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Vibration Recording and System Signature Tools for BHA Management.

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Abstract

Uncontrolled down-hole vibrations can result in drilling downtime and delayed production due to damaged or destroyed BHA components. Current methods of predicting and therefore mitigating these vibrations include the use of complex mathematical algorithms. The use of these mathematical simulations in order to approximate the vibrations caused by the interaction between the BHA and the borehole wall has become more available to operators. Because of the complex nature of the interaction of the drill string with the borehole, a great deal of effort has been applied to ensure a more accurate mathematical modeling of the engagement of single points of contact.

Any solution of an equation or systems of equations requires that the programming architects necessarily define a system and a set of assumptions for each engagement. This is typical in setting up systems of equations for analysis. Each point of engagement that is added to the modeling sequence necessarily takes the simulation result further from the reality of the drilling situation. A typical PDC bit can have 50 points of engagement just in the cutting structure. A large bit, such as a 26 inch bit can have over 100 singular points of engagement. Each point of engagement requires another set of assumptions further reducing the accuracy and ultimate reliability of the analysis.

For more reliable software and to allow drillers to have greater confidence in the predicted analysis relating to the system performance of their BHA's, future drilling will be enhanced by miniature vibration monitoring devices which will provide a System Signature of the BHA and its' borehole engagement. This signature will be obtained by placing miniature vibration recording devices all along the BHA wherever it is considered critical. In the presence of a predefined event, perhaps a 10 or 15 g event in any of the three to four axis of vibrations being monitored, the devices begin recording axial, lateral and torsional vibrations until the end of battery life, or about 250 hours.

Upon retrieval from the hole the information from these devices is collected, processed, and compared with the numerical model in order to improve the predicted modeling results. Improved predictive modeling provides operators with the tools needed to reduce NPT, and lost in hole charges. Properly cataloguing shock and vibration events will also provide operators the information to manage fatigue failure events with the equipment.

Introduction

Data collection at critical points on the drill string will create information that will help the drilling community to improve and refine analytical techniques for predicting downhole vibrations and tool failures.

The primary modes of vibration which are encountered in downhole applications can cause damage to downhole components, especially when harmonic resonance which is induced through the excitation of natural frequencies amplifies the force of these interactions.

Excessive force from drillstring vibrations can and does cause damage to downhole tools and BHA components, negatively affecting drilling operations every year in lost revenue in direct damage to tools and indirectly through NPT and delays in well-plan completion. Great value is derived from the use of real data. Reducing uncertainties in the data provided improves the overall cost to drill and operate. By increasing efficiency in the overall performance through detailed analysis and systematic benchmarking, operators are able to begin implementing TLD. Technical Limit Drilling is being used by some operators to drive significant improvement in operations.

Current mathematical models data collection methods are used in order to mitigate future losses caused by vibration. Small vibration sensing and recording devices, like the DataPlug™, when placed in key locations on the drill string will record raw, real data for retrieval and after-action analysis.

The Dataplug™ is a small device that senses and records vibration data for analysis.

Proper drillstring management, especially in the BHA can save time and resources.

Drill String Vibrations

Of particular importance is the existence of drill string excitations in the BHA(Bottom Hole Assembly). There are three primary modes of vibration found within the drill string; Axial, Torsional and Lateral.

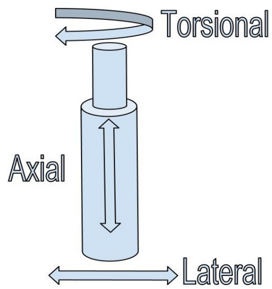


Diagram 1. Free Body Model for Primary Vibration Modes

Axial drill string vibration is the excitation encountered along the central axis of the drill string.

