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# Dynamic Modeling Software

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## Abstract

It is widely accepted within the oilfield service industry that bit drillstring dynamics significantly reduces drilling performance. To overcome this problem, dynamic services were introduced. They consist of measurement devices, analysis tools and training. This paper focuses on the analysis tools. Baker Hughes’ industry leading dynamic modeling software consists of three core products: BHASYS, BHASYS PRO, and BHASYS TD. The first program (BHASYS) addresses critical speeds analysis in a simple inclined borehole and is intended for use by operations at the wellsite. The second product (BHASYS PRO) addresses the statics and dynamics of the BHA in a 3D wellbore, is intended for use by engineering support personnel, and is in use worldwide by Baker Hughes. These two models are considered engineering models. The third product (BHASYS TD) is a time domain model. This research model is intended for use by engineering research personnel in analyzing BHA configurations, MWD tool design, and field tool failures in greater detail. Several case studies show the potential of presented modeling software.

## Introduction

Dynamic services consist of three major parts:

- Applying dynamics models in order to obtain an optimized bottomhole assembly design which is not susceptible to vibrations
- Using of downhole and surface measuring[3-6] devices to detect harmful drillstring vibrations.
- Training courses increase the awareness of the rig personnel regarding vibration problems and, make it possible to take remedial action.

This paper focuses on the presentation of drilling dynamics modeling software within a major service company.

Dynamics analysis models should increase stepwise in complexity. The original analytic models have, during the last decade, evolved through basic frequency domain models to sophisticated nonlinear time domain models. Analytical models are easy to use but only offer limited answers. These models are used in the pre-planning phase. Basic frequency domain models are used in the planning phase in the office for simple BHA design as well as on the rigsite for testing changes to BHAs. Advanced frequency models are used for predicting the behaviour of ‘designer’ BHAs in complex 3D wells. They are also used for post well analysis and for failure analysis. Application of these more advanced models requires profound dynamics knowledge and training. The inherent limitations of frequency domain models were overcome with sophisticated time domain models. The time domain approach permits modeling large displacements, post buckling behaviour and highly nonlinear dynamic phenomena like backward whirl. These models are used for detailed tool design, operating parameter and drilling practice recommendations. Due to the high resource demands the calculations are performed by engineering research personnel in a support role. This scalable approach offers the advantage of gaining confidence with the simpler models. In this paper analytical and basic frequency domain approaches are presented briefly while advanced frequency domain and timedomain models are discussed in more detail.

## Analytical models

In most cases analytical models are used to get a fast overview of natural axial and torsional frequencies of drillstrings in straight boreholes. Various boundary conditions at the bit and at the surface can be easily applied in theses models. The software NATFREQ utilizes this approach and is based on a publication by Finnie and Bailey[1].

For horizontal extended reach applications Heisig and Neubert[12] derived an analytical solution of threshold rotary speed:

$$f_{\min} = \frac{1}{2\pi}\sqrt{\frac{q}{r\mu} - \frac{WOB^2}{4EI\,\mu}} \tag{1}$$

Exceeding this critical frequency the drillstring starts a dangerous lateral snaking vibration. In eq. 1 q is the distributed weight per unit length, $\mu$ the distributed mass, EI the bending stiffness, r the radial clearance between drillstring and wellbore and WOB the weight on bit. From eq. 1 the well known Pasley Bogi buckling load[2] can be derived by setting $f_{min}$ to zero and resolving eq. 1 for WOB:

$$WOB_{crit} = 2\sqrt{EI\,\frac{q}{r}} \tag{2}$$

## Basic frequency domain models BHASYS

Basic finite element like models are used to calculate lateral, axial and torsional natural vibrations. A software program, BHASYS, based on such a model was developed by Paslay[15]. The drillstring components are discretized as pipes allowing for a detailed drillstring model. A straight inclined borehole is assumed for the analysis and the effects of drill collar-borehole wall are not taken into account. Since only mode shapes and critical speeds are computed, no absolute vibration deflections are derived. This allows only evaluation of potential damage due to resonance. The software runs on standard PCs with an easy to use graphical user interface. Example output from BHASYS is provided in **Figure 1**.

## Advanced frequency domain model BHASYS PRO

The drillstring dynamics simulation program BHASYS Pro is based on the finite element method developed by Heisig[8]. The drillstring is modeled with geometrically nonlinear beam elements. Deformations of the drill string are measured by three nodal displacements and three rotations (see **Figure 2)**:

Lateral displacements: $u_1$, $u_2$
Lateral rotations: $\theta_1$ , $\theta_2$
Axial displacement: $u_3$
Axial rotation: $\theta_3$

A penalty function approach confines the finite element nodes within the wellbore (see sketches of **Figure 3** and **4)**. In case a drillstring member hits the wall, a penetration dependent constraining force acts on the collar element. The model considers large pre-deformations of the drillstring by the 3D curved well bores. This formulation together with the geometrical nonlinearity enables the analysis of coupled lateral, axial and torsional vibrations in the frequency domain, the calculation of buckling loads and post-buckling behaviour.

