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Transient Vibration Analysis of the Bottomhole Assembly

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Abstract

Rotary steerable drilling systems, typically located at the end of the drilling assemblies, are exposed to extreme conditions. In addition to temperatures in excess of 390°F and pressures up to 25,000 psi, they must also convey compressive and bending loads, torque and rotation to the drill bit from the surface, as well as controlling the 3D trajectory of the wellbore.

Downhole shock and vibration sensors highlight the severity of the environment, but the root cause is difficult to determine based on sensor data alone. Industry standard predictive analysis techniques are incapable of detecting the effects of contact dynamics and real-world testing has shown that these are among the most damaging to downhole drilling tools, significantly reducing efficiency of the drilling process.

Careful application of the finite element transient dynamic analysis allows for new insights into downhole shock and vibration. By utilizing a combination of 1D beam elements and real 3D part geometries, the finite element analysis (FEA) models are able to predict the drilling assembly's dynamic signature, while still allowing for a timely solution process. This type of analysis enables complex drilling assemblies to be modelled within the confines of the wellbore and the results of complex contact interactions can be simulated.

Transient dynamic analysis enables drilling assemblies and downhole tools to be designed from the outset to minimize contact dynamics and avoid excitation of damaging structural resonances. In addition to improved design of downhole tools, the results of this analysis also show the drilling team what drilling parameters are optimum to minimize and mitigate shock and vibration while drilling.

Introduction

Rotary Steerable Systems (RSS) have become an essential part of today's drilling marketplace. They build upon the advantages of conventional directional drilling systems through offering improved directional control, better well bore quality and the capability to drill extended reach wells - typically where the horizontal displacement to vertical depth ratio for the well exceeds 2:1. A conventional RSS assembly is connected directly to the drill bit and either points or pushes the bit to control the trajectory of the wellbore while the drillstring continuously rotates. It is not uncommon for these assemblies to undergo high rotation speeds (in excess of 200 rpm) to allow for proper hole cleaning in long horizontal applications. The particular RSS discussed in this paper comprises a drill bit with polycrystalline diamond compact (PDC) cutters, a fulcrum or pivot stabilizer which contacts the formation and a hydraulic non-rotating steering unit.

Downhole tools operate in some of the most hazardous environments known to man with pressures exceeding 25,000 psi and temperatures in excess of 390°F not to mention the corrosive and abrasive formations and fluids that they are exposed to. As a result, drilling assemblies are extremely expensive to develop and downhole damage can result in costly repair bills and non-productive time, especially on a deepwater off-shore well where rig rates approach $500,000 per day.

There is a fine balance between optimizing drilling parameters to avoid tool damage and drilling as fast as possible. These two usually cause conflict and understanding the limitations of the drilling system and the point at which it becomes in imminent danger of failure are critical. Typically, drilling companies rely on advanced sensors to determine the severity of the downhole environment and the likelihood of tool failure, however, a significant effort within the industry is seeing wider adoption of advanced modelling techniques to better understand what goes on downhole, enabling improved operating techniques and improved drilling system design.

Typically, downhole tool damage and poor drilling efficiency is a result of shock and vibration. Vibration reduces energy that would otherwise be used to shear and crush the rock. Unintended dynamic behavior of the drill-string can have costly consequences both in terms of reduced rate of penetration (ROP) and damage to drillstring components [1, 2, 3 and 4].

This study focuses on the application of advanced modelling techniques to simulate and understand two lesser known vibration modes; high frequency torsional oscillations (HFTO); and backward whirl. Both of these modes typically go unaddressed due to the requirement for advanced downhole sensors and modelling techniques outside of industry standard methods.

In this paper, an advanced nonlinear finite element analysis model of two BHA systems was created in a commercial FEA package. The two BHAs are identical except for the placement of an extra stabilizer at a critical position along the BHA. The effect of the extra stabilizer is shown to reduce the vibration severity across the BHA. Numerical results are compared to real experimental data for verification.

Conventional BHA Analysis

Drilling assemblies vary significantly in their complexity and their configuration depends heavily on the well and section being drilled. A typical bottom hole assembly (BHA) connects above the drill bit and comprises of a steering tool to control wellbore trajectory, a navigation tool for obtaining inclination and azimuth, logging tools for determination of petrophysical and lithographical formation properties, a transmission tool which sends downhole data to surface by electromagnet and /or mud pulse telemetry, and drill collars / heavy weight drill pipe, used for transition to the drill pipe above. BHAs can range from 10's to 100's of feet long and there is an endless variety of BHA configurations depending on application.