In the case of an element acted upon by axial forces;
According to Craig and Kurdila (2008 section 12.1), if the assumptions for axial-deformation as treated in elementary mechanics of materials are:

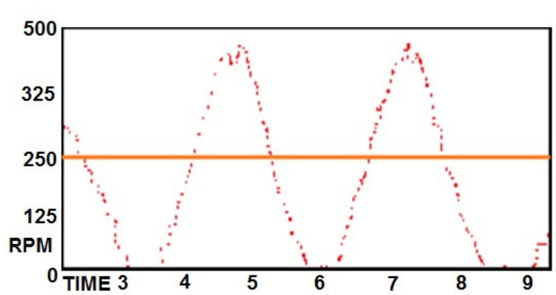
1- The central axis remains straight.
2- The cross sections remain planar and perpendicular with respect to the central axis.
3- The material is linearly elastic.
4- The material properties (E,ρ) are constant at a given cross section , but may vary with x.

The differential equation of motion for axial vibration of a linearly elastic bar is as follows:

$$\frac{\partial}{\partial x}\left(AE\frac{\partial u}{\partial x}\right)+p_x(x,t)=\rho A\frac{\partial^2 u}{\partial t^2} \quad , \quad 0<x<L$$

Equation 1. Axial Drill String Vibration, single DOF

Torsional drill string vibration, associated with stick slip is a variation of rotational acceleration. Severe cases of stick slip, as well as axial vibrations, can lead to "bit bounce" as the bit stops moving and the rotary continues to turn, the drill string twists and picks up off-bottom. When this happens the bit spins rapidly until violently re-engaging with the formation. In uncontrolled stick slip, the bit can spin up to six times faster than the rotary. This is very damaging to the bit and other tools in the BHA.



Graph 1. Classic Stick-Slip

According to Craig and Kurdila (2008 section 12.1) In the case of a rod Deformation and Torsion)
If the assumptions for torsional-deformation as treated in elementary mechanics of materials are:

1- The central axis remains straight.
2- The cross sections remain planar and perpendicular with respect to the central axis
3- Radial lines in each cross section remain straight and radial as the cross section rotates through angle theta about the central axis.
4- The material is linearly elastic; that is to say $\tau = G\gamma$, where τ is shear stress, γ is shear strain, and G is the modulus of elasticity.
5- The shear modulus is constant at a given cross section but may vary with x.

The differential equation of motion for torsional vibration of a relatively long linearly elastic rod with circular cross section is as follows:

$$\frac{\partial}{\partial x}\left(GI_p\frac{\partial \theta}{\partial x}\right)+t_\theta(x,t)=\rho I_p\frac{\partial^2 \theta}{\partial t^2} \quad , \quad 0<x<L$$

Equation 2. Torsional Drill String Vibration, Single DOF

Lateral drill string vibration, is extremely destructive and can cause large forces to impact the BHA damaging components.
According to Craig and Kurdila (2008 section 12.1) in the case of lateral vibrations of an element;
If the Bernoulli –Euler assumptions of elementary beam theory as treated in elementary mechanics of materials are:

1- The x-y plane is a principal plane of the beam, and it remains planar as the beam deforms in the y direction.
2- There is an axis of the beam, which undergoes no extension or contraction. This, the neutral axis is labeled the x axis. The original xz plane is called the neutral surface.
3- Cross sections, which are perpendicular to the neutral axis in the undeformed beam, remain planar and perpendicular to the neutral axis.
4- The material is linearly elastic, with the modulus of elasticity E(X); that is, the beam is homogeneous at any cross section.
5- Stresses σ_x and $\sigma_{y,}$ are negligible compared to $\sigma_{z.}$
6- Rotary Inertia may be neglected and the mass density is constant at each section so that the mass center coincides with the centroid of the cross section.

