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Drillstring Instability Modelling Techniques

Thesis Author:
Guliyeva Samira

Supervisor:
Prof. Raffaele Romagnoli

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Abbreviations

BHA	*Bottom hole assembly*
DDR	*Downhole Dynamic Recorder*
DDS	*Dynamic drilling sensor*
DQM	*Differential Quadrature method*
HWDP	*Heavy weight drill pipe*
LWD	*Logging while drilling*
MSE	*Mechanical specific energy*
MVC	*The Multi-Axis Vibration Chassis*
MWD	*Measurement while drilling*
RMS	*Root mean square*
ROP	*Rate of penetration*
RPM	*Revolutions per minute*
SF	*Collapse factor*
TOB	*Torque on bit*
WOB	*Weight on bit*

Formula terms

F	*Frequency [Hz]*
G	*Elastic moduli [GPa]*
H	*Displacement in lateral direction[m]*
L	*Length of arc, well and drill pipe [ft]*
Δ L	*Change in the string extension [m]*
N	*Rotational speed of the bit*
Δ P	*Collapse pressure [Pa]*
Q	*Torsional stress [ft·lbf]*
R	*Radius of the pipe [in]*
r_i	*Outer radius of the shaft [in]*
r_o	*Inner radius of the shaft [in]*
SF	*Collapse factor*
T	*Torque at cross section [ft·lbf]*
Θ	*Torsional deformation that occurs between BHA and the top drive [rad]*
ϕ	*Angle of deflection[rad]*

Introduction

Nowadays, there are serious challenges and difficulties in the petroleum industry and well drilling is one of them. Drilling of the well is considered as the most dangerous and expensive part of development of oil fields. New advanced technologies had been introduced for a more efficient and faster drilling process. The dynamics of drill string is a very complex phenomena and depends on dimensions of the well, its trajectory on drilling rig equipment, properties of formation and drilling mud, BHA and ex. The most common problem that we face in drilling operations is vibration which is deleterious to the lifetime of drillstring and down-hole assembly. Vibrations of drillstring are the major reason for string components' damage and inefficient drilling process. This vibration has a different basis, it can be due to borehole-drill string-drill bit interactions. As a result of the random nature of a variety of factors such as formation and bit interaction, drillstring and wellbore interaction vibrations are extremely complex. They involve a wide range of phenomena that make analysis difficult. There are three essential modes of vibrations during drilling: torsional, axial and lateral. For each type of model there is a set of specific phenomena that characterize it. Axial mode creates bit bounces which is resulting in tension and compression as a bit moves though hard formations. As a result, axial vibration causes destruction of bearings and bit cutters. Torsional vibrations create resistance to the downhole rotations. Such vibration as a torque can cause variation in angular velocity with time. The most dangerous form which we can observe is stick/slip. Stick/slip is torsional oscillation which makes it stationary for a while. This kind of vibration causes damage to drill collars and bits. There is no possibility to prevent stick/slip however we can use a mud motor if the excitation comes from the bit. Lateral vibration is the most devastating vibration, it is side to side motion, each side of the system has different tension states one from other. As BHA and drill string contact points start to interact we can face whirl of the system. Backward whirl creates high frequency and magnitude bending moments. The development of single or the coupled type of vibration mechanisms is prevalent cause of drillstring fatigue failure. The working principle of drillstring assembly that is used in the oil and gas industry has complex dynamic behavior. Thus, it is quite hard to forecast the system's behavior. It is crucial to understand the complexity of vibration in order to control and improve the constructive and destructive behavior of drillstring vibrations. To improve performance of system, work downhole motors and measuring systems are used. Petroleum drilling industry has been looking for a new way to enhance the drilling efficiency. Starting with use of shock and sensors molded in MWD and LWD tools or other memory devices. The operator's task is to find a balance between quick drilling and low risk while also creating a high-quality borehole. Drill strings in current drilling can be many kilometers long and barely a few inches wide. This indicates that a drill string made from solid steel pipes is prone to vibrating when triggered by a large enough force. There is a need for an increased ROP as a result of increased demands of the nowadays industry. The energy input via weight on bit and rate of rotation intended for rising ROP is dispersed through the dynamic motion of the drill string when vibrating a structure, implying that the total energy through weight on bit and rotation rate intended for enhanced ROP is dispersed through the relative motion of the drill string. Drill string vibrations have also been recognized as being one of the leading reasons for early bit and component damage. Further bit runs, replacement of components, fishing runs, and sidetrack activities all result in significant increases in costs and well construction time. As a result, reducing vibrations is desirable in order to maximize ROP and reduce downhole problems. There is no possibility to eliminate the entire vibrations because of the complexity of drillstring vibrations. This comes in complex with limited data availability from the downhole which makes the mitigation of vibration quite hard. Nevertheless, some measurement tools showed positive dynamics in detection and reduction of vibrations.

CHAPTER 1
Components of the drilling string

The tubulars and the components used in order to run drilling bit into the borehole's bottom is known as drilling string. Figure 1.1 shows the main parts of drill string, first upper part is Kelly which is connected to the drill pipe segment that contains the main drill pipe and heavy weight drill pipe connected to BHA, on the bottom of BHA is molded bit. BHA consist of a) drill collars; b) jar; c) stabilizers; d) bit sub. Drill bit is connected to the drilling collars through the bit sub and the lower part of drill collars are mounted to the drill bit to create weight on the bit (WOB). Stabilizers help us to address the direction of penetration of formation by drill bit. Drilling fluids move from top through drill string to the drill bit and circulate into space between drill string and bottom hole walls. Thanks to that process, cuttings created by penetration of the borehole are removed and taken to the surface by drilling fluid. Down below presented the main parts of drill stream.

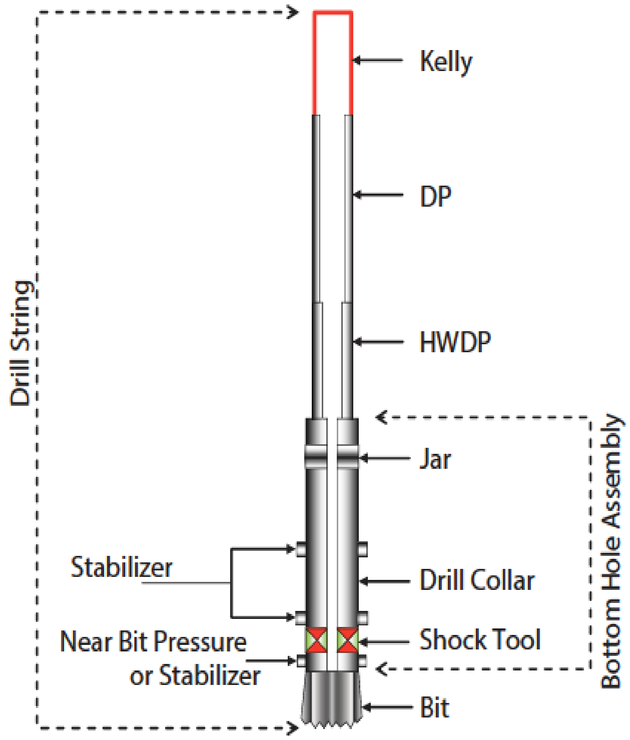

Figure 1.1 Drill string components

https://oilfieldteam.com/en/a/learning/Components-of-the-drill-string

The drill string serves a variety of purposes, including:

- Hold the drill bit in place
- Provide a flow passage for drilling fluids to travel from the Kelly or top drive to the drill bit
- Include a flow passage for drilling fluids

The bottom hole assembly (BHA) consists of the components above the bit, excluding the drill pipe.

1.1 Kelly

It is used to transfer the WOB and rotation to the drilling bit in order to penetrate the hole in formation. Transitions are performed through dill pipe and collars. Kelly is a heavy cylindrical device which has 4 or 6 sides. Made of high-quality chrome molybdenum steel that has been heat treated. It might be square or hexagonal. Square Kelly are less expensive than hexagonal Kelly, but hex Kelly are stronger, thus they're commonly used by rigs excavating deep holes, the most commonly used extension is 12.2m (40ft) or 16.5m (54ft). Kelly is a tube that runs through a device which is called Kelly bushing, they both together called Kelly drive. The Kelly-drive bushing connects to the master bushing, which is turned by the rotary table. The drill string and associated bit are rotated as a result of this. As the hole develops, Kelly moves down. Kelly consists of two additional elements, first is saver sub, second is Kelly cock. Saver sub connected to the bottom part to prevent fatigue of the threads. Kelly cock also a small sub which is placed under saver sub. It keeps construction damage from high pressures and in addition can be used to shut in pipes.

1.2 Drill pipe

The purpose of drilling pipe is to transfer the drilling mud and rotations to the bit. The main idea is to perform it under high pressures. DP experiences a huge number of forces and loads. The weight of pipe and the load that it carries endures to axial force, radial load appears due to pressure presented in the wellbore and as a result of dog leg there are radial stresses. Drilling pipe should bear all these loads, which is why the size and the material have to be chosen properly. Drill pipe produced in 3 main size classes: 1st class 18-22ft, 2nd

class 27-30ft, 3rd is 38-45ft. D, E, X95, G105, and S135 are the five grades available. The grades are available in a variety of sizes 2 3/8, 2 7/8, 3 ½, 4, 4 ½, 5, 5 ½, 6 5/8 in. With time because of long period exploitation, pipe classes change as a result of wear. First is a new pipe, class two the pipe with wall thickness approximately 65 percentage and class 3 is 55 percentage as well. Design of drill string takes in account the considerations about drill pipe weight, extension and grades of metal that are used for pipe. In order to determine main parameters to design string it is vital to consider depth of the well, size of penetrated hole, weight of mud, weight and extension of drill collars, SF, size of pipe. Characteristics that are used: collapse, torsion and shock loading. Collapse is an external pressure that causes yield of pipe or casing. Mud properties (density and height) are considered to be same in and out of pipe in case of usual exploitational conditions and as a result we have zero differential pressure along all pipelines which also means that we have zero collapse. In order to make the DST test pipe immersed to the hole partially empty in order to collect the sample for test. In order to calculate differential pressure along pipe for DST

$$\Delta P = 0.52\varrho_1 * L - 0.052\varrho_2(L - Y) \quad (1)$$

Y is equal to zero if the pipe is fully empty;

$$SF = \text{collapse resistance} / \Delta P \quad (2)$$

Collapse resistance is always presented in the tables and collapse pressure arrives from Δ P calculation. Generally, pipes experience both tension and compression stresses. Shock loading creates the possibility of a motion pipe. Can create pipe flaking in ultimate design. Pipe can also experience additional tensile force. Torsional stress calculated in (3)

$$Q = \frac{0.096167 * J * Y_m}{D} \quad (3)$$

Drill string design should consider critical speed of rotary table rotation. Longitudinal (axil) vibrations noticeable at surface, meanwhile torsional not seen because rotary table keeps in control angular motions. Lateral motions related to the drilling pipe. As we know these vibrations create resonance which results in fatigue and after time causes wear of tools. These vibrations of drill pipe should be coincided to the drill bit and calculated according to extension of drill string or collars and based on sizes of drilling pipes. Drilling collars are presented to be fixed at drilling bit and possibly mobile at coupling point of drill collars and drill pipe. The displacement frequency of the drill bit is regularly three cycles per bit revolution for 3-cone bits. In order to calculate frequency of oscillations at bit (4)

$$f = 3N * (\frac{1}{60}) \tag{4}$$

In this formula N is the rotation speed of the drill bit.

In order to calculate critical rotary speed

$$N = 20f \tag{5}$$

Natural frequencies:

Axial: $$f_1 = \frac{4212}{L_{dc}} \tag{6}$$

Torsional: $$f_2 = \frac{2662}{L_{dc}} \tag{7}$$

Drill bit rotations must be at speed less of higher than natural frequencies $f_1 and\ f_2$.String motions can be decreased by changing natural frequencies. Frequency can be changed by using a shock absorber, otherwise we can increase extension of drill pipes/collars. Another method we can use is mechanical damping.