From Hamilton's principle the nonlinear system of differential equations is derived:

$$\underline{\underline{M}}\,\underline{\ddot{u}}+\underline{F}_F\left(\underline{u},\underline{\dot{u}}\right)+\underline{F}_W\left(\underline{u},\underline{\dot{u}}\right)+\underline{F}_G\left(\underline{u}\right)=\underline{R}+\underline{F}_E\left(\underline{u},\underline{\dot{u}},t\right) \tag{3}$$

with
$\underline{u}$: displacements/rotations of nodes
$\underline{M}$: mass matrix
$\underline{F}_F$: distributed forces from the mud
$\underline{F}_W$: wall contact force
$\underline{F}_G$: nonlinear elastic forces
$\underline{R}$ : static forces (weight, buoyancy, WOB … )
$\underline{F}_E$: exciation forces (mass imbalances, … )

Dynamics analysis is performed in three steps:

- Steady state statics solution is obtained with Newton's scheme:

$$\begin{gathered}\underline{F}_W\left(\underline{u}\right)+\underline{F}_G\left(\underline{u}\right)=\underline{R}\\ \left(\frac{\partial \underline{F}_W}{\partial \underline{u}}\left(\underline{u}_n\right)+\frac{\partial \underline{F}_G}{\partial \underline{u}}\left(\underline{u}_n\right)\right)\Delta\underline{u}_{n+1}=\underline{F}_W\left(\underline{u}_n\right)+\underline{F}_G\left(\underline{u}_n\right)+\underline{R}\\ \underline{u}_{n+1}=\underline{u}_n+\Delta\underline{u}_{n+1}\end{gathered} \tag{4}$$

- For the natural vibration analysis eq. 3 is linearized about the steady state displacements $\underline{u}$ obtained from eq. 4. Assuming small deviations $\xi$ from this steady state solutions natural frequencies as well as mode shapes are calculated from

$$\begin{gathered}\underline{\underline{M}}\,\underline{\ddot{\xi}}+\underline{\underline{K}}\,\underline{\xi}=\underline{0}\\ \underline{\underline{K}}=\frac{\partial \underline{F}_G}{\partial \underline{u}}\left(\underline{u}_{Stat.}\right)+\frac{\partial \underline{F}_W}{\partial \underline{u}}\left(\underline{u}_{Stat.}\right)\\ \underline{\xi}=\underline{\hat{\xi}}e^{j\omega t}\\ \left(\underline{\underline{K}}-\omega^2\underline{\underline{M}}\right)\underline{\hat{\xi}}=\underline{0}\end{gathered} \tag{5}$$

- The last steps comprise the analysis of forced vibrations. Two excitation mechanisms are included in the model: axial bit excitation and mass imbalance excitation. The following set of differential equations describe the problem of (small) forced vibrations with harmonic excitation with frequency Ω,

$$\underline{\underline{M}}\quad\underline{\ddot{u}}\qquad\underline{\underline{B}}\quad\underline{\dot{u}}\qquad\underline{\underline{K}}\quad\underline{u}\qquad\underline{P}_{0C}\cos\Omega t\qquad\underline{P}_{0S}\sin\Omega t \tag{6}$$

Eq. 6 is solved by

$$\underline{u}(t)=\quad\underline{U}_C\cos(\Omega t)\qquad\underline{U}_S\sin(\Omega t) \tag{7}$$

From the dynamic displacements $\Delta\underline{u}(t)$ (eq. 7) dynamic axial loads, torsional and bending moments can be derived. As in BHASYS the graphical user interface is state of the art and easy to handle, see **Figure 5**.

## BHASYS Pro case study onshore Louisiana:

In this case the dynamics of a 6 ¾" motor-BHA in a near vertical bore hole had to be investigated because of several problems that were encountered. The analysis of the motor induced lateral vibrations showed that the assembly was operated near or at a critical speed of 10.8 Hz. **Figure 6** shows corresponding mode shape. Modifying the design by inserting additional stabilizers at the bearing housing and at the power section of the motor significantly reduced the dynamic bending loads, cf **Figures 7** and **8**. This analysis indicated that the best result could be achieved by placing a stabilizer at the middle of the power section. This analysis also suggested that a sufficient distance to higher critical speeds is reached by keeping the mud motor forcing frequencies below 13 Hz. A valuable feature of BHASYS PRO is also shown in **Figure 6**, as continuous wall contact in the upper part is calculated by the statics algorithm, no lateral dynamic deflection occurs in this portion of the drillstring.

### Time domain model

Due to the inherent limitations of frequency domain models (small vibration amplitudes, disregarding the impact of the drillstring components with the formation, friction forces, etc.) models are needed that consider the interaction of drilling system components [9, 10,13].

Such a model was derived based on the underlying theory of the advanced frequency domain model. This was accomplished by reverting some of the previously made assumptions and simplifications before. Eq. 6 is now solved in its original form by a Newmark integration scheme. This mathematical procedure enables the solution of problems involving large displacements in three-dimensionally curved wellbores. Complex excitation mechanisms, such as rotating bent subs or eccentric tools can be modeled. The nonlinear wall contact formulation enables the program to calculate forward whirl as well as highly destructive backward whirl vibrations of drillstrings.

### Case study reaming while drilling in the Gulf of Mexico

Several problems were reported during reaming while drilling operations of 9 ½” motor assemblies in vertical 20” boreholes. No excessive levels of lateral accelerations were observed by downhole dynamics measuring tools while drilling; during circulating off bottom slightly higher values occurred, see **Figure 9**. Due to the highly nonlinear excitation of the eccentric reamer, only a time domain analysis was appropriate to investigate the problem. **Figure 10** shows the finite element model in the steady state, **Figure 11** in the vibrating state.

Calculations confirmed the experience that acceleration levels were higher during circulating off-bottom than during drilling, although quite low in both cases. In contradiction, dynamic bending moments in the motor section were very high. Obviously, the acceleration measurement was too far away from the motor section to give precise information about the dynamic state of the lower portion of the BHA. The **Figures 12** and **13** show time simulation responses with a modified BHA. An additional stabilizer also helped in this case to reduce the magnitude of the bending moment.