Performing computer based BHA analysis is a vital part of any drilling campaign. It can be used to detect damaging downhole conditions, both dynamic and static, that may occur during the drilling process and enables the BHA or well plan to be configured accordingly. Computer based modelling offers a more cost effective and timely alternative to real-world testing.

Standard analysis methods developed for BHA analysis utilize a mixture of rigid-flexible multibody mechanical systems using the component mode synthesis method [5].

BHA analysis has two main purposes:

1. Static Analysis: BHAs typically pass through highly curved sections of the well. These impart cyclic bending moments in the BHA which could result in gross overload or fatigue damage to downhole tools and the threaded connections between them. Static BHA analysis calculates the equilibrium state of the BHA due to the effects of gravity, hole curvature and axial compressive loads or weight on bit (WOB). Important results for this type of analysis include: The shape of the deformed BHA, location of contact points between the BHA and the wellbore and stress and bending moment distributions throughout the BHA. The BHA and well plan can then be optimized quickly and efficiently to minimize the chance of downhole tool damage. Figure 1 shows example results of static BHA analysis. The plot shows the deformed BHA cross section, contact forces, bending moments and the von Mises stresses along the BHA length, respectively.

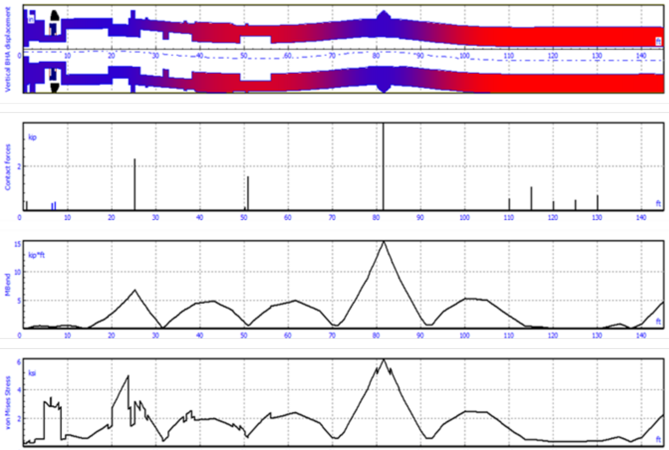

Figure 1: BHA static analysis results.

2. Vibration Analysis: Industry standard analysis techniques such as linear vibration and forced frequency response enable resonant modes to be determined and critical operating parameters to be approximated. Linear vibration analysis of the BHA is performed using kinematic and forced harmonic excitations. Vibration sources, such as the cutting processes of the drill bit, contact point interaction with wellbore wall, rotation of eccentric parts and operation of BHA components (mud motors, RSS assemblies, etc.) are accounted for. The implemented analysis procedure, which is based on linearization of the equations of motion, is widely used and with relatively small computational expense. Figure 2 shows simulation results of the maximum lateral displacements as extracted from frequency domain vibration analysis of a BHA. Utilizing the forced frequency responses, the model has the ability to detect dangerous rotation speeds in the BHA which can cause damaging downhole vibrations though excitation of critical structural resonances.

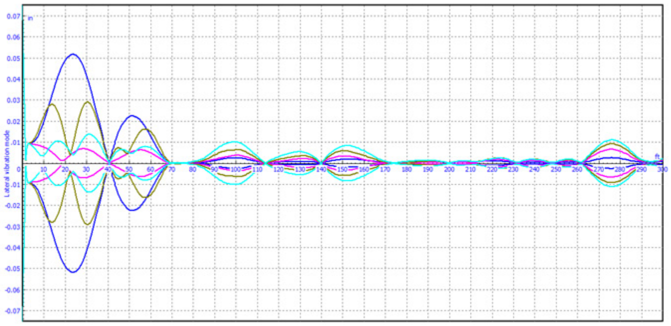

Figure 2: Results of linear vibration analysis.