1.3 Heavy weight drill pipe

When compared to the wall thickness of standard drill pipe, heavy weight drill pipe has a thicker wall. It is utilized rather than drill pipe in situations where stress amount is critical. The sharp contrast in cross section between the drill pipe and drill collars causes these stresses.

- The rigidity of the drill pipe compared to the drill collars
- The bouncing of the bit during drilling

The HWDP's major advantage is that it absorbs the stresses that are carried from the drill collars towards the drill pipe. The application of HWDP among drill collars and drill pipe can help to reduce the stress generated by the large stiffness variation. In order to keep compression during drilling deviated wells, the heavy weight pipe must be maintained in compression.

1.4 Jar

This is a vital part of equipment that should be used in every drilling string. The main purpose of drilling jars is to free the stacked pipe. A straight pull activates them, and they transmit an upward blow. As the jar placed above collars the drilling process should not be performed in compression.

1.5 Drill collars

Drill collars have a bigger outside diameter than pipe but a smaller interior diameter. Drill collars serve a variety of purposes:

- Apply the needed WOB
- Keep string in tension in order to prevent the bending and the fatigue
- In order to provide directional control
- Provide stiffness

Drill collars as drill pipes are affected by different forces such as bending/buckling, vibrations and compression/tension. It is a pipe with a thick wall that is used to put pressure on the bit and to preserve the drill pipe in tension. As the drill pipe has a lower stiffness when we are in conditions under compression it is possible to face buckling. In order to avoid it we should keep on neutral point. This point is placed below the drill pipe and it prevents failure because we have zero tension and compression at that position. Drill collars produced at the extension 9.5 m. The pin and box are separated from the pipe's body.

1.6 Shock sub

During drilling rough formations, a shock sub is utilized to attenuate the vibration created by the bit. It's usually placed just above bit to reduce bit bouncing loads. A steel spring in the shock sub absorbs vertical vibrations. Bit bouncing can be reduced for a variety of reasons:

- Increase life of bit by decreasing tooth impact
- Prevent damage of the string
- Minimize failure of surface equipment

1.7 Tool joints

It is a small tool which has a cylindrical form, it is molded to the both end of the pipe. These components are made separately from the pipe body and then molded to the pipe at the factory. Drill pipe tool couplings include high-strength, high-pressure threads that can endure hard drilling conditions as well as many tightening and loosening cycles. The locks are typically composed of heat-treated steel that is stronger than the steel used in the pipe body. The big diameter lock portion reduces stress on the area where the pipe is gripped with tongs. As a result, very minor cuts generated by tongs have no substantial impact on the drill pipe joint's strength or longevity.

1.8 Stabilizers

Stabilizers are placed in BHA and have blades molded on the outside surface. The blades can have spiral or straight types. Generally, there are three blades machined on the stabilizers. Stabilizers can have the following tasks:

- To reduce the buckling/bending
- Keep the string in concentric state in order to have greater WOB
- Avoiding stuck

Stabilizers might wear out and become under-gauge throughout activities. To ensure productivity, the stabilizers must be changed if they become 3/16" under-gauge.

CHAPTER 2

Definition of vibrancy

Fundamental concepts of vibratory are essential to understand the vibration of drill strings where different factors affect oscillation of the system.

2.1 Wave propagation

These are vibrations that pass through the system in the form of waves. So, the force that causes oscillation has influence firstly on the contact point and then it spreads all over the system. As a consequence the force applied to the one end of the drilling tube will have a time delay before reaching the other side of the pipe. If the wave propagation and particles shift in the same direction then it is called longitudinal waves. In other words, they are called compressional-tensional or axial waves. In other cases when particles shift perpendicularly to wave propagation it is lateral wave. Bending and torsional waves related to lateral.

2.2 Resonance and natural frequency

Natural frequency is the preferred frequency on which a system likes to vibrate. The most important parameters to determine natural frequency are its geometry and material properties. When a force is applied to the spring, it travels in the direction of the force that we applied. This happens till the moment when the spring's own force tries to return it to its initial position. This process happens under natural frequency. If the new force is applied to the system at the moment when we reach the original position, waves from two excitation sources will mix and as result increase the amplitude of the already merged wave. This phenomenon is called resonance and it can have a severe effect on drillstring, when we cannot allow the huge motions which may destroy the string components.

2.3 Damping effect

It is a process that takes energy from our system. Normally the system is shown as ideal cases. Theoretically the force applied to the system will preserve all energy. This is a situation when the pendulum is in constant oscillation or the spring remines in motion. In practice it was proved that this is not possible. As it said before, damping eliminates energy from our system and stops the string motion bringing it to a stable position. This is why resonance energy does not cause the failure of drill string during vibration. There are three kinds of damping: hysteretic, viscous and prevalent. A Vicious one develops on the contact between the steel and the mud. It is proportional to relative velocity at the end of the damping tool. Dampening effect is rising as the object movement through the viscous media is increased. Dispersion of energy which is the result of movement material's parts called Coulomb friction. To this terminus refer contact between the rock and bit. In order to describe hysteretic damping, structural damping. Whenever force is applied to the structure there is an energy loss because atoms during collision interact with different atoms as they travel toward each other.

- Viscous damping is related to the resistance of the body that travels with specific velocity the fluid. It is the most preferred type of damping because it is easy in calculations. Even if there is no viscous fluid it is possible to calculate the damping ratio by taking the experimental and theoretical data.
- Coulomb damping is the dissipation of energy that happens as a result of contact between two dry surfaces.
- Solid damping is a result of dispersion of internal energy. Each solid body attenuates all vibrations it encounters.

CHAPTER 3

Mechanical vibrations

Mechanical vibrations characterized as periodic exchange of potential with kinetic energy. The mass and the stiffness are essential parameters of such a mechanical system, to which we relate our drilling string. Components of mass connect two parameters: the force and acceleration of the system. (Newton’s 2nd law) Also the system has some damping that is connected to it. System forces and the displacement of it is connected by the stiffness element. (Hooke's law). Kinetic energy can be generated by the stiffness component's movement. Eventually, the displacement of energy will be handled by the damping element. Whenever it causes the system to damper, it will change potential and kinetic energy as heat, that will be lost. (Schmitz and Smith 2011). Free, forced and self-excited are the 3 major types of mechanical motion. It is extremely important to understand the main classes and types of vibrations in order to identify and try to eliminate the severe vibration trends.

3.1 Free motions

When a system is originally in an equilibrium position, it is disturbed by a force that moves it out of its equilibrium condition, causing free vibrations. The system will vibrate until it returns to its original state of equilibrium. Figure 3.1 depicts an example of free vibration behavior. Free vibration is shown as exponential decay, repeated reaction to the first extension. As the drill string cannot move in and become stacked in the bore hole, jar firing’s tries to free the pipe and in this situation the full drill string system starts to “free vibration”. This kind of vibrations are the result of excitation from primarily applied force. In case of no presence of external force the situation of string – borehole wall interaction can also be referred to as free motions. Because of the damping effect, the energy diminishes throughout time. There are a variety of factors that cause it nevertheless excitation of drill string is regarded as the more important one. Free oscillations when we don’t have damping, which extracts the energy from the system, is presented as “pendulum” where primary amplitude stays unchanged with time.

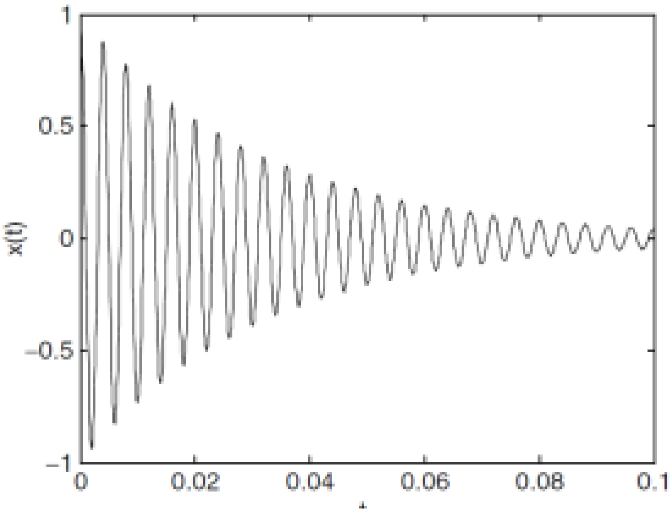

Figure 3.1 Free motions (Schmitz and Smith, 2011)

3.2 Forced motions

Forced vibration occurs when a continuous periodic excitation is supplied to the system instead of a single disturbance. As first force applied to the system, the system will exhibit transient state behavior before reaching steady state condition that have same response as the disturbance function and the frequency of vibration is equal to a forcing frequency. It's vital to mention that after the repeating disturbance ends, the system transforms into a free vibrating system that returns to its original equilibrium point. Figure 3.2 shows how forced vibration demonstrated in a magnitude to frequency domain (Schmitz and Smith 2011). Resonance occurs once the forcing frequency is equivalent to the natural one.

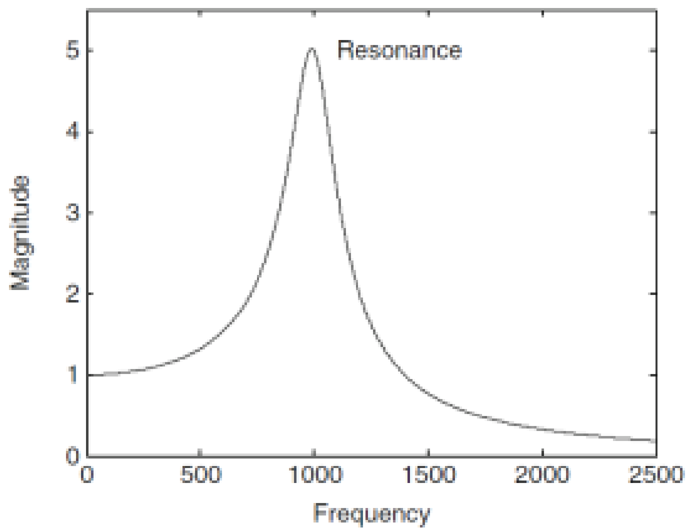

Figure 3.2 Forced vibrations

In contrast the forced vibrations/motions characterize systems that existed continuously by external energy not by a single extensional force. The example of forced vibration is disbalanced drilling. PDM could cause the disbalance, as the string rotates it will be excited for each round. So, it means that the frequency of excitation has a direct relationship with the velocity of rotation. As a result of the sudden resonance effect, it is possible to see high oscillations. In concordance, if there is a variation between natural frequency and the frequency that is the result of excitement of the system, amplitude decreases.

3.3 Self -excited motions

This type of vibration depends only on the effect that it causes, not on the vibrations that it creates in the system. This is the main difference between self-excited and forced vibrations, from other aspects they are quite similar. Also, it is important to mention that self-excited vibrations have a constant energy source while in case of forced vibrations we have periodic excitation's source of energy. As a result of friction between the walls of bore and string it is possible that string will stop rotation because of enough friction. The top drive will still continue to rotate because of the elastic qualities of the drilling pipe, it will transfer energy to the string in which parts were in stationary position in places of contact with borehole walls. After time as, top drive supplied enough energy to drill string, it starts to rotate as it overcomes frictional disrupting force. The friction between the string and the bow causes vibrations that produce a variety of sounds depending on how quickly the bow goes across the string. In figure below demonstrates this vibration type.