### Software Validation

Software models always require validation, either through laboratory testing or controlled field tests. BHASYS PRO and BHASYS TD were validated by controlled field tests. Static and dynamic bending moments were measured by using a Copilot downhole measuring sub at the Baker Hughes Experimental Test Area BETA in Beggs, Oklahoma, at different depths; see **Figure 14** for a statics sample. The agreement between measured and simulated static bending moments is good. **Figure 15** shows autospectra of the measured bending moment together with simulated mode shapes and natural frequencies again. See Jogi et al[7] for another example. BHASYS TD was able to adequately simulate measured history of a backward whirl situation of a rotary BHA in a vertical hole, see **Figure 16**. Magnitudes of simulated backward whirl bending moments as well as the backward whirl frequency match the measurements.

### Conclusions

With the previous presented case studies, it was shown that applying dynamic modeling software can significantly improve drilling performance and can also help in better understanding the drilling process. The application of sophisticated nonlinear dynamics methods offers an enormous potential in predicting BHA dynamics including whirl situations. Three software products are now in use for routine frequency domain engineering analysis as well as drilling dynamics advanced analysis in the time domain.

### Acknowledgements

Presented models were mainly developed during the course of the Joint Dynamics Project between Baker Hughes INTEQ and Hughes Christensen Co. Volker Krüger, John Macpherson, Gerald Heisig, Pushkar Jogi, Mark Dykstra and consultant Jonathon Hanson mainly contributed to its success. Professor Eberhard Brommundt of Technical University in Braunschweig enabled the theoretical platform of our research models. Darin Warling did excellent programming work for the BHASYS-PRO GUI.

### Nomenclature

*BHA = bottomhole assembly*
*Copilot = downhole dynamics measuring sub*
*DOF = degrees of freedom*
*FD = frequency domain*
*GUI = graphical user interface*
*ROP = drilling rate of penetration*
*rpm = revolutions per minute*
*TOB = torque on bit*
*TD = time domain*
*WOB = weight on bit*

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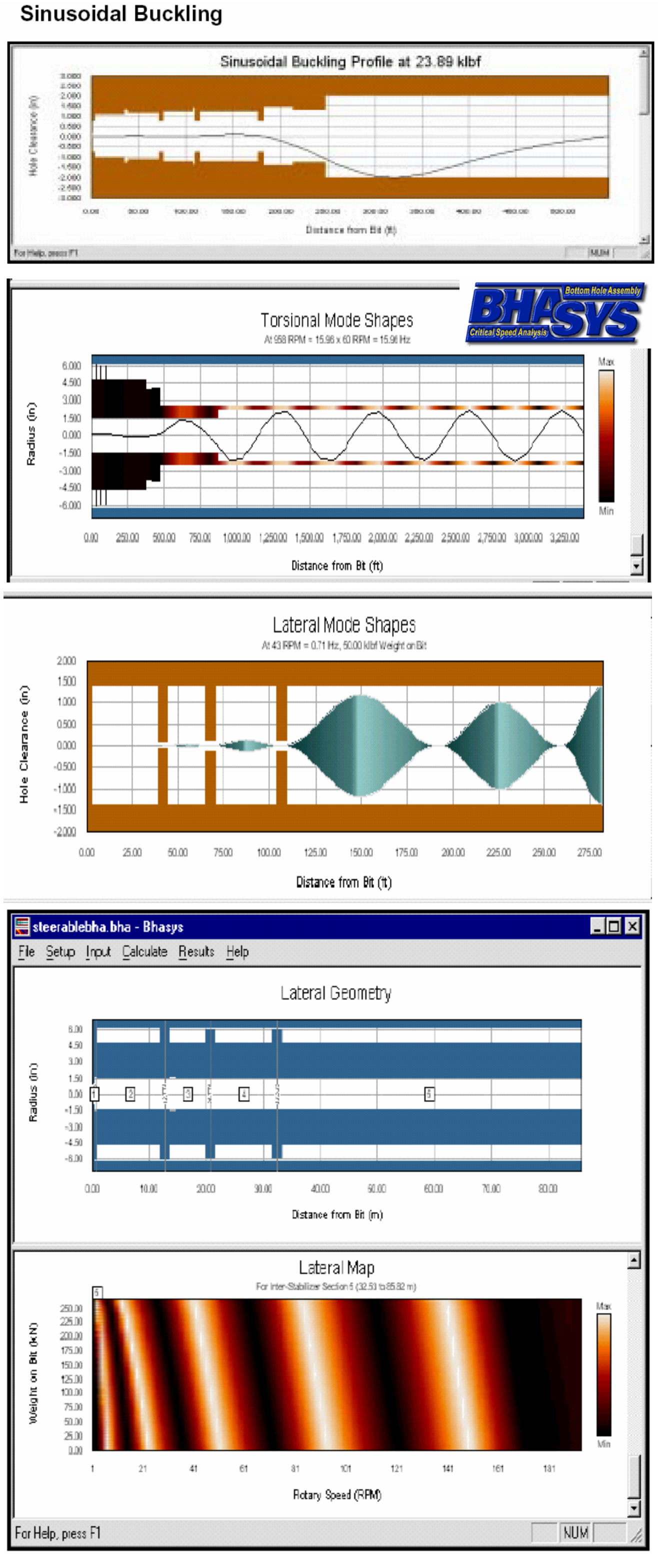