In the past, historical and empirical data was heavily relied on to determine BHA suitability. Nowadays even the most fundamental analysis methods as previously described have proved invaluable and have been a major step in the right direction; however, there are some significant limitations. Typically, these limitations are overcome by over stabilizing the assembly, which is a common practice in rotor-dynamic problems. In the imperfect world of oil exploration, stabilization - specifically the number of stabilizers and their clearance with the drilled borehole - is under close scrutiny by drilling companies. Higher levels of stabilization are commonly considered to increase the chance of getting stuck in hole when drilling mobile or swelling formations. In addition, stabilizers can restrict the flow of rock cuttings and cause pressure spikes, which can damage formations and downhole tools. Stabilizers may also increase torque and drag putting higher loads on surface power systems and reducing the depth or lateral extension of the well. Particular focus recently has turned to efficient and effective stabilization rather than maximum stabilization and in order to evaluate this, more advanced time domain based simulation techniques are required.

Motivation for Time Domain Analysis

The main advantage of both the static and frequency domain vibration analysis methods previously described is the fast solution time in which the analysis can be performed. Each BHA static and vibration analysis case can be completed within minutes. The fast solution time is particularly useful for vibration analysis where the model requires the ability to predict the response behavior for multiple WOBs and RPMs for each position in the well.

Although the results of both static and linear vibration analysis have been validated both experimentally and against full FEA models, its benefits are not without drawbacks:

- Frequency domain analysis is performed using linearized (simplified) equations of motion.
- Time dependent or transient effects, such as those resulting from contact, are not possible to determine from frequency domain vibration analysis.
- Due to the analysis methods used (frequency domain), natural contact with the wellbore boundary is not possible. Therefore contact regions have to be manually imposed.
- Contact is imposed at specific regions along the BHA based on results of the statics analysis. These contact points determine the node location and are fixed during linear vibration analysis.
- Very limited outputs are available: lateral, axial and torsional displacements only.
- No acceleration data is available.
- The analysis is sensitive to the location and amplitude of excitations applied to the BHA. It is extremely difficult to determine what the true input excitations should be, especially when multiple contact points exist and limited sensor data is available.

In contrast to frequency domain techniques, time domain analysis allows contact between the BHA and borehole to occur “naturally”, thereby eliminating all of the aforementioned limitations of the frequency domain approach. The advantages of time domain analysis are:

- The model is analyzed using nonlinear equations of motion, accounting for real physics.
- Forces occur naturally due to contact with the wellbore rather than relying on manual definition by user.
- A large set of output data, e.g. displacements, accelerations (lateral, torsional and axial) are available.
- Special contact formulations can be applied to account for drill bits & stabilizers (bit-rock interaction).
- Results can be easily correlated to real world sensor data – vibration severity is generated in terms of acceleration which is directly measured by downhole sensors.
- Interpretation of results can highlight the presence of contact dynamics such as backward whirl and the interaction/coupling between dynamic modes.
- Time domain analysis is based on real-physics and therefore is far more representative of the downhole environment.

There are, however, some notable drawbacks:

- Solution time can be considerably higher than frequency domain analysis (hours compared to minutes).
- Requires the user to have a special skill set, but in some circumstances the process can be semi-automated.
- Not suitable for wide distribution; only used in special cases when time allows for extra solution time.

Time Domain Analysis of BHA Systems

To demonstrate the application of time domain analysis, two test BHAs were analyzed. The two BHAs consisted of an 8.5 inch diameter PDC drill bit, point-the-bit RSS, integrated directional sonde (IDS), multi-frequency resistivity (MFR) tool, and drill collars. The only difference between the two BHAs is the addition of a stabilizer to the top end of the MFR. The BHA configurations used in the analysis are shown in Figure 3. By analyzing these two systems using the time domain finite element analysis a better understanding of the effects of stabilization can be achieved on the overall stability of the test BHA.