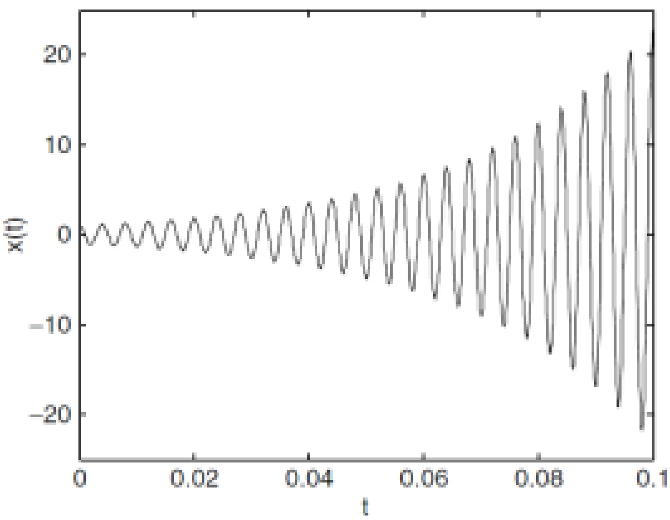

Figure 3.3 Self excited forces (Schmitz and Smith, 2011)

CHAPTER 4

Vibration models

Drill string faces a variety of forces that cause vibrations of it. Consequently, three types of modes of vibration are studied: axial, torsional and lateral. These models can be created by one another and also can be seen in coupled versions. Because of the set of specific features of each vibration, engineers can recognize the type of vibration mode. This is the main reason why it is so important to research and analyze vibration modes and their working mechanisms. Torsional vibrations cause slip/stick which is caused by non-linear friction during interaction of bit and formations, lateral creates so called whirl, the motion of bit in borehole, while axial produces bit bouncing, as result of drill bit contact with loose rock. Each of these models have their own specific case of occurrence, which is related to the type of wells, bit and formations.

4.1 Uncoupled type of models

Many models have been developed to study vibration modes. Models are divided into two categories: coupled and uncoupled. Most of the primary models-uncoupled. The main idea of using modeling is to predict the reaction of each vibration mode as an available limited exploitational conditions. Advantage of simulating different models is that they are simple and fast in computations. For each vibration nature its own model is created.

4.1.1 Axial model

The vibration along the drill string is referred to as axial/longitudinal. For years axial and torsional vibrations were obvious because they have the ability to appear on the surface. During axial vibration it is seen bouncing off equipment on the surface. The axial load on drill string is composed of two components: static and dynamic. Static component has the upper limit of weight on the bit because after that range buckling happens. The dynamic one mostly related to bit/rock interaction and compensated the WOB during penetration of well. In the case of the uncoupled axial model there was used differential equations taking in account lateral bar vibration. (Kreisle and Vance, 1970)). In the primary study by using the mentioned equation it was possible to get natural frequencies of axial oscillation of a given string. Experimental studies helped to measure resulting force and displacement of the top of the drill sting that was created by axial mode of vibration (Finnie and Bailey (1960)). Study about discontinuous contact of drill bit teeth on axial oscillations showed that axial vibrations could be seen on the surface (Paslay and Bogy (1963)). Common damped equation of axial vibration was linearized to study axial oscillations of drill string. To get rid of undesired vibrations shock sub with low stiffness was used. During research it was also proved that BHA length affects the energy transfer to the drill bit. Deep wells during tripping face axial vibrations. Non-coupled axial vibration model was used to understand possible load on drill string during the process of tripping. In this model the mud damping and also joint tools were taken into account. As a result of research dynamic load of drill string can be less than drill string weight in static conditions (Lubinski (1988)). To reduce drill string and wellbore friction while tripping it was present the idea of using static model and rotation of drill string. Future studies showed that quasi statistical analysis gives a more realistic model than static one. When there is a bit bounce the drill string will go up and go out the normal penetration area and create vibrations. Because there is a used roller cone bit we have a frequency which is three times higher that rotational speed of bit, because rotation happens on structure with 3 lobes.

As the frequency is calibrated to the harmonic frequency then there is a rise of amplitude. In the graphic it is shown that when we have rotational speed at 100 rpm the harmonic becomes 108 rpm; this is why amplitude increases. Different harmonics related to the properties of string such as extension of pipe and the damping effect.

4.1.2 Lateral model

Lateral motions are bending or reverse oscillations, related to transverse rotation of string. There is not much information about vibrations occurring in the downhole that is the reason why it is harder to define lateral ones. The main reason for lateral vibration's attenuation is that there are high frequencies which have dispersive nature. To study lateral vibration analytical and finite element models were used. Due to the reverse movements of drill string to get mathematical models mostly used beam elements. For this purpose, Euler-Bernoulli beam theory is used (Baltus, C. (2007)). The lateral vibration models are grouped into two groups: single- and three-dimensional planes. Lateral models assume that bending is not coupled with torsional and axial oscillations. This oscillation mode is recognized as a severe reason for non-functioning of BHA and drill string.

- Whirl of BHA

BHA whirl is the situation when we have bending of drill collars as a reason of rotational force. In the situation when the center of mass is not located in the center while the centrifugal force is applied to the center of mass it is possible to observe curvature of collars. Important aspect is distance between stabilizers center to the center of mass.

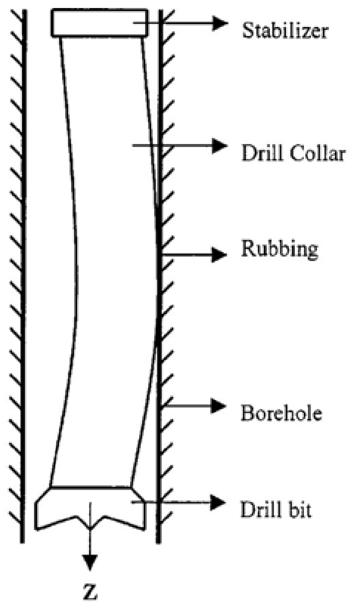

Figure 4.1 Bending of drilling collar

When we have significant curvature that is quite enough to allow contact between collars and walls then whirling happens. When there is narrowing of borehole it happens that there is reduction of drill collars collapse but increase of whirling. In case there is whirling in the direction of drillstring moves in borehole- forward whirl. When there is one cycle around the hole, the collar has the same point of contact with the wall. When the slippage effect is minimal enough, the pipe will roll on the borehole wall, generating backward whirl. The pipe slides along the borehole wall in the opposite direction of drill string rotation in this style of whirl. When there is no slippage effect, the term "pure backward whirl" is used to characterize backward whirl. As a result of low displacement in the back whirl makes no possibility to have one contact point between collars/borehole, nevertheless it is easy to recognize it on surface friction.

- Whirl of bit

Bit whirl is similar to BHA whirl in that the bit's initial center of rotation is pushed away from the geometric center of the bore by an initial eccentricity force. An extra adhesion force is created when the bit gets in contact with the bottom area. The instantaneous center of spin will be at the contact point if there is no slip in between the bit and the formation. This is the same as an automobile tire, where the immediate center of rotation is at the tire-road contact point. It is preferable to prevent bit whirl entirely, as one of the whirl type's disadvantages is that it is renewable. Brett et al. (1989) demonstrated that once the bit swirl started, both field and laboratory observations revealed a regeneration propensity. This is caused by a combination of two things. The first one is centrifugal force, which is particularly strong in swirl dynamics and is amplified at high rotating speeds. The whirl's centrifugal force pushes the bit off center, increasing abrasion with the structure. The second aspect is that the bit teeth are constructed to have the center of rotation at the center geometry of the well in order to reduce drill force unbalance. When this rule is broken, the cutters are no longer lined out for full coverage, which increases the drilling force imbalance. A whirling bit would dig an over gauged hole, and this will occur until the drill collars' restoring force overcomes the whirling bit's regeneration forces (Brett et al. 1989). This results in the formation of sills in the well as well as cycling periods of over gauge and true measurement drill. Because of this tendency, caliper logs are an excellent diagnostic tool for detecting spinning activity, since these cycles of true- and over-gauged drilling possible to identify.

4.1.3 Torsional model

The most used common model - torsional pendulum. This model assumes that BHA is rigid body and related to collars and rotary table, pipes assumed without inertia. (Lin and Wang, 1991; Jansen and Steen, 1995; Tucker and Wang, 1999). Various changes had been applied to the initial torsional model in order to study different parts and their effect on vibration. Such phenomena as stick/slip and whirling was studied by a model with two degrees of freedom. Parametric investigation of rotary table, weight on the bit and speed of rotary table, less but not least it was taken in account the rock stiffness according to the penetration rate. Thus, it was seen that experimental results are in row with field measurements. The purpose of a rotary system is to keep a consistent rotation speed. Subsea dynamic sensors demonstrate that the bit and bottom hole assembly typically reflect this (BHA). This is owing to the string limits as a transmission line as a result of the numerous additional demands placed on it. Because drill string length rises, the string gets more elastic in torsion (Gallagher et al. 1994). The drill string is frequently shown as a torsional string that has a large mass at the ends, which represents the BHA. As a result, downhole torque tends to oscillate around surface torque.

- Stick/slip

The drill bit can come to a halt due to downhole occurrences. Rotation may be hampered by a tight hole, severe doglegs, caseating, or substantial drag. To start rotating the bit after it has come to a halt, more torque is required than to keep it rolling. The fundamental source of stick-slip vibrations has been the subject of several theories. The discrepancy in torque input to overcoming the friction force in the string was initially considered to be the cause of stick-slip (Kyllingstad and Halsey 1987). For moving objects, the discrepancy between "static" and "dynamic" torque is equivalent to the difference between static and dynamic adhesion. Theorized subsequently to be the main cause of stick-slip is the torque decline seen at the bit with increasing rotational speeds (Brett 1992). Later, it was claimed that the inverse correlation between torque and rotary speed is a symptom of stick-slip. (Richard et al. 2004). According to the Richard-Germay-Detournay (RGD) model, the coupling of axial and torsional vibrations of the bit is the major cause of stick-slip vibrations. Despite variations in root effect research of stick-slip vibrations, scholars had acknowledged that stick-slip can be caused by bit or friction induced motions. The bit rotation rate slows down during the "slip" stage of stick/slip until the bit comes to a halt or is shifted outside the neutral point. Small intervals of backward rotation can be noticed in the later situation. Figure 4.2 shows how the RPM approaches negative sign before a new stick stage is launched, as shown by field measurements of stick-slip. The bit finally comes to a halt, and another cycle of stick/slip begins. Because polycrystalline diamond compact (PDC) bits are more aggressive than roller cone bits, they are more prone to stick/slip vibrations.

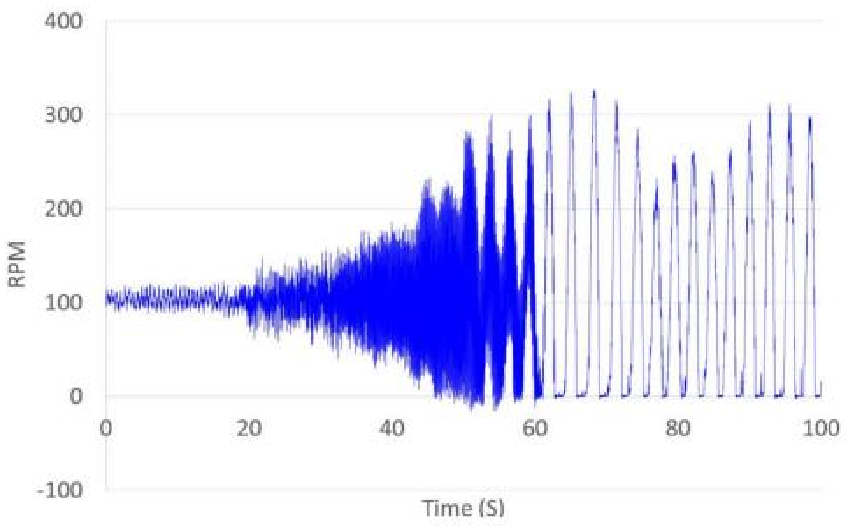

Figure 4.2 RPM measurements in the downhole

Torsional vibration characterized with high frequencies can also be called torsional oscillation resonance. This kind of vibration is characterized with frequencies that are higher than that of stick/slip. In 1998 researches by testing called “Amoco” evaluated very quick wear of bit, when bit penetrates the tough formations. Thanks to DDS the data can be analyzed to give high values of frequency. The high bit’s rate detects the presence of downhole phenomena that is ignored by observation of surface parameters. In scenarios when angular movement starts to grow in direction top to bottom in the direction of bit, drill string is simulated as a pendulum in order to recognize and evaluate stick/slip.