This is the differential equation of motion governing transverse (lateral) vibration of a beam that satisfies the assumptions stated above:

$$\frac{\partial^2}{\partial x^2}\left(EI\frac{\partial^2 v}{\partial x^2}\right)+\rho A\left(\frac{\partial^2 v}{\partial t^2}\right)=p_y(x,t) \quad , \quad 0<x<L$$

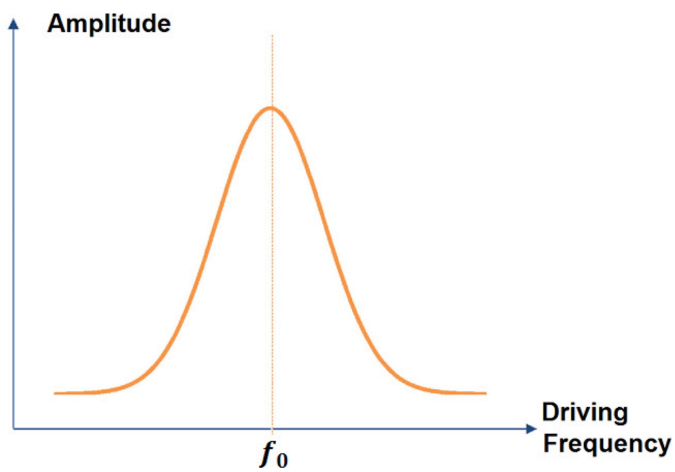
Equation 3. Lateral Drill String Vibration, Single DOF

Mathematical modeling can be a powerful tool as long as the user understands the limitations. These classical differential equations were developed using single degrees of freedom. Force body diagrams isolating and simplifying the problem are useful for definition and solution of classical problems in mechanics of materials, however not only are the degrees of freedom in real life much more than a single point, the number of points fluctuates as the drill string encounters friction in the borehole wall. Changes in rpms, weight on bit, mud weight and type, and formation variance add to the mix.

Reasonable significant digits begin to diminish as the problem becomes more complex and 'real'. The theory behind the math is strong and unquestioned. The reasonable application of this theoretical modeling breaks down as the real world problem begins to be more clearly defined.

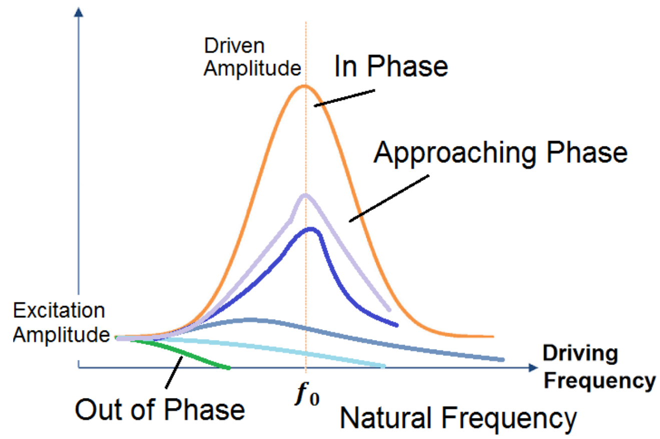
Natural Frequency and Harmonic Resonance

Every physical object or system of objects has a natural frequency. The natural frequency of and object or system of objects is the frequency at which a system will vibrate freely.



Graph 2. Natural Frequency

Forced excitation, or vibration occurs when an object or system of objects experiences an excitation. As the frequency of the forced excitation approaches the natural frequency, the system begins to resonate and the maximum efficiency of energy acceptance and utilization gathered from the excitation source is produced.



Graph 3. Natural Frequency In and Out of Phase with Excitation Frequency

Sources of Induced Vibration

Drill String vibration can occur as a result of the engagement of cutters in the PDC bit with the formation. Vibrations can occur as a result of BHA components interaction with the system; the oscillations of the motor, the engagement of the stabilizer, and especially the reamer. Because the top drive is necessarily inducing cyclic vibrations into the drill string through the rpms that it is turning, all points of contact within the drillstring directly affect the overall dynamics of the drilling system. From the top drive to the bit head and all parts in between, there is unavoidable contact and resistance to the contact between the drilling system and the borehole and formation.