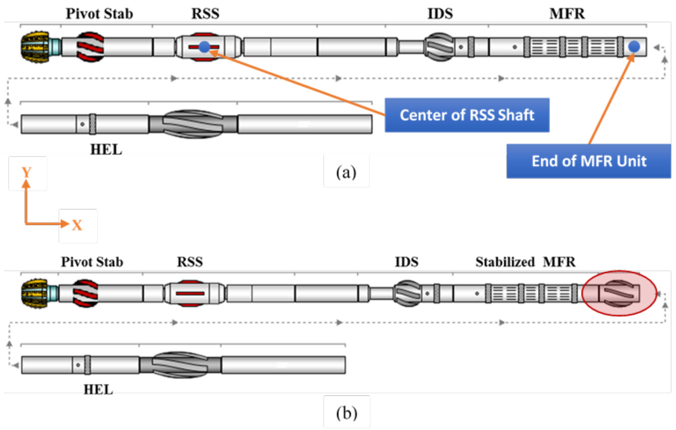

Figure 3: Test BHAs: (a) Case 01: Non-Stabilized MFR model; (b) Case 02: Stabilized MFR model.

There are several challenges in efficiently applying the finite element analysis to the BHAs described in Figure 3. The ratio of the model's length to the typical diameter is in the order of 10^5, which prohibits using shell and solid elements. Beam elements are a good candidate, however, they are most suited for static analysis of BHA systems and frequency domain vibration analysis. Beam elements are represented by a line in space with a homogenous circular cross section, they are not capable of capturing the complex contact dynamics that occur with the wellbore during rotation.

An effective approach to perform time domain finite element analysis is to use a mixture of beam and solid (or shell) elements. Beam elements can be used for uniform parts of the BHA, e.g. drill pipes and drill collars, without any loss of accuracy. Parts that have more complex non-uniform geometry, e.g. stabilizers, can be created using solid or shell elements. Kinematic coupling is then used to connect the different types of elements so that consistent motion and responses are transferred correctly. This is an efficient approach allowing the effect of 3D part geometries on contact dynamics to be assessed without unduly increasing simulation time.

Figure 4 shows the analyzed BHA model with the locations where 3D geometry were used. The other areas of the BHA were represented with beam elements.

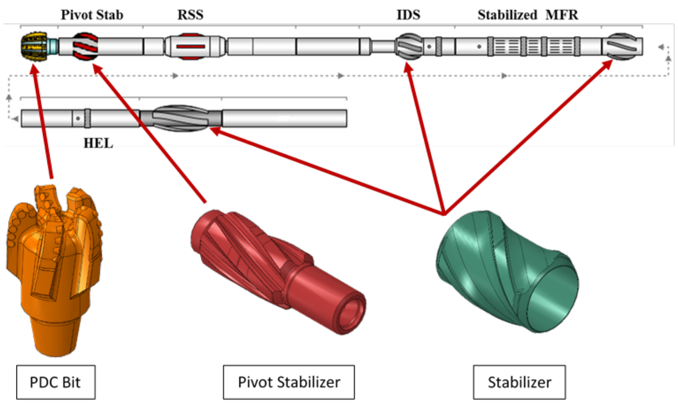

Figure 4: BHA model with location of 3D geometry parts.

Time Domain Analysis Results

1. Horizontal Orientation

Figure 5 shows the lateral vibrations (y-axis) for both analyzed models (with and without stabilizer) as recorded at the center of the RSS shaft. Figure 6 shows the results obtained for both models at the top of the MFR Tool. In horizontal orientation gravity is applied along the Y-axis. As seen from the two figures, initially, as the model progresses, gravity acts to pull the BHA to be in contact with the wellbore. However, as contact between the non-uniform geometries and the wellbore progresses, the RSS shaft begins to oscillate. Although this oscillation cannot be completely eliminated, it is beneficial if it is reduced as much as possible to minimize the workload on the RSS steering unit and to improve directional stability. In the model without the added MFR stabilizer it can be observed that the RSS shaft exhibits larger amplitude oscillations. Although the stabilized MFR was located more than 45 ft above the RSS unit, the effect on the overall stability of the system is apparent.