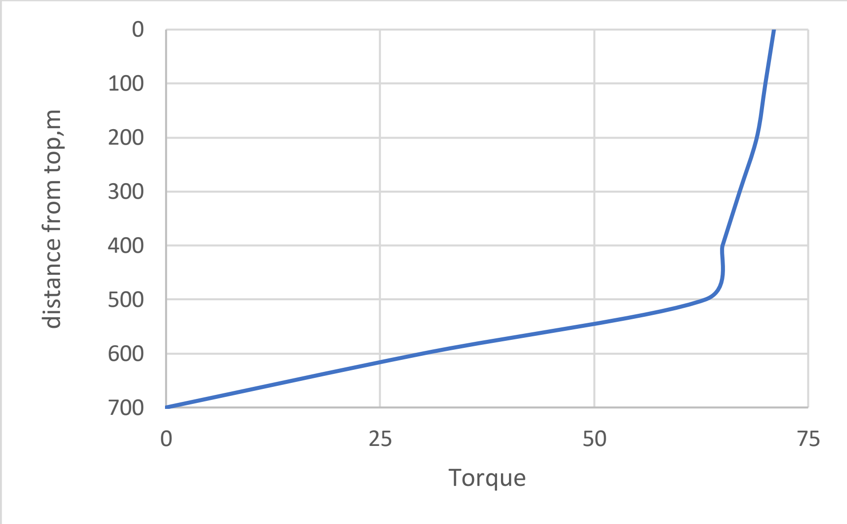

Figure 4.3 Drill string torque profile during stick/slip

When torsional resonance occurs, the drill collars vibrate at natural frequencies that are substantially higher than the drillstring's overall frequency. Figure 4.4 depicts the first harmonic for torsional resonance. The deflection during torsional resonance appears to be even less significant, yet it varies across the drillstring. The BHA is basically free at the top because the drill pipe is just less rigid than that of the collar. The collars may vibrate as a prismatic bar placed on bearings due to these border constraints.

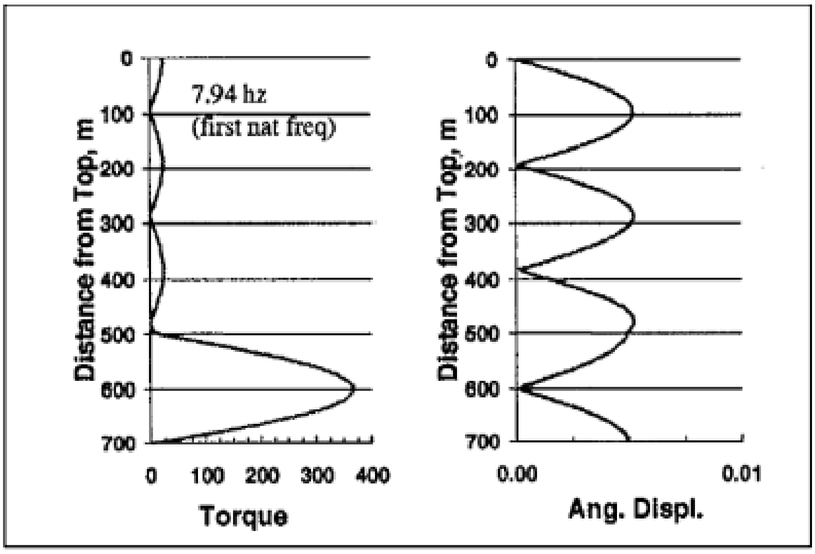

Figure 4.4 Torsional resonance

The development of torsional resonance has been shown to be extremely widespread with the increased usage dynamic sensors employing higher - frequency components in the BHA. Although altering the surface RPM above a wide range, Lines et al. (2013) discovered that the drill collars resonate at a frequency of 66 Hz and multiples of this harmonic. Figure 4.5 illustrates the frequency spectrum. When drilling various portions of the well, the researchers noted that the collars resonated at 66 Hz with a wide range of amplitude. As a result, the strength of vibrations at this resonance frequency could be substantially influenced by drilling situations. The drillstring will go through 1 million stress cycles in 4.2 hours at a frequency of 66 Hz, that relies on oscillation amplitude which tells about very rapid fatigue fail.

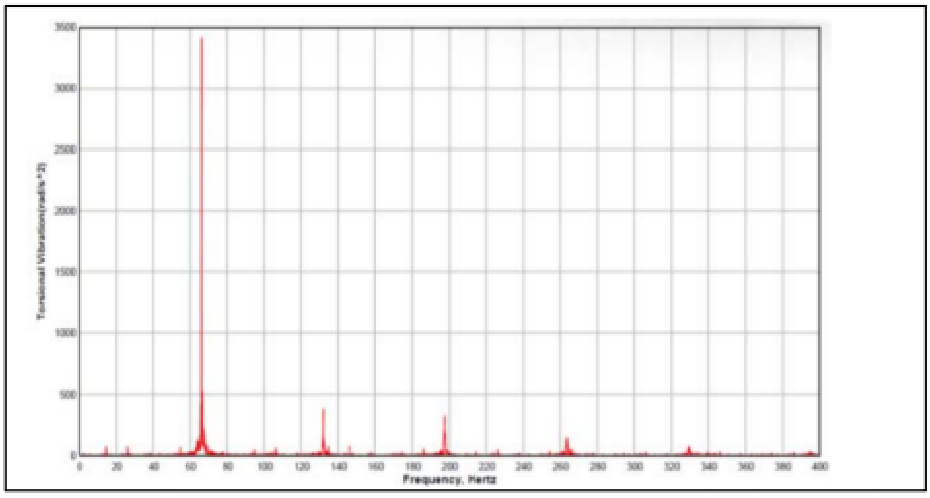

Figure 4.5 Frequency spectrum from a DDS recording (Lines et al. 2013)

4.2 Coupled vibration models

The main reason of coupling different vibration modes are

- rock and bit interactions
- drill string curvature
- torque
- modification from tension to compression of axial force lengthwise of drill string.

Coupling various vibration modes helps to forecast the dynamic behavior in high accuracy. These coupled models can be in two possible ways: linear or non-linear.

Extremely explored coupled models are:

- axial and torsional
- axial and lateral
- torsional and bending

By analysis each vibration motions are vital in determining physical processes, the harmonic patterns that in in real situations are typically more complex. That related to the numerous forces' borehole, as well as the capacity of specific vibration model to create other mode.

When encountering significant stick-slip while drilling, one example is the sudden and irregular movement of the drill string in the lateral direction while there is slip period.

4.2.1 Axial – lateral vibrations

Lateral motions can cause defects and deformations of drill string. Axial extension becomes short because the full drill string faces deformations and bending. The points where there are nodes connected and that present the case of attenuation of lateral motions will have a reductional effect on such behavior. Nevertheless, lateral vibrations are the most frequently occurring and severe oscillation type which causes the vibration of a full drillstring and shows the relationship with the axial one. Numerical calculations are the main evidence of such process occurrence.

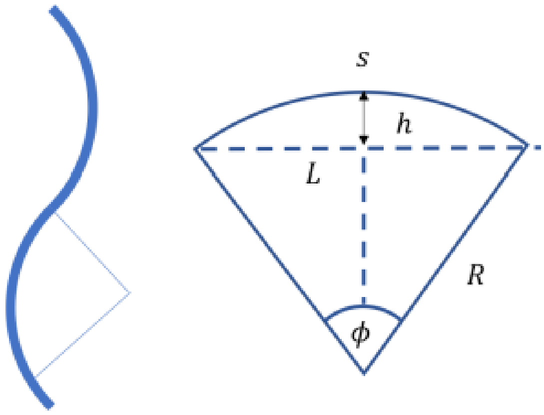

Figure 4.6 Demonstrates drill string deformed shape as result of lateral vibration (Larsen 2014)

In situations when string deviates, the shown segment with have a form of arc

$$S = R\,\phi \quad (8)$$

$$\Delta L = s - L = R\,[\phi - 2\sin 0.5\,\phi] \quad (9)$$

$$H = R\,[1 - 0.5\cos\phi] \quad (10)$$

$$\Delta L = H\,[\,(\phi - 2\sin 0.5\phi) / (1 - \cos 0.5\phi)] \quad (11)$$

By trial and error, the angle is established till the values on both sides are equal. S and H can be calculated by assuming that the drill string deviation is limited by the wellbore and pipe size in the segment that is studied. As a result, the drill string length reduction can be determined per each cycle every cycle can be calculated. For instance, for a string of length 12 ¼ with collars 8'', H is equal to 0.1m. By knowing values of s that equal to 10m and value of ϕ which is 0.08 respectively, putting these values to the equation of Delta L was found that drill string length reduction to be $3 * 10^{-3}$m in each wave.

The reason for the bit with rock interaction happens mainly because of WOB. The effects of lateral oscillations on mechanical stability was investigated to see under what situations axial vibrations can generate increase of amplitude. The idea of this theory is that axial oscillations can be transferred to lateral one. According to the Dunayev study the first deviation which is quite small is the initial string position. At time t1 it is given the maximum value of axial forces and it steeply decreases as it reaches t2. The axial force changes sign, causing the diversion to reduce. The lateral displacement returns to neutral after the axial load has finished its cycle. The lateral vibration has received an amount of energy expressed as extra kinetic energy. Within the next hemi cycle of deflection, this energy leads to a significant increase of lateral displacement. Each axial force cycle results in a continuously rise of lateral displacement amplitude, which is known as parametric resonance. The term "parametric resonance" is not the same as "traditional resonance," which is widely practiced in drill string-dynamics simulations. Instead of a discrete natural frequency as a traditional resonance, the critical frequency spectrum is a collection of zones. These areas are based on the amplitudes of WOB oscillations, and it is proven that as WOB approaches zero.

- In situation of coupling stick and slip

MSE measurement shows how much energy is used during penetration. When there is a whirl, raising the WOB usually lowers the MSE. This is due to the fact that boosting the WOB reduces whirling tendency. There is less energy spent on cuttings and friction as a result of this process. MSE surveys across the world have indicated that whirl produce 40% of footage. Stabilizers and other full gauge components in the BHA serve as nodal points, which means they can't move laterally in the bore. As a result, side forces are focused in these areas. When significant amplitude lateral vibrations occur, the side forces become more powerful. Based on this side stresses, rounded shoulders can be observed on the edges of the stabilizers. Because bit whirl creates over gauged holes, bit whirl and BHA swirl are linked. That indicates that nodal areas in the BHA such as stabilizers, which were previously stated, also have more freedom to travel laterally. The intensity of the BHA whirl is amplified as the BHA has far more space to accelerate laterally in. As a consequence, stabilizers as well as other full-gauge equipment are subjected to high lateral stresses and side forces. These enormous side forces cause greater bore friction, which causes huge amplitude torque swings.

Differential Quadrature method is used in order to compute non-linear equations to get as a result the BHA segments shapes and also to gain natural frequencies natural or fundamental are called the frequencies at which the structure preferably vibrates and moves. For all-natural frequencies there are linked mode shapes. The biggest displacement happens at the first fundamental frequency. Investigating continuous coupled models, it is possible to establish the best position of stabilizers which have a great impact on drill string instability. In order to find the stable condition of the system, the root of the 1st and 2nd derivative of system energy should be found. Choosing the best location of the set of stabilizers gives highest WOB and stable lateral oscillation.

Using the LaGrange approach and taking in account mud vibration and bit/rock interaction it is possible to immediately obtain resonance and whirling. To develop the effect of vibration creation tools on drill strings shown by the LaGrange equation. The outcome was checked by application of FEM. This calculation included the effects of: axial nonlinear stiffness, torque and axial force.

4.2.2 Axial – torsional vibrations

Drill strings that acquire a particular length would always be torsional flexible. As a reason, the pipes would not spin as if it were a rigid body. The BHA is frequently under and over shifted in rotation throughout stick-slip. The spin is the shear strain, and the turning tension is the shear stress inside the string. When solid rods are exposed to torsional stress, they will reduce axially (2013). Figure 4.7 depicts axial shortness as a result of twisting. The extent of one "fiber" along the circular pipe is depicted by the red line. Fiber extension remains unchanged, but when twisted, it takes on a helical shape.

