drillstring. Furthermore, if the tension limit of drillstring components is not exceeded at any depth along the entire borehole, there is no danger of drillstring parting at any depth.

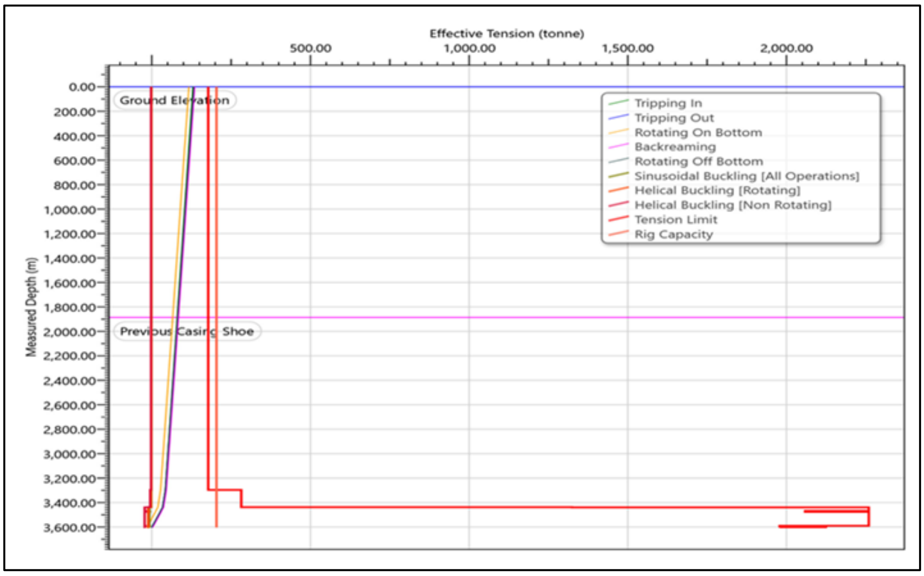


Figure 4. 18 drillstring effective tension plot

4.4.5 Weight on bit (WOB) plot for 12 ¼ "drillstring

Maximum weight on bit that depicted in Figure 4.19 may induce helical or sinusoidal buckling. While drilling the well ZB-202, extreme care has been taken to ensure that the weight on bit held at the corresponding bit depths below the values shown in Figure 4.19. If the weight on bit at the corresponding bit depths exceeds the maximum weight on bit, the drillstring will suffer from buckling according to the corresponding buckling mode

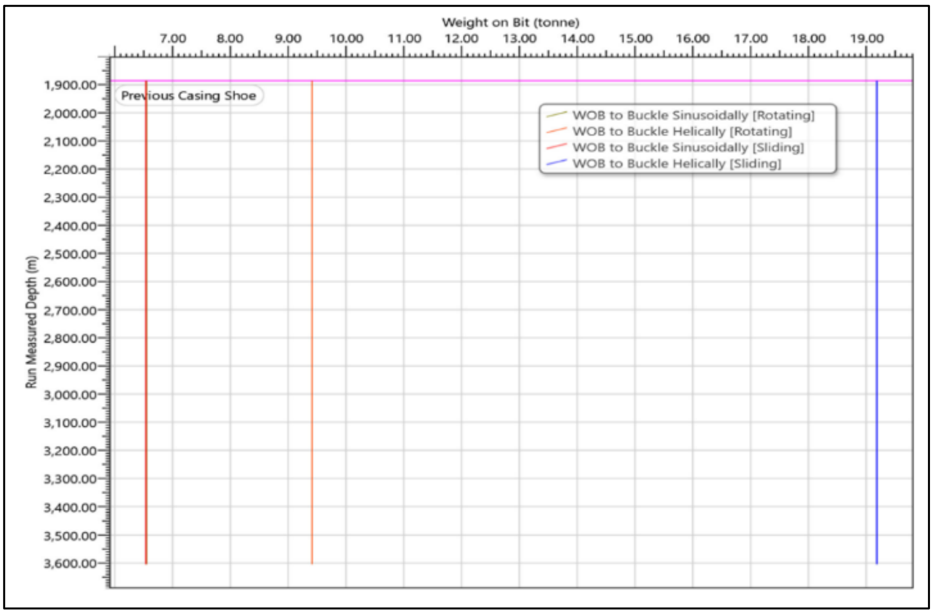


Figure 4. 19 weight on bit plot

CHAPTER FIVE

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

5.1 Conclusions

The lateral vibrations may cause a significant amount of failures in all the drillstring components (BHA, drill pipe, drilling accessories). The impacts that generated by lateral vibrations can be higher than those which result from torsional or axial vibrations. For that reason, the drillstring collides with the wellbore wall during lateral vibrations, causing massive shocks.

The drawbacks of the lateral vibrations, it cannot be measured reliably from surface by means of sensor devices unless the well is shallow. Therefore, in this thesis, a dynamic Finite Element Analysis of a drillstring was set up to conduct vibration studies. Moreover, Modal and Harmonic analysis were conducted to define the drillstring critical frequencies, mode shapes, and frequency response. The results of this study are important for understanding the influence of lateral vibration of the drillstring. This result can be used to define the appropriate operating ranges of rotary speed for the drillstring and to describe the lateral displacement for a number of frequencies of a critical component. When the drillstring length is short, the relative maximum amplitude will be small.

Benchmark simulation of experimental data were compared with the results of case studies using real data from field. As a rule of thumb, it can be understood that the more the mass and longer the drillstring, the lower is the lateral resonant frequency. When comparison between field and experiment data, ANSYS model has produced very close results, therefore, ANSYS is suitable program to be used for vibration studies by drilling engineers. Since the vibration is related to torque and drag, LANDMARK software has been utilized to obtain torque and drag analysis. In conclusion the dynamic mathematical model was validated by Finite Element Analysis (FEA) package. Based on the prediction of this model, drillers can determine the drilling parameter before staring the drilling process and adjust the drilling parameter when the axial vibration is over limit. Thus, the drilling performance is improved, and drilling time and cost are reduced.

5.2 Recommendation

- Drillstring instability should be modelled more accurately by taking longer part of drillstring which that need software and computer with advance technology.
- The rock mechanical strength is an important factor that need to be studied since it has high impact on the drillstring vibration.
- More studies should be carried out to find the effect of additional tools such as MWD, mud motor and steerable tools on lateral vibrations.
- The effect of wellbore geometry should also be integrated in the model in order to understand its effect on vibrations
- Torsional and axial vibration should also be studied with its appropriate boundary conditions.
- Downhole shock recorders are recommended to be run, especially in ERD wells.

5.3 Future Work

Since the vibration of drillstring is complicated and the requirement of predictive ability is more and more accurate, the dynamic model becomes very complex. However, there is no available model that includes all the factors that impact the vibration of drillstring. Several extensions to this work can be done and foreseen to be implemented in the future to develop a comprehensive dynamic model. The following are some suggested future works for the improvement:

- Drillstring modelling of deviated or horizontal wells.
- Investigate the impact of contact area between drillstring and borehole wall.
- Possible lost circulation zones should be considered since there will be no fluid outside the drillstring, which may reduce viscous damping ratios.

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