**Fig. 1 – Example of BHASYS output: a) Sinusoidal buckling, b) Torsional and lateral mode shapes and critical speeds. c) Lateral Map showing lateral critical speed vs weight on bit**

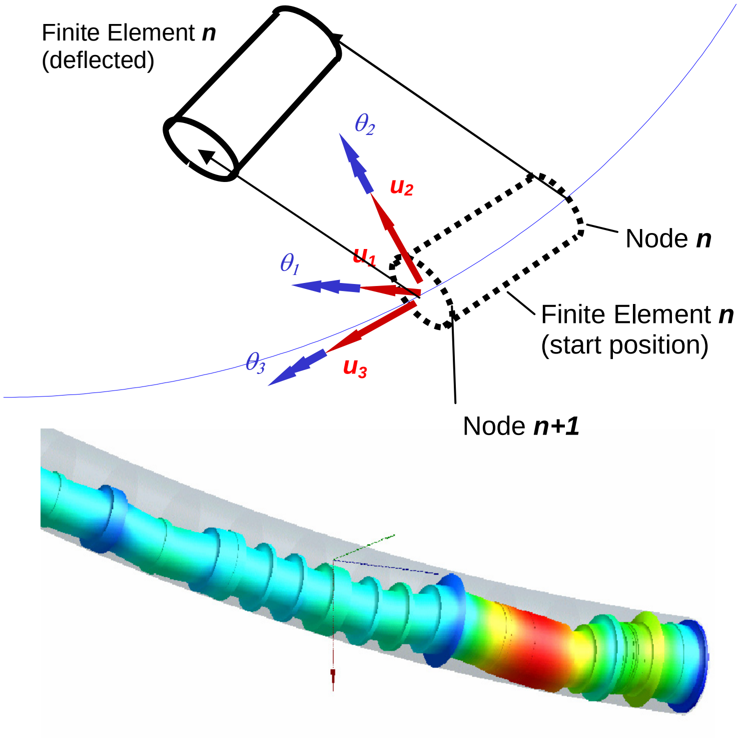


**Fig. 2 – Customized 3D finite beam element realized for BHASYS PRO**

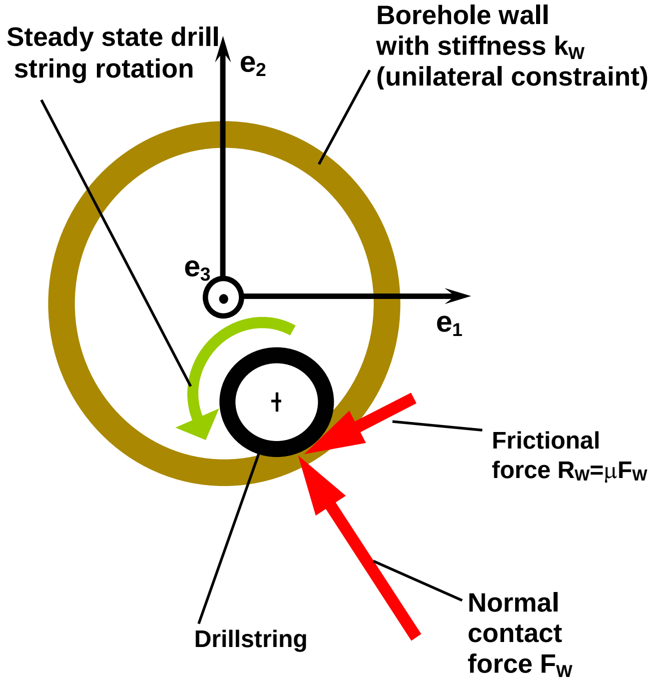


**Fig. 3 – Wall contact concept**

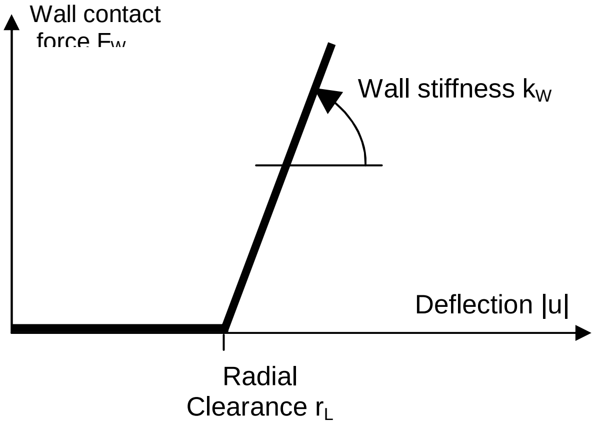
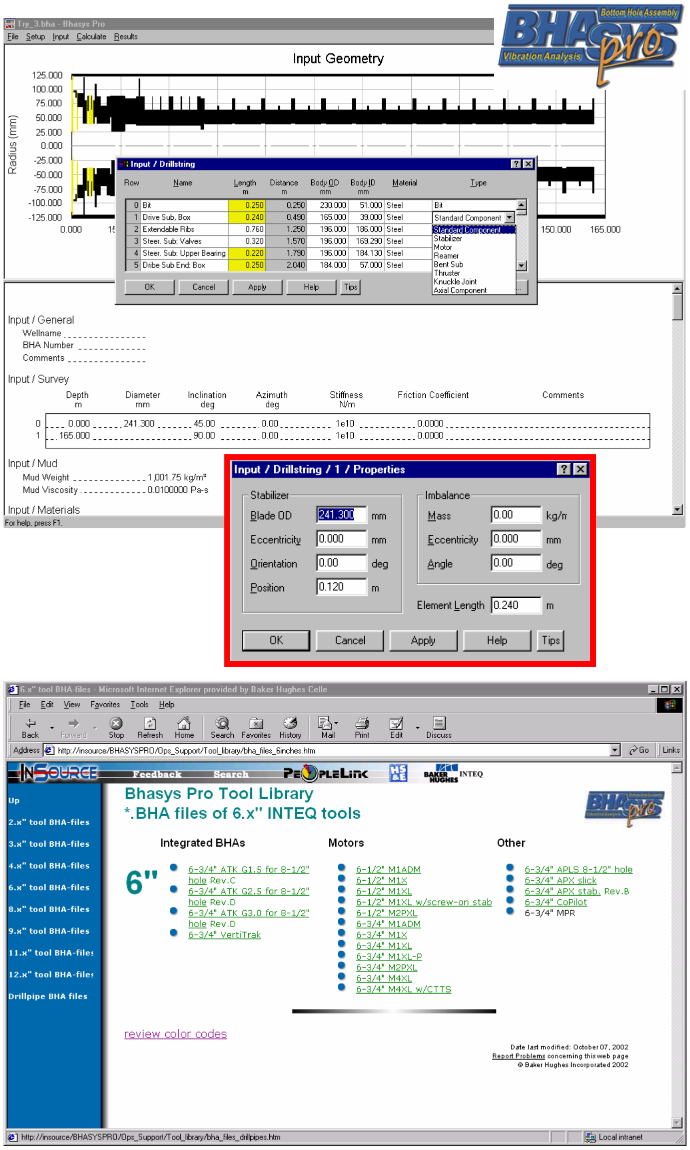