Current Methodologies of Attenuating the Negative Effects of Drill String Mechanics

Mathematical Modeling and Direct Sampling are the primary methods of addressing tool failure that are the result of unmitigated damaging forces encountered in cases of extreme Drill String excitation.

There are many very recognizable mathematical tools for predicting downhole vibrations. Using mathematical models for designing the BHA and its' components can save rig time. Mathematical modeling is used as a design tool for bits, and reamers where notional ROP's are 'improved' in the model by making slight changes to the cuttings structures. Changes such as changing side rake or back rake in incremental degrees. Changing the number of cutters, the number of blades, the helix of the blades, etc…This is a very powerful tool, because math is very obedient. As a tool, there are also some weakness that should be addressed. It is impossible to predict the condition of the borehole wall in nearly all cases and because of this a notional, and typically homogenous material is chosen as the formation. The modeling software is unable to predict washouts, pump irregularities and other issues that stretch the ability of the user to fully define the engagement scenario. The mathematical simulation requires and ideal set of parameters.

Recording the actual vibrations is another method that is not without precedent. The strength of the actual data is that mathematical models may be corrected and improved with real information. The real data provides a more accurate picture of what is occurring downhole. Major limitations to currently available vibration recording equipment, is the large size and positionally dependent nature of their deployment. Typical recording devices are either subs or large devices that must be 'made-up' at the tool-joint. To compound the problem of limited real-estate on the drill string, once a position has been approved, the results must be mathematically manipulated in order to hypothesize what has happened many meters away from the actual collection point. Formation changes drastically in very small increments, this affects derived results that rely on single points of real data for mathematical supposition. Adding additional elements to the BHA in order to record vibrations can result in bad data. Lengthening the BHA necessarily changes the natural frequency. Complex electronics in the drill string can also affect hydraulics when made up at the tool joint as an additional internal component.

Real Solution to Theoretical Problem

Proper acquisition and management of vibration data will provide industry with the tools needed to identify and mitigate sources of damaging vibrations.

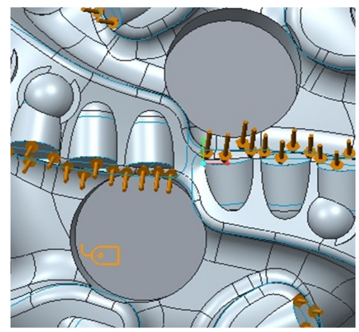
The programming architects writing the simulation software must necessarily define a system and a set of assumptions for each engagement. This is typical in setting up systems of equations for analysis. A typical PDC bit can have 50 points of engagement just in the cutting structure; a large bit can have over 100 individual points.

Each point of engagement is another set of assumptions stacked upon previous sets of assumptions which invariably decreases the accuracy and ultimate reliability of the modeling software. Skilled programmers and the users of these simulations know that offset data, and real vibration data is important in validating and refining their work.

Current software models are very sensitive to user input. The software is given parameters that cutters are engaging the formation at a particular penetration depth. Changing the inclination or penetration depth (depth of cut) of the cutter by ten thousandths increments could possibly have a profound effect on the modeled outcome.

Picture 1. Central Cutters

It is well known that manufacturing tolerance can easily move cutters around plus or minus ten thousandths of an inch. In order to account for this in the model, every possible outcome could be considered resulting in unreasonably compounded numbers of simulations.



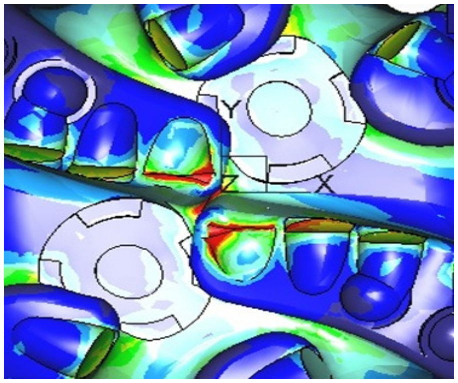
Picture 2. Central Cutters with Force Vectors

PDC Bits work in shear, the difference a ten thousandth swing in manufacturing tolerance can make in the simulation versus real response could be extreme depending upon where it took place.