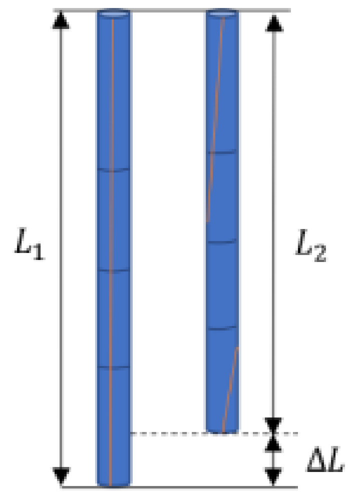

Figure 4.7 Twist of pipe which causes shortening (red line presents fiber along the pipe)

The coordinates that characterize spiral

$$\vec{r}(\theta) = [R \cos\theta \; R \sin\theta \; H_p \; \theta] \quad (12)$$

$$H_p = \frac{L}{\Theta} \quad (13)$$

This formula shows that when twisting increases there is a decrease of angle of slope. $\Theta = \frac{TL_o}{Gl_p}$ This way we calculate the total system's twist, by taking in account the constant values of cross section zone, torque values and the system stiffness. The extent of a red fiber in Figure 3.9 is constant, and it can be determined for the spiral by considering the integral from every progressive length starting from top till the point of full twist at the bottom parts.

$$L_o = \int ds = \int_0^{\Theta} \sqrt{R^2 + h_p^2}$$

(14)

$$L_o = \Theta\sqrt{R^2 + h_p^2} \quad (15)$$

In order to calculate a mathematical equation taking 550 feet extension for BHA. Taking in account that the BHA is displaced 2 spins from the top down to the bit during stick-slip, BHA will be shorten to 0.2 inches. Considering a stick-slip frequency 0.5 Hz, the BHA will crash into the formation every two seconds, propelled by the momentum produced by the load in the short distance. Drill pipe is slightly elastic than drill collar, as result the shortening distance might be even higher.

Finite element analysis is used for both non-linear and linear models in various operational situations. Axial-torsional vibrations studied using non-linear analysis. Linear one could be found through non-linear. After research it was provided that non-linear models have numerical and quality differences in comparison with linear models. Qualitative differences can be seen while making computations of forces and torques. In situations of stick-slip, a non-linear model shows geometrical coupling between vibrations, which has a significant effect while this is not observed in the linear case.

FEM is created via discretization of imaginary work of different constituent elements, such as inertia, strain field. Damping and forces that was applied. Linear function is used for axial and torsional vibrations to make a discretization. Non-linear model in addition to bit torque has geometrical coupling according to stain displacement. From the very beginning nonlinear and linear models vary in drill/bit rotary speed after the process of stick-slip, but this is not the only case, because force selection varies in the first place. Nevertheless, the supervision is the main step-in long-term analysis of the drilling process in order to find the right control methodology. In forthcoming research to obtain control techniques will be considered a non-linear model to perform parametric analysis.

4.2.3 Bending- torsional vibrations

Considering the bit and rock interaction, a set of various equations arrived. In order to solve these equations Newtonian method in polar coordinate system used. By doing experimental search it was verified that stick/slip phenomena vanish as whirl appears. Using the 4 DoF model which takes in consideration: lateral-torsional whirling oscillation and also wellbore/string friction it is possible to predict the effect of position of drill string and friction coefficient. All these models can be coupled together and can evaluate the

WOB and TOB as an outcome of cutting rock. Mud characteristics can also influence the stick/slip, bit bouncing and buckling of drill string. Obviously, a wide range of complex patterns were observed in order to predict the dynamic response of the drill string. Depending on computation time and main aim of modeling the vibration types should be properly chosen. As drill string is not just a construction that oscillates in air with only simple external force, but to make an accurate prediction it is mandatory to take in account the boundary conditions and the interaction between bit/formation.

CHAPTER 5

Parameters affecting drill string vibrations

Analyzing the fundamental causes of drill string oscillations is a vital step toward eliminating them. In this chapter discussed and analyzes various features of drilling process that has an effect on drill string's dynamic response. The variability of the formations, coupled with the multiple drill string components, makes it almost impossible to entirely eliminate the causes of vibrations. However, if the engineers want to reduce costs associated with hazardous vibrations, they must understand fully the physical effects of various characteristics in the wellbore and drill string.

5.1 Nature of rock formation

There are different factors that in some way create vibrations. One of the factors that we should take into account is formation which we penetrate. Knowing that most of the vibrations are located in points of rock-bit and borehole-string interactions. General tendency shows that the harder formation the more issues in the drilling process. As a result of this statement, with an increase of rock formation strength the drill string vibrations eventually start to grow. The stiffness of a rock is governed by its cementation component, whereas particle size as well as mineral content control its abrasion resistance. The dramatic fluctuations in formation strength are caused by soft soils and clays. This could be a source of vibrations, particularly when these underlain strata are drilled at a shallow depth. Drilling down the layers that have various stiffness at a high angle causes forces to change across the bit face, resulting in extremely unstable torque. Not only hard formations have a number of difficulties, but also loose and soft formations cause challenges during penetration. They create over gauged sections as a result of washout of formation.

5.2 Drilling pipes

The essential attention was put on the design of BHA in order to make it strong enough to withstand extreme vibrations during the penetration process. Drill string for 90-95% consists of drilling pipe, nevertheless there is less effort toward designing of drill pipes. The idea of this statement is that BHA has a high outer diameter that the drilling pipe has and as the result it is part of drilling collars which has a contact with formation rock. The essential factors for designing drill pipe is taking in account an inertia of the system and stiffness of pipe's rotation. This formula calculates torsional deflection of pipe between BHA and top drive of system that takes in account homogeneous material:

$$\vartheta = \frac{TL}{Gl_p} \tag{16}$$

where ϑ is torsional deformation that occurs between BHA and the top drive;

T – torque at cross section;

L- pipes length;

G- elastic moduli;

J- inertia moment of cross section;

An inertia of momentum is equal

$$J = \frac{\pi}{2}(r_o^4 - r_i^4) \tag{17}$$

$where\ r_o\ and\ r_i$ are the inner and outer radius of the shaft.

Because the radius influences the polar moment of inertia as a function increased to the fourth power, increasing the pipe's outer diameter while maintaining the thickness constant and increasing moment of inertia. While using same material for drill pipe sizes and maintaining the torque constant, this would result in a 19% decrease of torsional deformation.

As a consequence, the torsional elasticity is decreased, leading to more coordinated rotary motion between a top-bottom of the pipe.

5.3 Bit type

Often the bit is cheap compared with all well costs. Most of the time it contains 1% of total cost of a well, nevertheless it is a vital part of drilling construction and the only part of the drill operational system that has contact with walls of wellbore more than 77% in total. The bit choice has a direct relationship with vibration mode, the main reason of it is that bit is an internal component of ROP detection. As roller cone bits cause rock compressive failures, the majority of the rock removal is done with only a crusher machine. The depth of formations drilled is proportional to the WOB, and the elimination of the formation is based on the rotating speed, similar to a fixed cutting bit such as a PDC bit. This bit causes shear failure of the system components, as a result of different cutting operations. Torque also depends on formation type that has been penetrated. PDC bit's significant torque makes this bit subjected to stick/slip motions. An expanding weight on bit means that more cutters are exposed at each cycle, as a consequence it increases PDC bit's reactive torque. High amplitude torsional vibrations appear when raising the rotational speed or by increasing weight on bit.

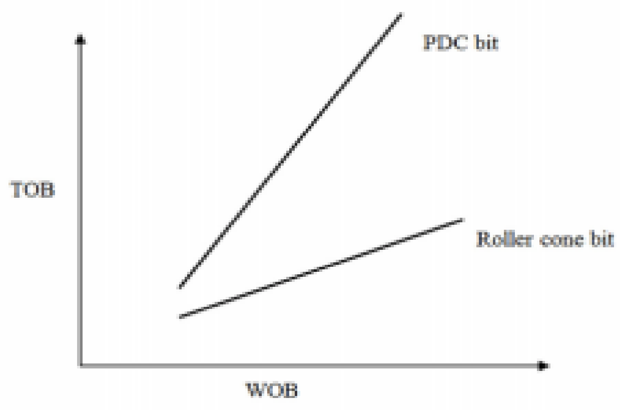

Figure 5.1 Difference between roller cone and PDC bits

As a result of the creation of three lobed patterns in the rock formation, three cone type bits which characterized more to axial vibrations, but for PDC are not characterized to axial one. Roller bits have less cutters, so they do not experience a whirl of bit. Essential to note that whirl of BHA may happen with any bit.The main problem that has to be solved is balancing the center of bit that should be in the center of mass constantly in order to reduce the bit rolling around the walls of the wellbore. So, it is important to balance the forces of cutters to control the position of the bit to be in the center.

5.4 Dimensions of borehole

Drill string oscillations occur in vertical and horizontal wellbores. Type of the well is affected by size and angle of borehole, as it influences BHA position and string stability. In vertical positions string will be subjected to whirl and bounce of bit. There are some constraints that create such behavior and the most notable is reduced interaction with walls of the hole. Mostly the low side of the well is in interaction with drill string. With an angle of 15° drilling buckling is reduced because the normal force should be overcome in the drill string contact with the wellbore. Friction creates the stick/slip with a high slope of inclination. Torsional energy that should approach the bit is decreased as a result of high friction torque that is produced along length. That will increase the possibility of the system to increase torsional moment in order to overcome frictional force. One of other reasons for torque is the roughness of the borehole walls. The severity of dogleg must be prevented considering that a smoother borehole lowers the torque. The dynamic of drill string is related to BHA's outer diameter. It shows how BHA can have deformations in lateral way until it touches the wellbore walls. When an over- or under- gauged hole is drilled the size of borehole is direct proportionality with vibration type. So as the result, walls no longer create a burden for BHA and it leads to the appearance of whirling and lateral vibrations. As a consequence under-gauged parts produce stick/slip by increasing the system torque.

5.5 BHA stabilizer

Initially it was considered that drilling in the vertical wells was based on the idea that it is quite easy to penetrate vertical wells. Lately, it was exploited that drilling vertical wells is not that simple task even in homogeneous porous media. There are many studies related to stabilizers because it is the main tool to center the BHA and for controlling angle of inclination. The role of stabilizers by placing BHA is also to provide the reduction of vibrations. This creates decreasing contact between drilling pipe and well borehole. From the name it is easy to understand that their design is mainly focused on creating a stable position for BHA.

CHAPTER 6

Drill string modelling methodologies

The studies related to drill string dynamic behaviour started in the 1960s in order to improve the drilling operations and to decrease the price of drilling process. (Darien and Livesay 1968) (Shor, Pryor and Oort 2014). The models with time started to be more complex with development of technologies and computerization of many systems.

6.1 Analytical modelling

Analytical modelling consists of two common types:

- soft string model
- stiff string model

While the soft string model assumes that drill sting and wellbore have continuous contact, the stiff string specifically determines bending and considers possible interactions with the wellbore. In order to recreate a drill string behaviour, the simplest way to model it is as a pendulum. The scheme below was designed to describe longitudinal and angular motions, considering that vibrations are independent. The diagram assumes also that different types of vibrations along the string are unrelated to one another. The result of comparison of forecast with some experimental measurements which were done by surface equipment showed that it is possible to obtain properly predicted longitude and angular oscillations, but not lateral vibrations.

However, friction is an important issue to consider while taking measurements in the field. The energy dissipation across the drill-string owing to solid and viscous damping is another major element ignored by the authors of this hypothesis.

Later, more complicated analytical models with more complex systems were constructed with the goal of more precisely forecasting the dynamic behaviour of the drill-string. A "lumped mass torsional model" is the name for this type of analytical model. A torsional model of a drill-string is described by this system, with each disk representing a drill-pipe. As the drilling operation progresses, the system becomes more sophisticated. This model describes four different types of elements: The top-rotary system, the 'p' number of pipes, which are described as linear springs with torsional stiffness K_t and torsional damping C_t the bottom-hole assembly, which includes the drill-collars, and the drill-bit This form of model, even though more exact than the one described above, is becoming increasingly difficult to solve analytically, requiring simplifications.