**Fig. 4 – Wall stiffness**



Input / Drillstring

| Row | Name | Length m | Distance m | Body OD mm | Body ID mm | Material | Type |
|---|---|---|---|---|---|---|---|
| 0 | Bit | 0.250 | 0.250 | 230.000 | 51.000 | Steel | Bit |
| 1 | Drive Sub, Box | 0.240 | 0.490 | 165.000 | 39.000 | Steel | Standard Component |
| 2 | Extendable Ribs | 0.760 | 1.250 | 196.000 | 186.000 | Steel | |
| 3 | Steer. Sub: Valves | 0.320 | 1.570 | 196.000 | 169.290 | Steel | |
| 4 | Steer. Sub: Upper Bearing | 0.220 | 1.790 | 196.000 | 184.130 | Steel | |
| 5 | Dribe Sub End: Box | 0.250 | 2.040 | 184.000 | 57.000 | Steel | |

Input / General
Wellname
BHA Number
Comments

Input / Survey

| | Depth m | Diameter mm | Inclination deg | Azimuth deg | Stiffness N/m | Friction Coefficient | Comments |
|---|---|---|---|---|---|---|---|
| 0 | 0.000 | 241.300 | 45.00 | 0.00 | 1e10 | 0.0000 | |
| 1 | 165.000 | | 90.00 | 0.00 | 1e10 | 0.0000 | |

Input / Mud
Mud Weight 1,001.75 kg/m³
Mud Viscosity 0.0100000 Pa-s

Input / Materials

For help, press F1.

Input / Drillstring / 1 / Properties

Stabilizer
Blade OD 241.300 mm
Eccentricity 0.000 mm
Orientation 0.00 deg
Position 0.120 m

Imbalance
Mass 0.00 kg/m
Eccentricity 0.000 mm
Angle 0.00 deg

Element Length 0.240 m

http://insource/BHASYSPRO/Ops_Support/Tool_library/bha_files_6inches.htm

Bhasys Pro Tool Library
*.BHA files of 6.x" INTEQ tools

6"

Integrated BHAs
- 6-3/4" ATK G1.5 for 8-1/2" hole Rev.C
- 6-3/4" ATK G2.5 for 8-1/2" hole Rev.D
- 6-3/4" ATK G3.0 for 8-1/2" hole Rev.D
- 6-3/4" VertiTrak

Motors
- 6-1/2" M1ADM
- 6-1/2" M1X
- 6-1/2" M1XL
- 6-1/2" M1XL w/screw-on stab
- 6-1/2" M2PXL
- 6-3/4" M1ADM
- 6-3/4" M1X
- 6-3/4" M1XL
- 6-3/4" M1XL-P
- 6-3/4" M2PXL
- 6-3/4" M4XL
- 6-3/4" M4XL w/CTTS

Other
- 6-3/4" APLS 8-1/2" hole
- 6-3/4" APX slick
- 6-3/4" APX stab. Rev.B
- 6-3/4" CoPilot
- 6-3/4" MPR

review color codes

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http://insource/BHASYSPRO/Ops_Support/Tool_library/bha_files_drillpipes.htm