In a medium sized bit, there can easily be more than 28 cutters. It must be noted that the solution of just one bit head could have as many as 4^{28} variances if each cutter placement was acknowledged as having the possibility of plus or minus only 6 and 10 thousandths movement per cutter. That is well over 72,000 trillion possible force combinations just on the bit. The variances are important because the program dutifully executes operations in the presence of data beyond its control. With one vibration sensor holding 4 accelerometers collecting real data there is simply no reasonable substitute.

It may be effectively argued that plus or minus a few thousandths here and there makes no difference. This is conceptually problematic in that the most sophisticated software on the market has probably not yet made an accounting for the fact that cutters not directly on profile still engage the formation, in that case the cutter doesn't mathematically exist.

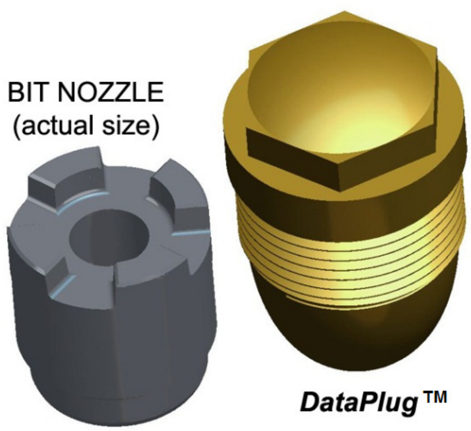
The cutter normal forces experienced in the center of the bit are far greater than anywhere else on the bit and therefore have a much greater effect on performance and force balance of the bit. If one of these cutters is off profile the simulation really breaks down and needs reality reinforcement.



Picture 3. Resultant Forces on Cutters

For more reliable software the system performance BHA's will be monitored. Because the simulations can save time, they are important tools, because the stakes in modern drilling are so high, future drilling will be enhanced by tiny vibration monitoring devices which will provide a System Signature of the BHA and its' borehole engagement to assist the modeling programmers.

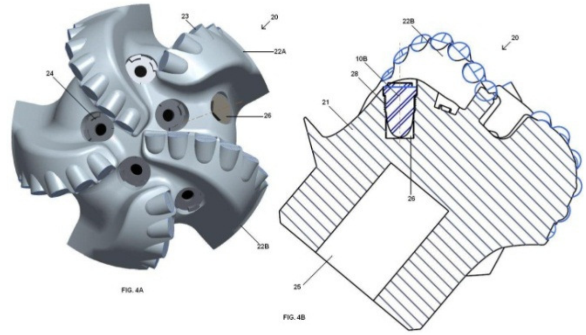
The DataPlug™



The first generation device is bulky by comparison to its ultimate deployment. About the size of a typical nozzle, the device is designed only to begin recording once a pre-determined event has taken place. Once recording begins, it continues uninterrupted at a particular frequency until the battery is depleted. Battery life is extended, and heat issues are mitigated through the use of peltier technology and vibration collecting energy cells. Peltier devices capture energy in the form of heart and convert it to electric energy.

The current design has four accelerometers. It has one each for Axial, and Lateral excitation and two to measure the Torsional vibrations. When the device is retrieved from the drillstring, the data is downloaded and analyzed. The analyzed data can be used in many ways. By gathering data from discrete locations, a standardized "System Signature" may be developed and evaluated.

This system signature is obtained by placing the miniature vibration recording devices all along the BHA wherever it is considered critical. A typical location could be an extra nozzle orifice pre-positioned in the bit-head (reference Picture 4.)



Picture 4. PDC Bit with Vibration Monitor

Upon retrieval from the hole the information from these devices is analyzed and compared with the numerical model to improve modeling results and to provide drillers with a system signature of the BHA that is derived from actual, node specific data.