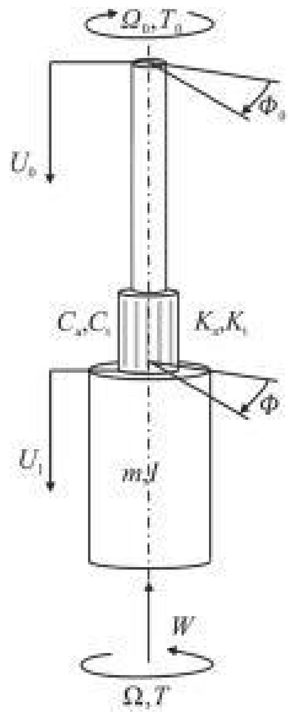

Figure 6.1 Drill string with lumped mass representing

BHA (m, I), cylinder simulation the stiffness (K_a, K_t) and damping (C_a, C_t).

Whereas vibrations are less intense and energy is more quickly dispersed in horizontal wells due to the large friction forces applied to the drill-string, vibrations are still evident and can have a considerable influence on bottom hole assembly tools. Particularly in extended-reach wells, which become distinguished by a large horizontal deviation ratio in relation to genuine vertical depth. The behaviour of the drill-string in these parts was studied and understood using dynamic simulation.

Figure 6.2 shows an example of this type of study, in which the authors take a near straight part of an elongated reach well shape and examine all of the forces acting in a segment of drillstring between two stabilizers. This research considers torque and drag, buckling, and mechanical motion at the BHA.

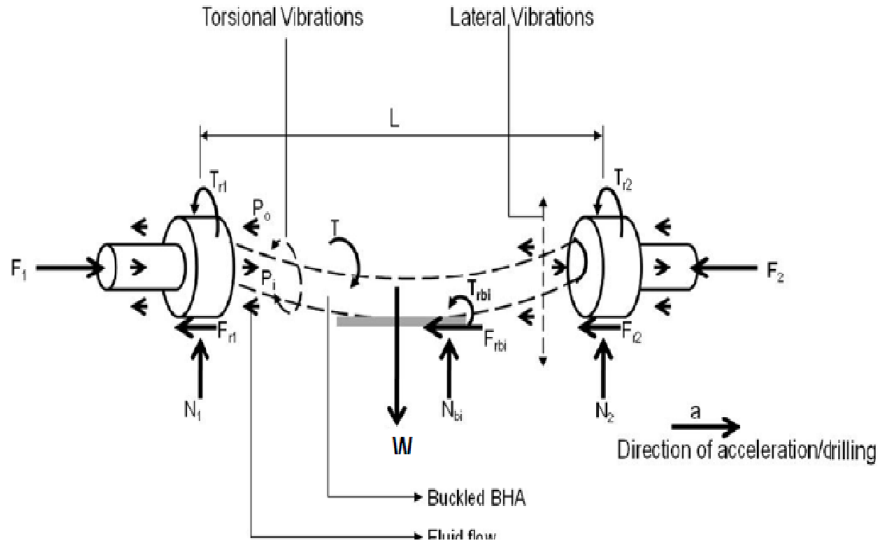

Figure 6.2 Analytical model representation by horizontal stick

6.2 Finite Element modelling

The Finite Element Approach (FEM) is a well-known and commonly utilized numerical solution technique for mathematical and engineering tasks. Considerable progress has been achieved in where to apply this method to other engineering domains, and the expansion of computer tools that made it more affordable to a broader range of people. This approach can be used to tackle a wide range of issues, including but not limited to structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential issues. It's especially beneficial when working with multiple geometries, material properties, and loadings that are either too difficult to solve analytically or are simply inconceivable. The finite element approach is intriguing because it is expressed as a system of algebraic equations rather than a system of differential equations. This approach divides the system into separate pieces that are connected by vertices known as nodes. The problem calculates algebraically for every node and component, rather than tackling the physical and mathematical problem for the complete system throughout one stage. Even though this technique provides convenience by reducing the issue, there will still be some doubt in the results because the outcomes are usually dependent on how precise the problem's fragments (mesh generation) is and how small the sequential changes are. When working with a transient analysis, such as vibration analysis, meshing and time step selection are crucial to the solution's completion. Finite Element Method applied to non-linear vibrations of the drill-string effectively in 1978. The research concentrated on the drill-string BHA. Problem reduced by employing beam elements and a regular grid with basic beam and examined four distinct setups through position of stabilizers. Another significant addition to the understanding of string dynamics was to investigate in linear motion, the impact of a shaft immersed in a dense annular fluid. Fluid impact have a major effect on the shaft's transverse modes of vibration. Finite element numerical approach was developed to solve the analytical model. Some FEM studies have concentrated on a single type of vibration without taking into consideration unique situations such as wellbore-to-drill-string contact. Depicting discretization of the BHA model, which considers well borehole contact. The research showed a good correlation between experimental and field data, highlighting the uncertainties involved with collection of drilling-string motions. The most recent approach is to use “ABAQUS” software to model an experimental setup to examine the stick-slip effect. The goal was to correlate the stress and strains involved of drill-string oscillations to the experimental downscaled model, thus researchers modelled the material qualities as an anisotropic and flexible composite. On the figure below the FEM model is illustrated together with the analytical approximation. The information about geometry, materials, and meshing method, as well as studies to determine the equivalent shaft stiffness for the model. By comparison of simulation results to their experimental results showed that they were nearly identical. AS concentration was on stick-slip motions, the extra attention was payed to creating the TOB curves.

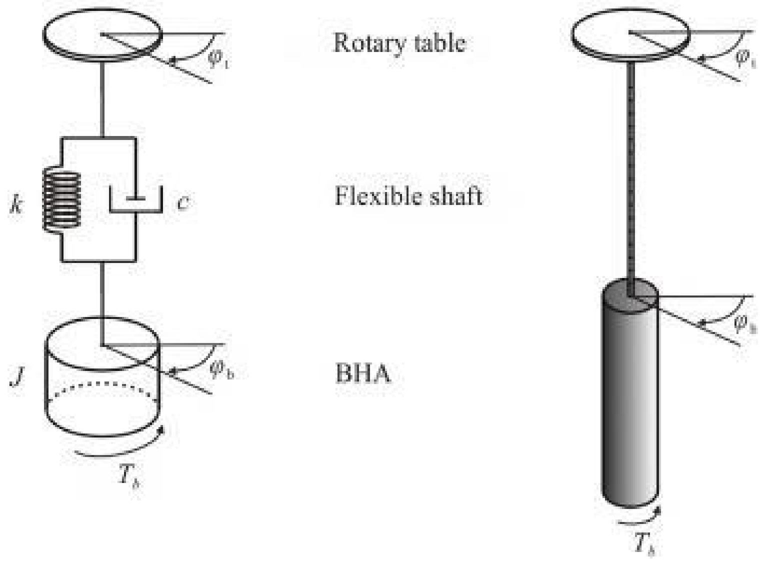

Figure 6.3 Continuous equivalent model provided by using FEM

(Kapitaniak et al (2015)).

This study's technique is noteworthy since it calibrates the model with experimental downscaled simulations in order to accurately anticipate stick-slip vibration and consequent prevention. However, a larger installation in the subsequent steps must be used because it is not as bound to downscaling factors and can only generate vertical geometries.

Additional issue is that it neglects the combined effects of the three vibration types. Stick-slip vibration is the most common and usually the most harmful, but the combined influence of these modes must be considered in order to accurately forecast drill-string behaviour and develop mitigation strategies.

Furthermore, there was an important research done in 2013. In this research it was proposed a mathematical model based on nonlinear differential equations that are defined separately for drill pipes and bottom-hole assembly to examine the stick-slip phenomena impacting components. The bit-rock contact was modelled by nonlinear friction forces. Mathematical model gives information about the influence of parameters on ROP. If we increase RPM surface we will have conversion of stick/slip into torsional oscillation and increase the ROP. By decreasing weight , the stick/slip will increase. While performing dynamic analysis it is also the main key to take in account drill-string stiffness and inertia. increasing stiffness, we will get a rise of ROP, on the contrast increased inertial mass will decrease it.

6.3 Experimental studies

The number of experimental models that are far less than analytical and mathematical models. The main reason is that it is hard to rescale huge size pipelines into experimental specimens. Moreover, it is quite costly to prepare equipment and tools for the experimental process. Nevertheless, it has a huge interest for many inventors. The latest research was done by Kapitaniak et al (2015). As previously stated, the main goal was to develop and validate a mathematical and numerical model based on experimental formulations. They did not create a downscaled model of a real-world setting, but they did create a testing environment to make qualitative understanding of sector detrimental occurrences. The setup intended to replicate proper TOB and WOB, and, most critically, string stiffness in order to induce whirling or stick/slip oscillations. it was done by using a flexible shaft made up of multiple layers of tiny wires.

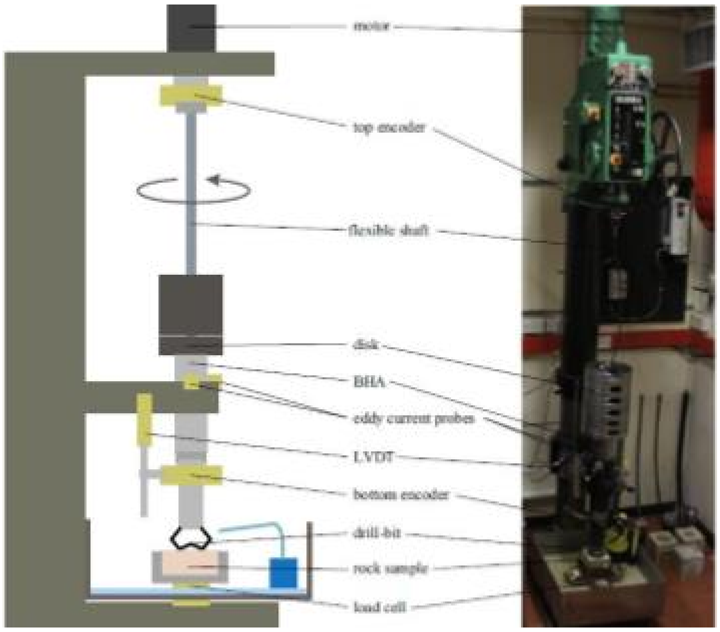

Figure 6.4 Experimental setup

To explore the bit-rock contact an actual bit and rock was used. By replacing the flexible shaft by a stiffer one then increasing the WOB meanwhile observing the work on the TOB. This experiment showed that increasing the WOB enhanced the TOB, as it was expected.

moreover, it was reported that the TOB declines for a short time period then it will increase again after hitting a limit (Kapitaniak, et al. 2015).

CHAPTER 7

Consequences of drill string failure

As a result of drill string vibration can cause major damage to the drill bit and the main parts of the drill string. Damage of bit, instability of wellbore and loss of energy are result of drill string vibration. Based on particular research, vibration is severe and most hazardous to drill pipe and collars. Different vibration models are presented and each of them has various effects on the drilling process.

Mode of vibration / type	Response
Axial / bit bouncing	Damage of BHA decrease of ROP
Lateral/stick-slip	Decreased ROP BHA washout Cost increase
Torsional/ whirl	Decreased ROP Wear of stabilizers Extension of borehole size Washout of BHA

Table 7.1 Vibration effects on the drillstring components and borehole

7.1 Reduction of penetration rate

The reduction of ROP is very important because it is directly related to the total costs of the drilling system as it is a part of productional operations. In the drilling operational systems, it is assumed that high values of rate of penetration denote the poor quality of the well. A common assumption in the drilling industry is that high ROP means poor wellbore quality. The quantities of energy supplied into the system can be increased by raising WOB or RPM. On the contrary, an increase of the ROP value is expected because energy is applied to the system. In case there is no increase in ROP it means that the energy disperses to the other parts of the system. Energy could be dissipated as a result of vibrations or interactions between the borehole and string. Increasing WOB and RPM causes decrease of ROP. In the points in which these processes occur an expansion of wellbore dimensions happens. Consequently, increase of wellbore size produces lowering of ROP value.