**Fig. 5 – Sample input screens of BHASYS PRO and view of a Tool Library**

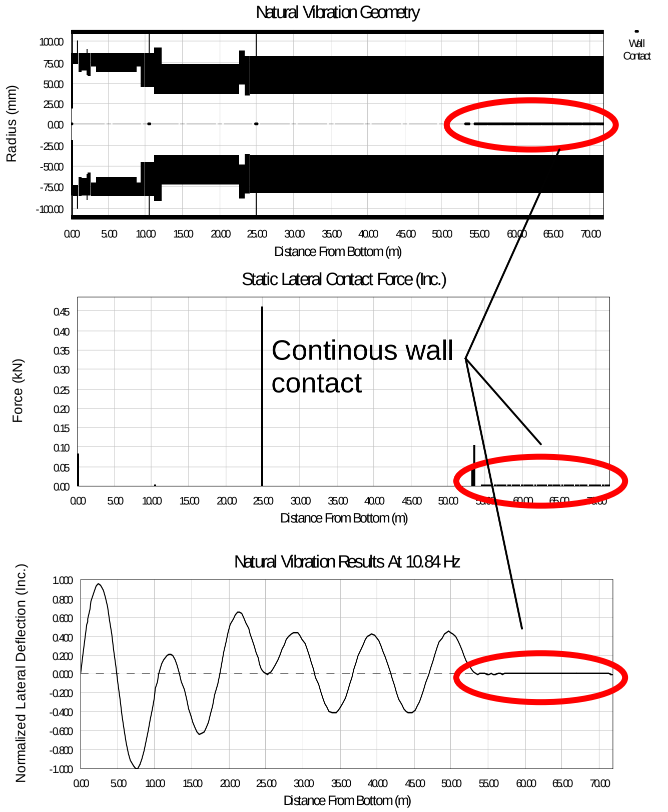

**Fig. 6 - Bottom Hole Assembly 6 ¾" M1XL used on Well Unit B #135: Configuration, wall contact forces natural frequency at 11Hz**

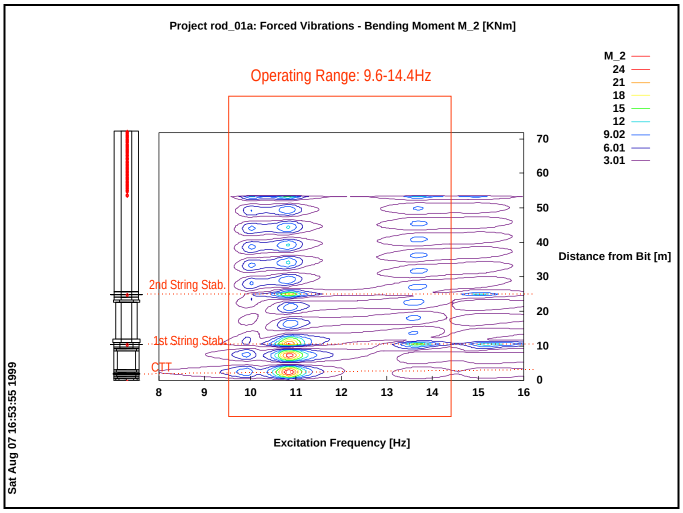

**Fig. 7 – Bending moments of the original BHA configuration**

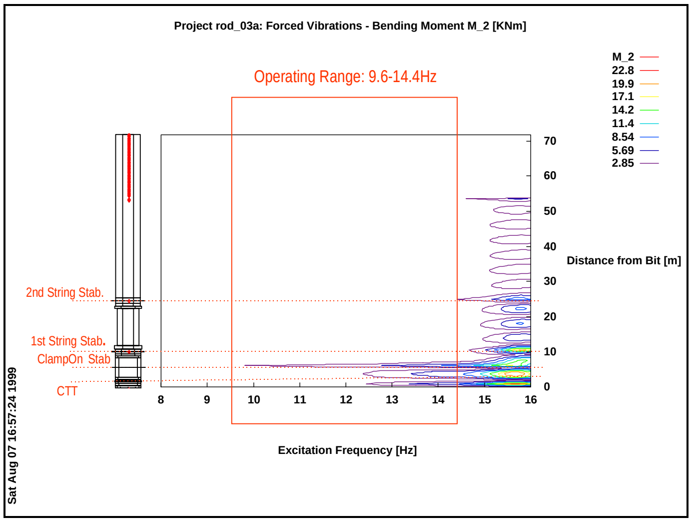

Fig. 8 Reduced dynamic bending moment with additional clamp-on stabilizer on motor section

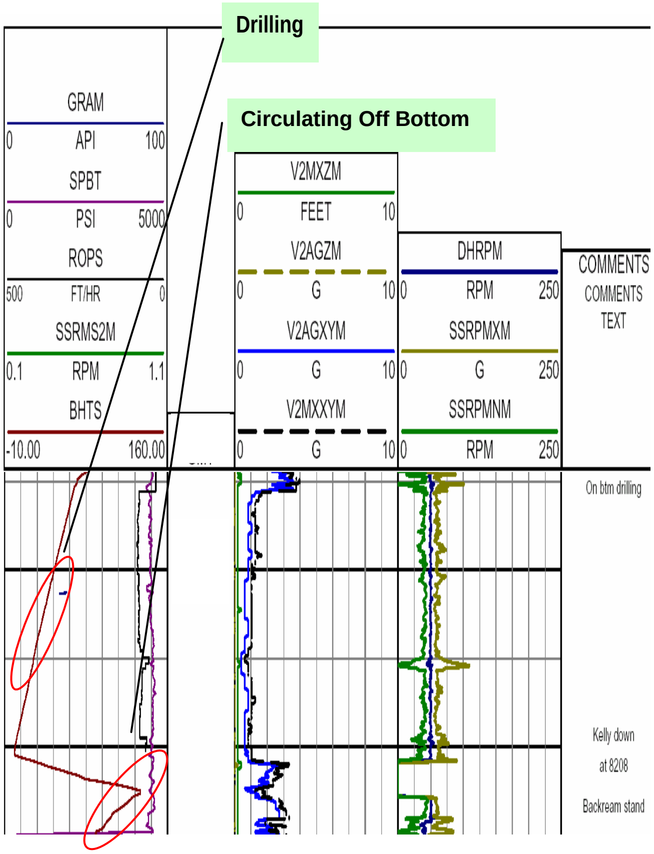

Fig. 9 - Acceleration measurements RWD application in the Gulf of Mexico (left red curve indicating block position, middle blue and black curves indicating acceleration level)