What is the value to real data?

If a driller receives a redeployed MWD that was damaged in a previous drilling engagement, the driller may be inadvertently held liable for the damage if there is no reliable record of the BHA-Borehole interaction.

Typically, when an MWD or LWD device is recovered from operations it is cleaned and tested. O-Rings are replaced and it is redeployed. Damage could possibly have occurred weakening the system in a way that testing does not reveal.

The driller who is able to pinpoint the origin of particularly violent vibrations can also point to root cause of destructive vibrations. Combining real data collection with mathematical analysis and preventative maintenance of down hole tools will allow the driller to have lower insurance rates and reduced exposure to liability with respect to tools damaged or exhibiting the results of damage during a run. Many times, damage which has occurred in earlier runs is not readily apparent when a tool is reworked for redeployment. Laboratory tools allow greater analysis of failures after the tool has been recovered. A solder crack may not be apparent if the electrical system passes a field test and is redeployed. But even modest vibrations can finish the destruction caused by an earlier, more vigorous engagement.

Current methods of monitoring vibration include "subs" placed in the BHA which record a variety of data at specific points. MWD and LWD modules can also record data. Some attempts are made to predict drill string interaction with the formation through mathematical calculations. All of these methods are very expensive and usually require some degree of assumption in order to point to vibration origins. For example; excessive vibration recorded at the MWD may be blamed on the interaction of the bit, or the reamer. This is supposition based on data from the MWD node far removed from the supposed source.

A common problem is one in which an MWD or LWD has failed due to excessive vibrations. Because of the cost of LIH charges, there is liability involved when one fails and there is often intensive disagreement as to which component induced the vibration that ultimately caused catastrophic failure of the MWD/LWD unit. Damaged Beyond Repair (DBR) charges, cost of replacing the tool and rigtime associated with these failures can be excessive. DBR charges for an MWD/LWD unit are standard. Offshore daily rig rates also apply. Through tripping out of the hole and replacing failed tools while accepting DBR charges for the original tool the line between a profit win and a profit fail can easily be crossed.

Costs of not monitoring the vibrational forces acting upon MWD/LWD components occur in many ways: The recent loss of downhole communication with an MWD component in a drillship operating in deep water GOM resulted in NPT of more than $1 million USD. The typical way to ensure a lower NPT for MWD/LWD components is to enact strict preventative maintenance programs that call for replacing some components at regular intervals whether they need to be replaced or not. This is very expensive and time consuming. Uncontrolled vibrations can reduce ROP and lower tool performance. Some damage that has occurred to tools is not readily observable and can be passed on to future customers if strict preventative maintenance is not adhered to. Unfortunately, these maintenance schedules are normally created as a result of studying frequency of failures.

Conclusions

The DataPlug™ which has been developed by OTS International, Inc. and is ready for commercialization this year, will be used in conjunction with mathematic modeling and regular maintenance in the case of MWD/LWD tools in order to improve performance and survivability. Utilizing the Dataplug™ will reduce drilling cost and liability by aiding in the optimization of the drillstring. Vibration data will be recorded and sources of vibration will be accurately identified. Drilling dynamics are affected by vibration, identifying and controlling these vibrations is necessary as drilling environments become more challenging. The DataPlug™ will help the drilling community meet these challenges.

Acknowledgments

OTS International, Inc.

Nomenclature

BHA = *Bottomhole assembly*
DOF =*Degrees of Freedom*
GOM = *Gulf of Mexico*
LIH = *Lost in Hole*
LWD = *Logging While Drilling*
MWD = *Measurements While Drilling*
NPT = *Non Productive Time*
POOH = *Pull out of hole*
ROP =*Rate of Penetration*
RPM =*Revolutions per Minute*
TOR =*Torque*
TD = *Total Depth*
WOB =*Weight on Bit*
m = *meter(s)*

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