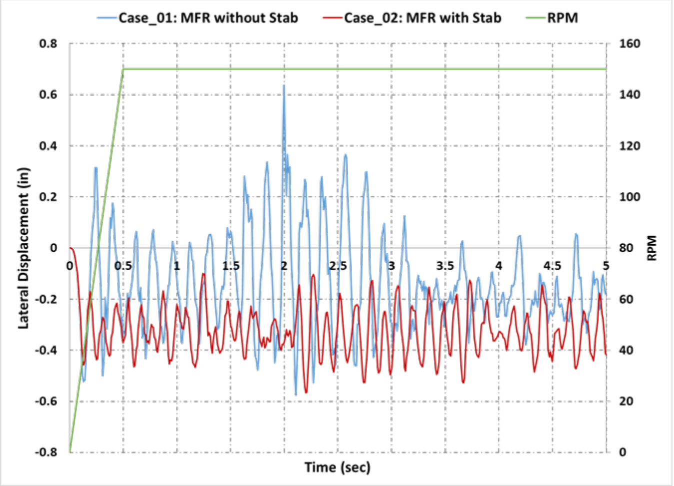

Figure 5: Lateral vibrations (y-axis) for horizontal BHA case at middle of RSS point.

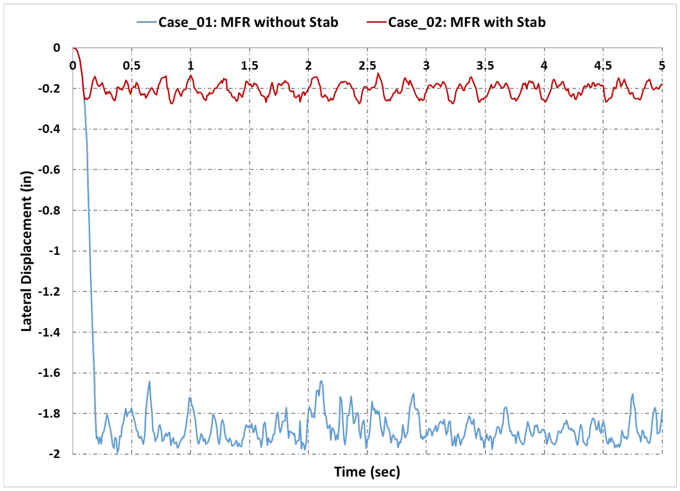

Figure 6: Lateral vibrations for horizontal BHA case at end of MFR unit. The larger lateral displacement of the MFR without stab case is due to MFR sagging as a result of gravity.

Figure 7 shows the angular accelerations (vibrations) at the center of the RSS shaft. Figure 8 shows the FFT (PSD) of the torsional accelerations as show in Figure 7. From the FFT plot, we notice that the dominant frequency is at 59.5 Hz, which corresponds well with observed field data for similar BHA as shown in Lines et al. [7] (see Figure 12).

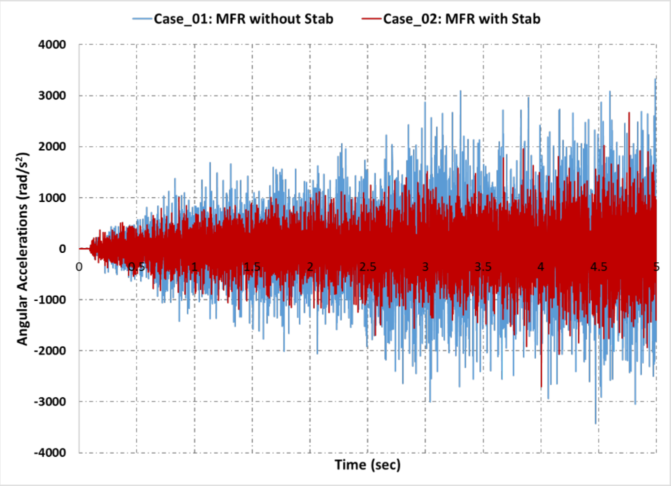

Figure 7: Angular accelerations at center of RSS shaft.

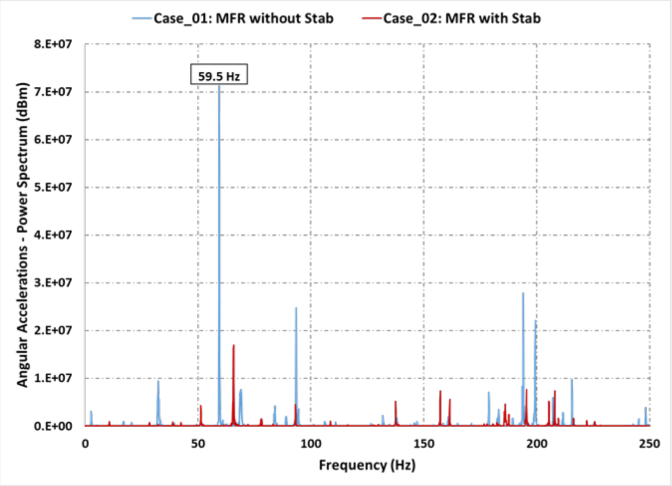

Figure 8: FFT of angular accelerations at center of RSS shaft.