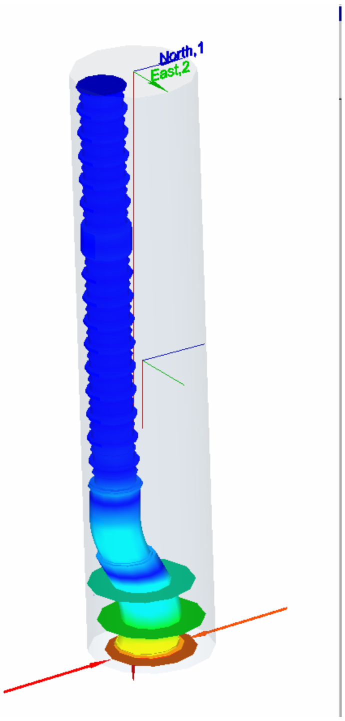

Fig. 10 – Finite element model for time domain simulations

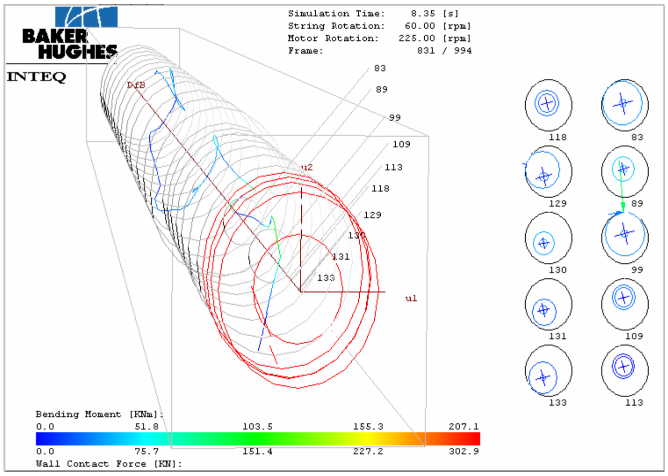

Fig. 11 - Dynamic deflection state together with wall contact nodal information (the view is directed uphole to surface)

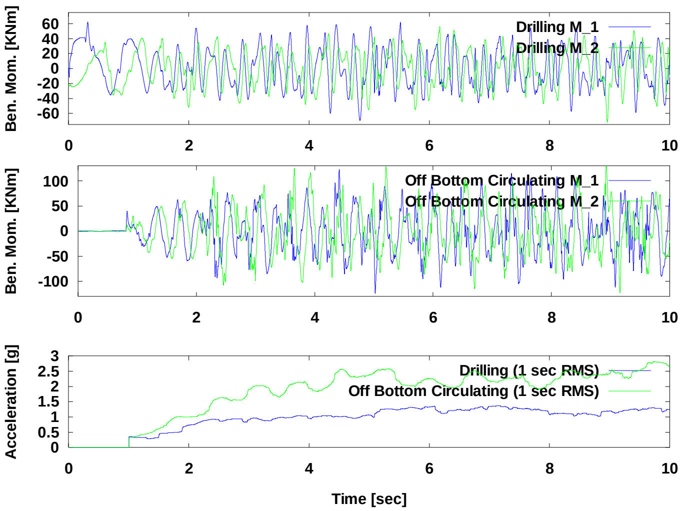

Fig. 12 - Acceleration, bending moments of original BHA

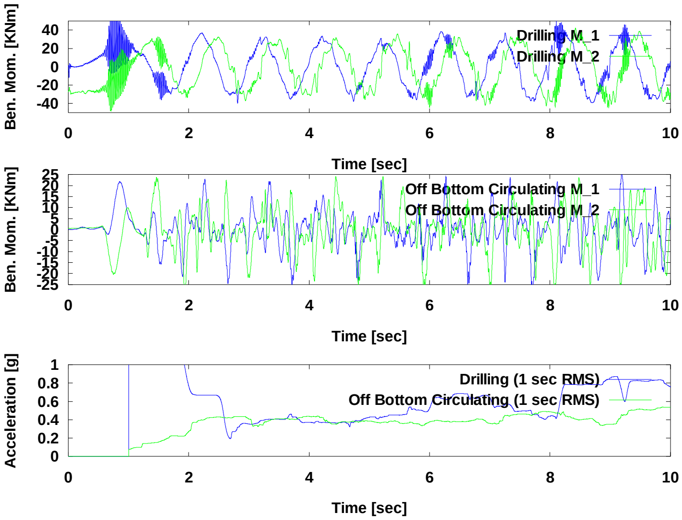

Fig. 13 - Acceleration, bending moments of modified BHA with additional stabilizer