7.2 Instability of the wellbore

In the petroleum industry, high-quality wellbores are those that feature little number of tight holes, hole enlargements, or multiple minor doglegs. The wellbore condition could be essential to the reservoir performance. This is certainly relevant in wells that are going to be fractured, because the quality of the wellbore will have a direct impact on the completing design. Packers must have a specific wellbore condition to be pressure sealed. High number of doglegs and variety of the hole sizes will improve systems friction as a result will decrease wellbore's reach. Instability of the wellbore can be the harmful to the drilling process. problems related to the wellbore quality include pack offs, washout, time needed for reaming and tripping, pipe stacking, loss of mud and possibly a poor cementation. The formation of mechanical damage leads to the expanded hole size. In this case cleaning capacity of the hole reduced as annular velocity decreases. According to Santos et al. (1999) study mechanical failure of rock occurs when the stress higher than the rock's strength. Nevertheless, vibrations occur at different frequencies. The rock would fracture as result of the fatigue at stresses under the rock's strength, depending on the magnitude of these lateral impacts. According to the Khaled and Shokir (2017) calculations the amount of cycles required to trigger the damage of the rock formation at the different fractions of the rock strength. Whirl can produce fatigue damage in the formation in seconds to minutes, based on the amplitude of vibrations.

7.3 Possible Downhole damages

Failure to the drill string equipment and components can be highly costly. In addition to the destruction of expensive instruments, the drilling operation's completion may be reliant on the tools' continuous production. A failing RSS, for example, can result in a lack of steerability. In this instance, continuing to drill could risk the ability to hit that target. The operator’s task is to trip out the tool and replace it, then run it again into the well. The run out tool should be inspected in order to understand the basis of the damages. Thus, the vibration modes have their own unique damage features, so it is important to make a post run check that will reveal the vibration type that is present in the downhole.

CHAPTER 8

Mitigation of drillstring vibrations

Numerous technologies developed during the last decades in order to decrease vibrations. Nevertheless, it is essential to mitigate oscillations on the initial steps before starting drilling operations. Predicted quantities of vibration must be determined during the pre-drilling process using drill string dynamic memory data or well logs. Once all design requirements have been met, service organizations should model and assess multiple BHA configurations in order to maximize the possibility of picking the least vibration sensitive BHA. Numerous field experiments have confirmed significant reductions in vibrations due to BHA vibration modeling, with some providing up to 60% gains in ROP and a 150 % growth in drilling length.

8.1 Indication of penetration rate

While drilling, surface data and real-time MWD measurements must be constantly monitored. Numerous vibration types are hard or even not possible to detect using MWD measurements supplied by mud pulse. That shows that even if real-time measurements show no considerable quantities of vibration, dynamic memory data must be evaluated after the run. There is a wrong statement that high rate of penetration as a result of wellbore high quality. The modelling helps to indicate the RPM value diapasons but real drilling process shows that the models are not that accurate. An indication of energy being lost in a system is that formation and system parameters stay the same. In order to estimate the vibrations in the downhole memory gauges should be inspected. Each run to the borehole should be analyzed and if pre-drill checking is performed then it is an indication of future successful operations. Vibrations can be observed during post-run inspections of equipment. The drill string is commonly damaged in particular ways by various vibration types.

Predrilling	Well analysis Identification of risk Modelling of BHA To inform the related persons
During drilling	MWD data observation Surface tools monitoring Control parameter to prevent resonance ROP monitoring
Post drilling	Monitor memory data Post run analysis of tools Monitoring of BHA Report all borehole run

Table 8.1 Workflow of the common drilling process

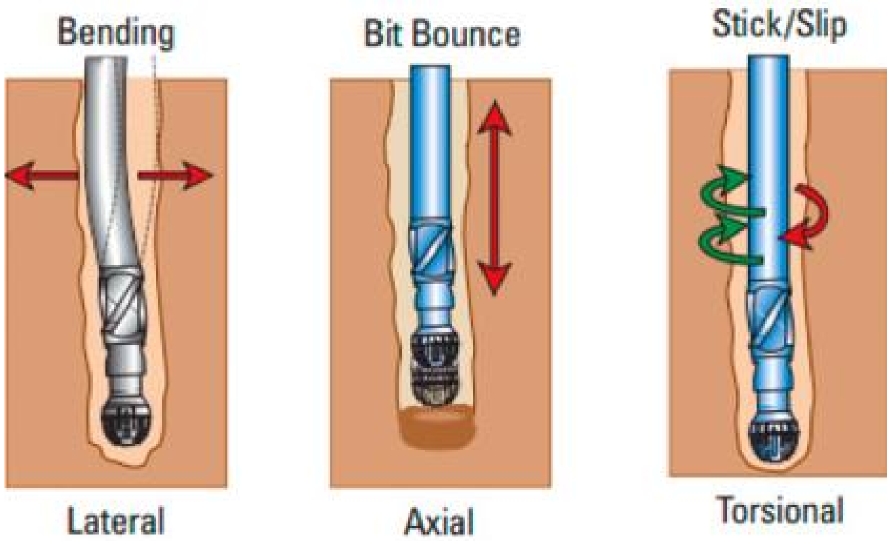

Figure 8.1 Representation of vibration types

There are other subtle vibrations that are assumed to influence the fatigue and fracture formation, ultimately contributing to component failure, in addition to these intense excitations that can lead to quick collapse in the drilling process. These include the energy transfer between axial, lateral, and torsional vibration caused by the drill string and BHA interactions with their environment. Drilling techniques and initial situations of condition can have a significant effect on the nature of such inter-mode coupling. Axial vibration occurs in two types during the drilling process. As bit is still in touch with the rock there is vertical vibration. When connection is continuously lost as the bit bounces on and off the bottom, this is known as bit bounce. There are numerous components that might cause axial vibration reduction or increase:

- Hardness of rock properties
- Borehole angle
- viscosity of the fluid
- length of the BHA

Vibrations of this nature are prevalent throughout the drilling process. The initial interaction of the drill bit with the rock on the bottom causes axial vibration in the drill string. After descending the bit to the bottom, an excessive speed causes the bit to bounce. As they can go from the bottoms of the well to the surface, this model has long been recognized and supported, whereas lateral vibration models are frequently stuck below the neutral point. When a roller bit is used there are axial vibrations occurring. Axial oscillations can be beneficial in the drilling process because it affects WOB and ROP. In vertical wells energy transition happens easier where hard rocks are presented. Torsional oscillation is caused when the string spinning is slowed or stopped at the bottom and then released whenever the torque exceeds the friction that stops the string from rotating. There are various things that can cause reduction or on contrary the increase of torsional motions:

- weight of the BHA
- type of the bit
- angle of the borehole
- lubricant mud

Application of constant speed of rotation does not provide the continuous oscillation of the drill bit. The application of a consistent rotating speed at the surface does not always convert into a continuous rotational motion of the drill bit, according to downhole measurements. Because of WOB increase in WOB, severe doglegs causing drill bit to a halt. Because of the rotary table's enormous inertia, drill string torsional oscillation went undetected for some period. The longer the drill assembly remains in stick/slip mode, the more severe the torsional oscillations are, maintaining constant rotating speed. The stick/slip frequency approaching the drill string torsional natural frequency as the rotating speed to reach the critical speed. By using MWD equipment drill string stick/slip severity can be determined. Rotation of string assembly managed by modification of the WOB and rotary speed. In order to reduce downhole vibration, it is essential to change bit type or BHA. Lateral vibrations created by non-centered rotation of the bit, creating interaction with bore walls. As a result of such movements an imbalance produces axial, torsional and lateral oscillations. The lateral vibrations are oscillations that do not spread to the surface that is why they are not recognized for a long duration of time. But using MWD tools it is possible to recognize vibration in more short durations. This motion destroys walls of the borehole and modifies the direction of the string. Whirling is lateral oscillation phenomena that is the result of the bit face's instantaneous centre of rotation travels forward, backward, or chaotically as the bit rotates. The whirling of the BHA is a very important lateral vibration phenomenon. Whirling is a circumstance in which the bit face's instantaneous center of rotation travels forward, backward, or chaotically as the bit rotates. Including both PDC and RC bits, the magnitude of vibration caused by bit whirl increases with the form intensity. The BHA works in compression that is why it is most likely a place where whirling and buckling happens. Back whirling is the most likely occurring type of lateral vibrations. In the case that the friction between both the stabilizers and the borehole exceeds structural and hydrodynamic damping forces, backward whirl can occur. There is major damage caused by backward whirling to the drill assembly.

8.2 Tools to measure the vibrations

In the 1960s the first attempt was made to register and analyze surface and downhole vibrations. At the surface we can detect vibrations thanks to torque and pressure fluctuations. MWD and LWD tools were later investigated in order to detect downhole vibrations. Several real-time vibration modes have been introduced due to new technologies. These models predict critical rotational speeds that cause lateral vibration, which should be minimized. The main purpose of real-time vibration simulation is to design BHA operational parameters. On the other hand, well data shows that these models have many overburdens from a practical point of view. Another method for determining vibration levels is surface vibration measurement. Fluctuations in surface torque gives information on vibration in the well. Each vibration mechanism has its own set of recognition factors, which can be used to determine the type of vibration. There are two types of vibration measurements considered in the borehole. The first is a memory measuring device that measures and records vibration so that it can be retrieved and analyzed later. The second group includes real-time vibration measurements. The "BlackBox" is an example of a memory measurement tool. The "BlackBox" is a memory mode vibration recording tool that can be used along the whole BHA. This device contains lithium batteries and has 200 hours of working capacity. The gadget registers three types of vibrations: maximum lateral oscillations, RMS and stick / slip. This device can be placed in any point of the BHA to monitor the dynamic behavior of the entire system. In order to acquire a better representation of the dynamic behavior of the entire drill string, it is preferable to consider more than one device that is installed in the BHA.

Figure 8.2 BlackBox (Murdock, 2011)

DDR is an MWD equipment that uses an accelerometer to record lateral vibrations. The DDR gadget is equipped with a battery and can measure lateral vibrations at 400 Hz by writing data each 2.6 seconds. MWD and LWD tools are commonly used to install DDR. The Multi-Axis Vibration Chassis (MVC), a four-axis shock measuring equipment, is one of the real-time vibration measurement tools. The strain gauge used to measure torsional vibration are the first axis of the device. The other three axes are related to the system, which includes a vibration registration and accelerometers on the board. In the MWD tool, the system is installed on a special chassis. The RMS vibration of the tools is also measured by the vibration recording system.

Vibration mode	Stick/Slip	Bit Bounce	Coupling	BHA Whirl
Surface	Torque at the surface, RPM, Top Drive halting, ROP reduction	RPM at surface, WOB, ROP reduction	WOB, ROP reduction	ROP reduction
Downhole	Torsional vibration with low frequency	Axial vibrations	Lateral, torsional and axial vibration	High frequency lateral and torsional vibration
Tool damage	PDC Cutter damage, Drill string twist off or washout	Bit damage and BHA washout	String twist and washout	Torque of cutter or stabilizers

Table 8.2 Vibration modes and their damage to the equipment

“Tele Scope” is a high speed MWD tool. With extensive downhole information, “Tele Scope” can transfer measured data from a variety of instruments. Real-time updates on downhole shocks, vibration, and flow are among the data collected. Other MWD and logging devices can be used with the instruments.

8.3 Vibration reduction tools

The industry took in the account the vibration effect. Two devices have been introduced that are used in the BHA to reduce the impact of vibration on the BHA. Anti-stall technology (AST) is now an anti-vibration device that includes a mechanical hydraulic converter in the lower segment of the drillstring (Figure 8.3). Under normal conditions, the device will transmit torque plus weight as an inactive part of the BHA. If the energy transmission to the bit becomes irregular, the tool is designed to actively adjust the bit tracking to ameliorate the situation and give the most stable settings possible. The AST device's operation can be summarized as follows:

- When the bit speed drops, the AST contracts, and reactive torque builds quickly (bit stall indication).
- The AST will gradually relieve the collected tension once the bit is back up to speed.