2. Near Vertical Orientation:

In the near vertical orientation (1° inclination), the damping effect provided by gravity on the MFR is no longer present. Initially the MFR oscillates at small amplitudes within the wellbore. As momentum and energy levels increase, the MFR enters a resonant frequency and quickly transitions into an uncontrolled and destructive vibration mode. Live animations of the analysis (not available in document) clearly highlight this destructive behavior. Figure 9 shows the results at the middle of the RSS shaft while Figure 10 is a comparison of the lateral vibrations near the end of the MFR. The figures show the extreme lateral vibration resulting from the un-stabilized MFR and how, in contrast, the addition of the stabilizer significantly reduces vibration amplitude.

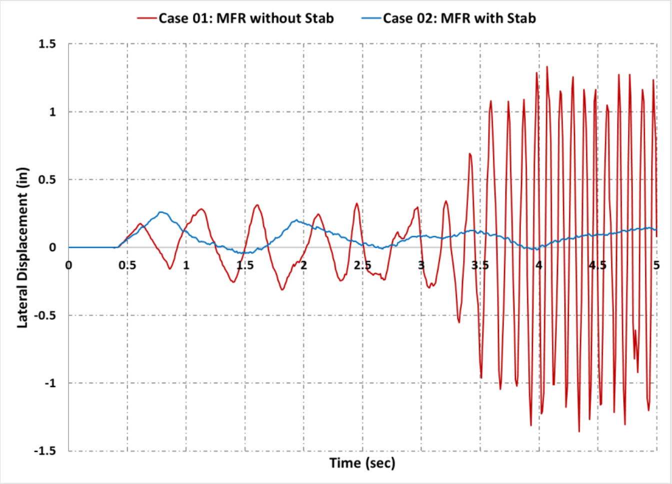

Figure 9: Lateral vibrations at middle of the RSS shaft for vertical orientation.

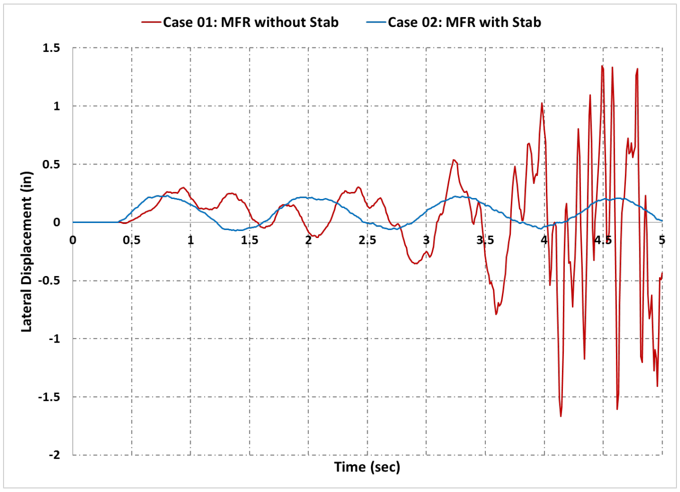

Figure 10: Lateral vibrations at end of MFR unit for vertical orientation.

3. Whirl Detection:

One of the main objectives from time domain analysis is to investigate if finite element models are capable of detecting whirl (forward and backward). Our area of interest for whirl detection and elimination is at the RSS stabilizer (as shown in Figure 3) but the technique is equally applicable to all rotating elements which contact the stationary borehole. By extracting the lateral displacements for the pivot stabilizer and plotting them versus time, a clear picture of whirl presence can be shown.

Figure 11 shows the plot of backward whirl initiation for case #1 (without MFR stabilizer) and the full history for case #2 (with MFR stabilizer). Both the applied RPM rotation and the nodal history rotational direction for backward whirl are indicated. From the plot several things are noticed:

- Backward whirl is clearly visible in the analysis for Case #1 (MFR without stabilizer) as indicated both by the circular pattern of the nodal history and also by the fact that the nodal rotational history is opposite that of the applied RPM.
- Adding a stabilizer to the top MFR (Case #2) has been effective at eliminating the dangerous backward whirl. The stabilizer rolls benignly at the bottom of the borehole.

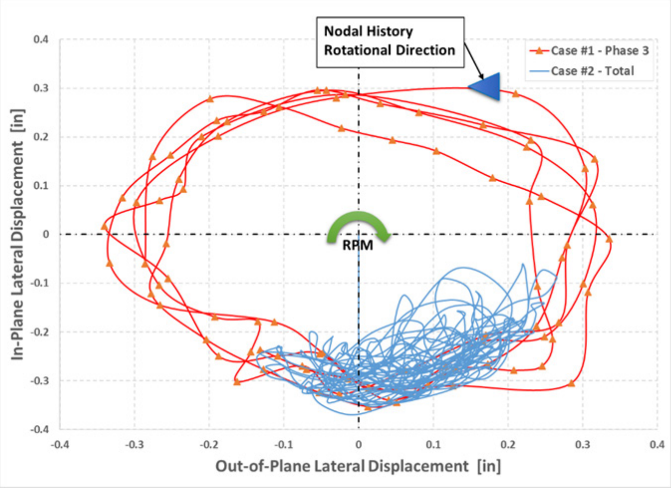

Figure 11: Lateral displacement history at center of pivot stabilizer for Case #1 and full nodal history for Case #2.

Experimental Results

During a drilling study with a BHA similar to the one discussed here, the downhole dynamics sensor [8] detected HFTO. Figure 12 shows a rapid sample captured at the initiation of HFTO while drilling with an 8.5-in bit through a formation of chalk and marl (both carbonates). Note the presence of a strong 60 Hz frequency content in torsional, lateral and angular data. This data correlates well with the torsional acceleration frequency predicted by the analysis model of 59.5 Hz as shown in Figure 8.

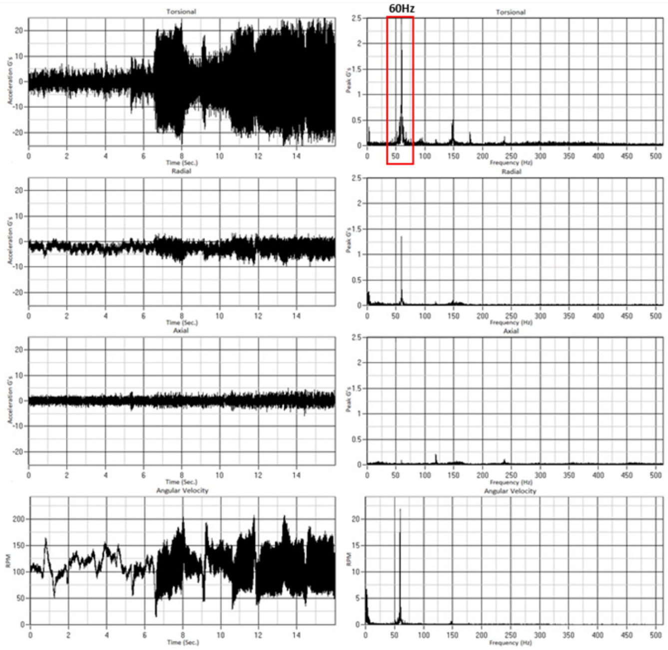

Figure 12: Rapid sample data showing HFTO.

Conclusions

Using a nonlinear finite element analysis model provided a very powerful tool in predicting the dynamic behavior of BHAs. The ability to integrate real 3D parts in the analysis enables the simulation of real physics, especially those relating to contact dynamics.

Time domain analysis of the BHA, although computationally expensive compared to industry standard techniques, offers valuable insights that linearized frequency-domain vibration analysis is incapable of. Clear indication of lateral vibration, damaging whirling modes and HFTO at areas of interest can be predicted before drilling an actual well.

It was also shown that the numerical predictions matched some of the experimental results for the same system.

Future improvements on the modelling methods developed and presented here include adding rock removal due to contact (hole enlargement), adding fluid-structure interaction (FSI) to gauge the damping effects of fluid and modelling of nonsymmetrical parts. Also, analysis automation is a priority in order for wider user participation.

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