The AST actively strives to maintain the forces in the downhole. The AST's goal is to reduce drill string breakdowns and overload while simultaneously enhancing drilling efficiency and increasing penetration rates. The AST device, shown in Figure 8.3, is made up from 1- telescopic unit, 2- helical spline, 3- compressible spring. The compressed spring will be overcome by an excessive torsion force of magnitude, causing rotation of both two parts, lower telescopic component and the outer helical spline to rotate. As an outcome, the total length of the AST is reduced, and the drill bit's push is relieved. Once the bit is restored to full speed, the spring's accumulated force is released. Excessive torsion is converted into a linear force by the helical threading. The AST device is equipped with a powerful shock absorber that is modeled in order to prevent BHA from experiencing axial vibrations.

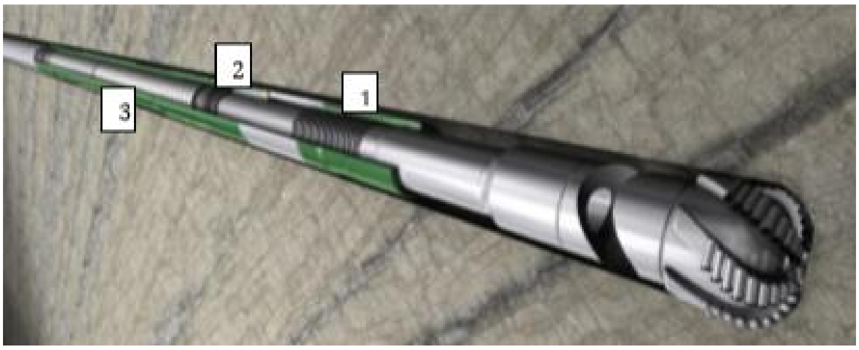

Figure 8.3 AST Tool (www.tomax.no, 2012)

CHAPTER 9

Modelling real data

Drilling process in the deep wells most frequently faces difficulties related to the vibration, unpredictable torque, and stick/slip which total drilling productivity. These issues not only reduce the drilling efficiency but also cause damage to the downhole instruments. These concerns become a burden in order to achieve planned total drilling depth. In this real case study presented modelling of the horizontal well.

9.1 Method of analysis

The main idea of this study is to see the effect of stiffness on the BHA elements and on the total drillstring vibrations. The investigation will be carried out by examining torsional vibration and stick-slip in actual horizontal well using data produced by MWD instruments. Using FEM analysis, the most stable torsional dynamic analysis will be detected through multiple rebuilds of BHA. The best value estimated will be used for the next drilling process of horizontal well. The research was performed in the Petronas company and was implemented in the field. The methodology consists of two stages: planning and drilling. Planning stage consists of static and dynamic modelling assessment and analyses of their advantages and disadvantages. During the drilling process data was collected, monitored in real time and compared with modelled one.

9.2 Result of the study

The goal is to establish a relationship between stiffness of the pipe and the stick/slip, as well as drilling parameters during drilling operations. The expected outcomes are next:

1. Recognize relationship between stick/slip and the stiffness
2. Develop a reliable solution for BHA design
3. Provide the reference in order to drill new well

The dynamic of the drilling string, which includes torsional (stick/slip), lateral and axial vibrations, whirl of the BHA creates obstacles in drilling in horizontal segment. Due to the obvious contrast among static and dynamic friction, stick/slip happens when energy is absorbed and released. Stick-slip in the drilling process can decrease drilling efficiency and consequently the ROP.

The main approaches used in the industry to estimate mechanics of the drillstring are the next ones:

1. Static analysis
2. Transient dynamic analysis
3. Modal analysis
4. Well propagation analysis

Static analysis – used to forecast the torque and drag of the string, supposing that the drillstring is stable in the wellbore and maintain the same deformation along the time.

Transient dynamic analysis- calculates all time histories of location-force during a certain time period. For this purpose, the UNIX platform is used. This simulation is much more accurate than static BHA modelling. The performance of the entire drillstring is predicted by the simulation outcomes, that contains vibration, stresses and the ROP forecast.

The interaction between the rock and cutters is performed every time when the lab receives new cutting structure design. All the measurements are stored in the database.

Modal analysis- estimates natural frequencies in the string, considering border conditions. In real cases boundaries always change, that is why there is no possibility to consider them as stable value.

Well propagation analysis- using a static computational engine based on the estimated BHA deformation and a simple bit propagation methodology, well propagation analysis is designed to determine the directional capability of a drill-string.

Stick-slip happened in an 8.5 in hole segment in one of the wells in the BTJT field, causing the BHA twist-off. The drill string configuration was adjusted using FEA dynamic analysis.

Methodology of the analysis:

1. Change values of well friction factor and the formation homogeneous nature in order to calibrate the model that underwent a twist of BHA in the 8.5 inch segment.
2. Improve the design of the drilling string considering model from BTJT27

3. After BHA parameters are adjusted the map of the drilling characteristics is provided.

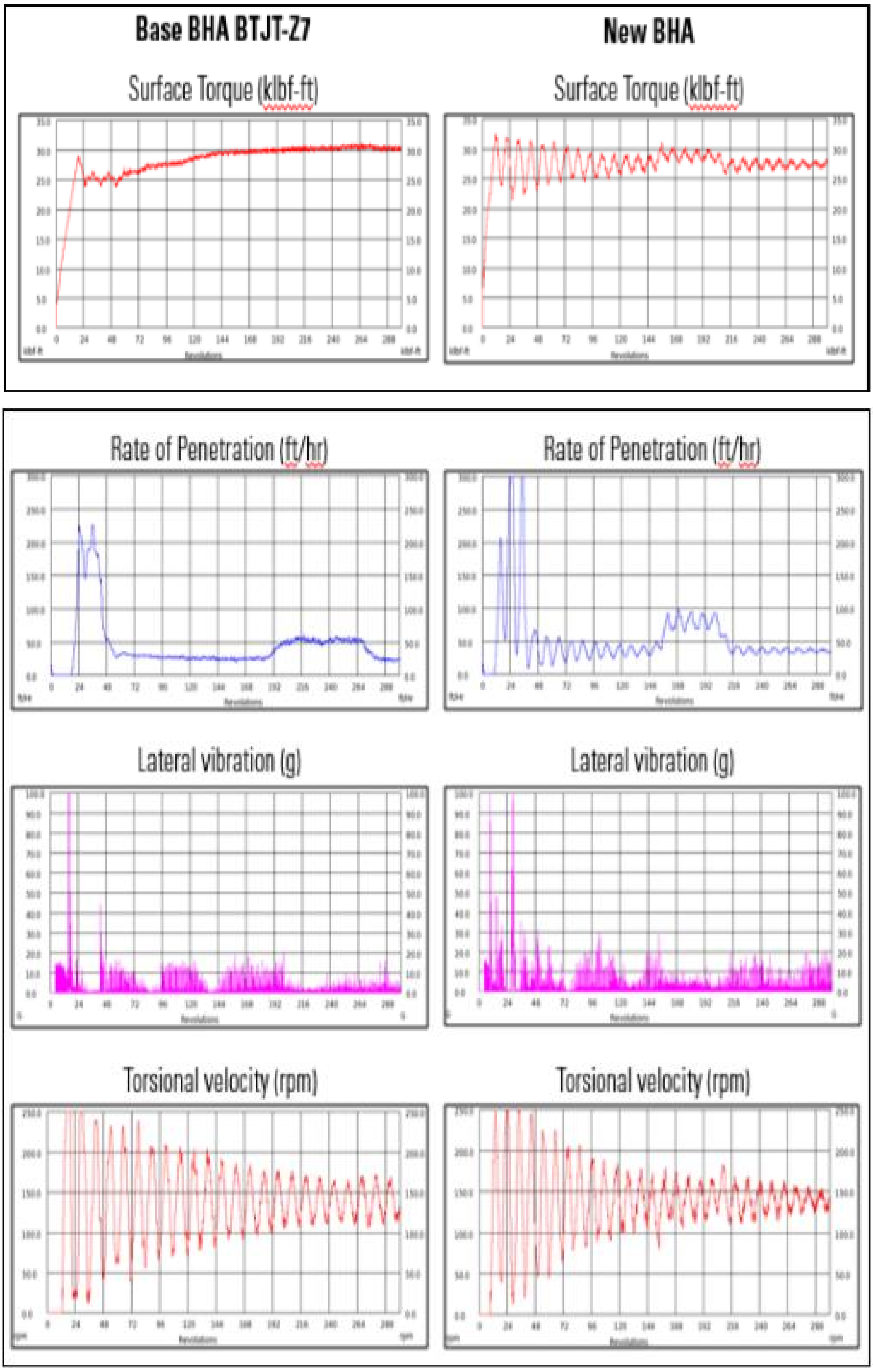

Figure 9.1 Analysis for Modelling

Regarding the simulation – method and results, can be indicated that:

1. 1. In horizontal wells the pipe stiffness has a significant impact on stick-slip severity. As a result, mitigation strategies must be developed properly.

2. Directional well design, planning, and reducing risk should be done more carefully.

3. The size, stiffness, and arrangement of the drill pipe will all have an effect on the severity of the stick-slip.

4. The results of this analysis is inclined to offer real solutions to a number of challenges that caused loss of time and money during earlier drilling projects.

Conclusion

In this thesis work main aspects related to drill string vibrations and the ways to mitigate them was studied. Firstly, the vital concepts related to the nature of vibration and the mechanics of different vibrational modes occurrence have been highlighted. Free, self-excited and forced vibrations were reviewed. Vibration occurs in three modes: lateral, torsional, and axial. Vibrations can be uncoupled, that means each vibrational type occurs separately. And they can be coupled which is the combination of these three modes of vibration. These three types of vibrations help to indicate response and also direction of drillstring that runs into the borehole. Axial mode is creating bit bounces which produce tension and compression as a bit passes through hard formation. Torsional vibrations cause difficulties to the downhole rotations. Torque can cause variation in angular velocity over time. The most dangerous form which we can observe is stick/slip. Strick/slip - torsional oscillation which makes bit stationary for a while. This kind of vibration causes damage to drill collars and bits. As the result of drillstring shortening, coupling torsional- axial or axial-lateral vibrations is common. Severe vibrations can create damage to the components of the drillstring, cause the huge coasts and also lead to the borehole trips in and out. Not only drillstring components face significant failures but also the wellbore instabilities occurring. Fatigue failure of the rock, which occur when lateral vibrations move the drillstring and cause it to interact with the borehole wall, can cause wellbore instabilities. The main wrong assumption related to wellbore instability is that the quality of wellbore comes from the ROP, nevertheless that happens rarely by considering the possible issues caused by wellbore instability.

Essential part of the work focused on the drillstring vibration modelling and remediation techniques. Analytical study, FEM and experimental set up discussed by taking in account limitations of the experimental setups and ways to solve them. There are two FEM models presented. Each of them considers the idea of coupling three modes into one single vibrational mode. First model monitored the dynamic behavior of the BHA in case when one mode of vibration is applied versus the case when there are three vibration modes present in the system. Moreover, the impact of magnitude change was demonstrated. The aim of using stabilizers in bottom hole assemblies was mentioned in order to reduce vibration spread substantially. It was also discovered that when just one vibration mode is used, the magnitude of the vibration response is way greater than in case when all vibrations are used. This statement is the basis for the second model. The second study widened the definition of the first by comparing four distinct materials when only one mode was induced reverse to the case when all three modes were used. The vibration response reduces if all the vibration modes are included, as a result of energy redistribution. When there is one mode of vibration it is possible to predict the type of vibration because each vibrational mode has its specific features and also by using equations while in case of multiple vibrations the behavior of the system changes and it no longer follows the same behavior. This could help to reduce downhole vibrations by creating additional controlled vibrations. Other vibrations may reduce the size of the damage to the acceptable level. In order to verify the model experimental investigation is used. To calibrate simulated models the experimental set up with scaled parameters is used. This experimental model has the idea to solve the issue that other models failed to overcome. The essential goal of this thesis work is to contribute to existing studies in order to reduce the vibrations and to drill well in the cost efficient, safe and environmentally-friendly way.

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