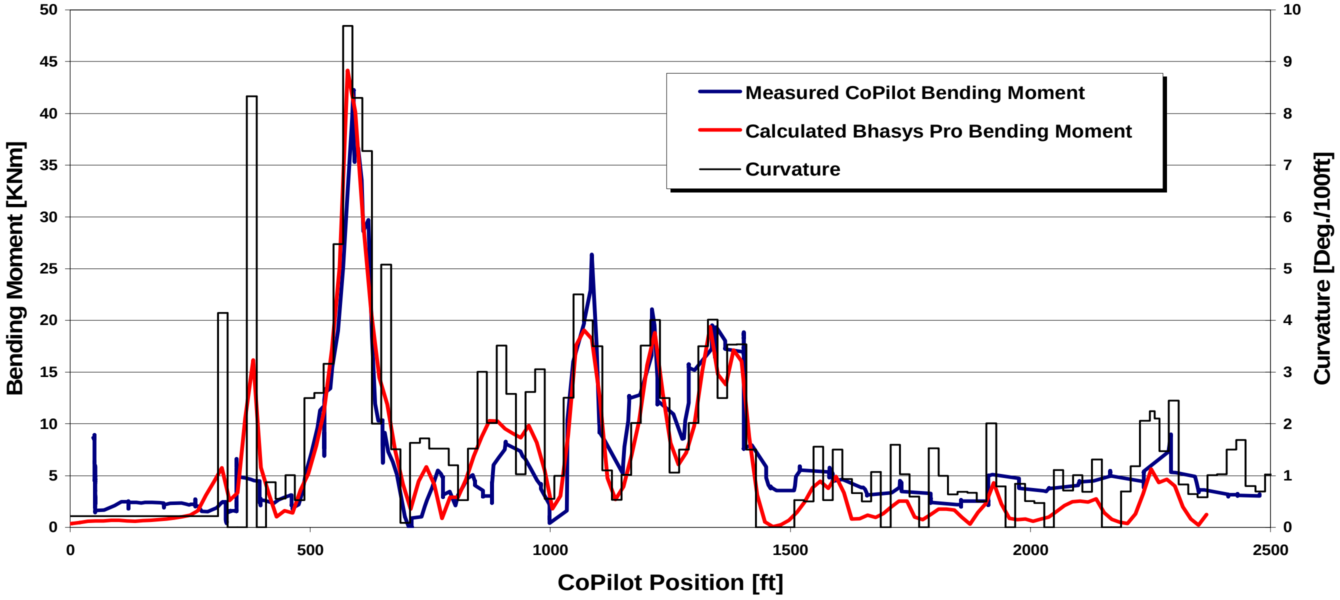

Fig. 14 - PRO statics validation: Measured (CoPilot at BETA) vs. calculated static bending moments

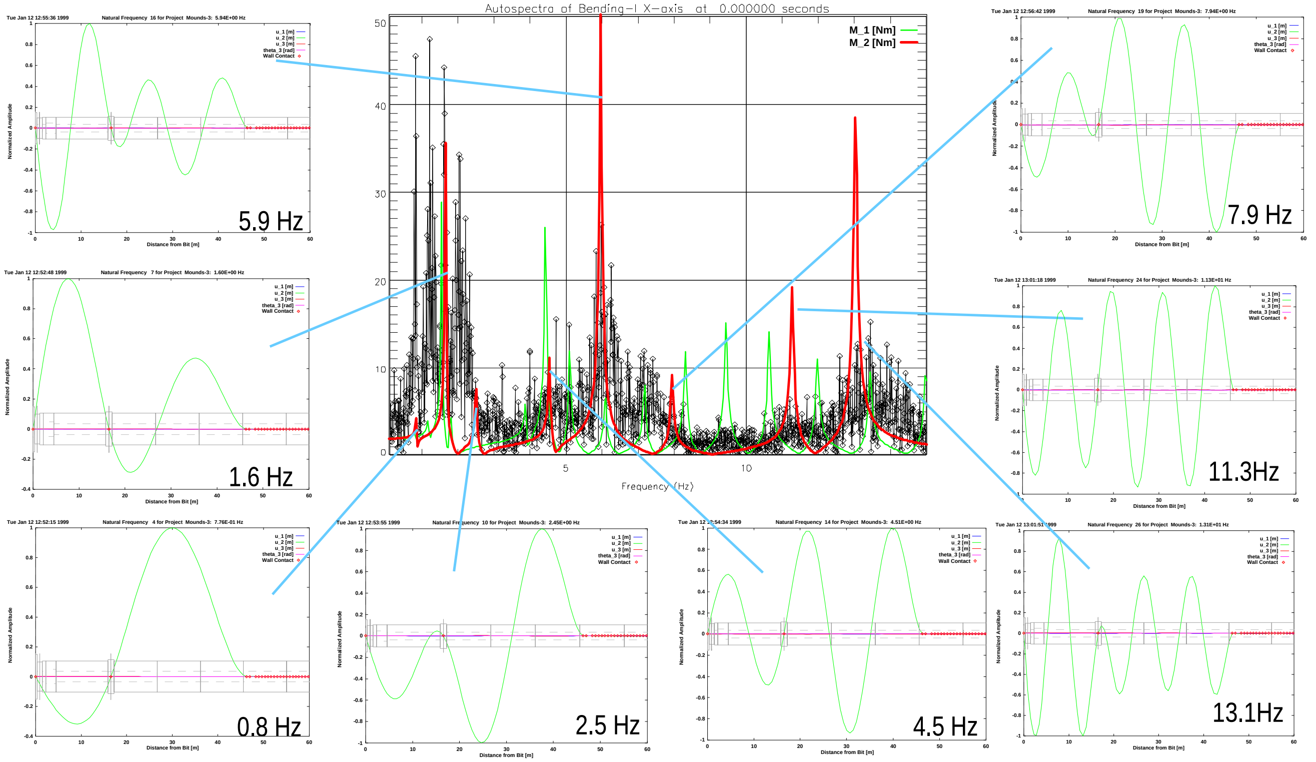

**Fig. 15 - Validation of BHASYS PRO: natural frequencies, mode shapes (simulated) and dynamic bending moments measured by Copilot**

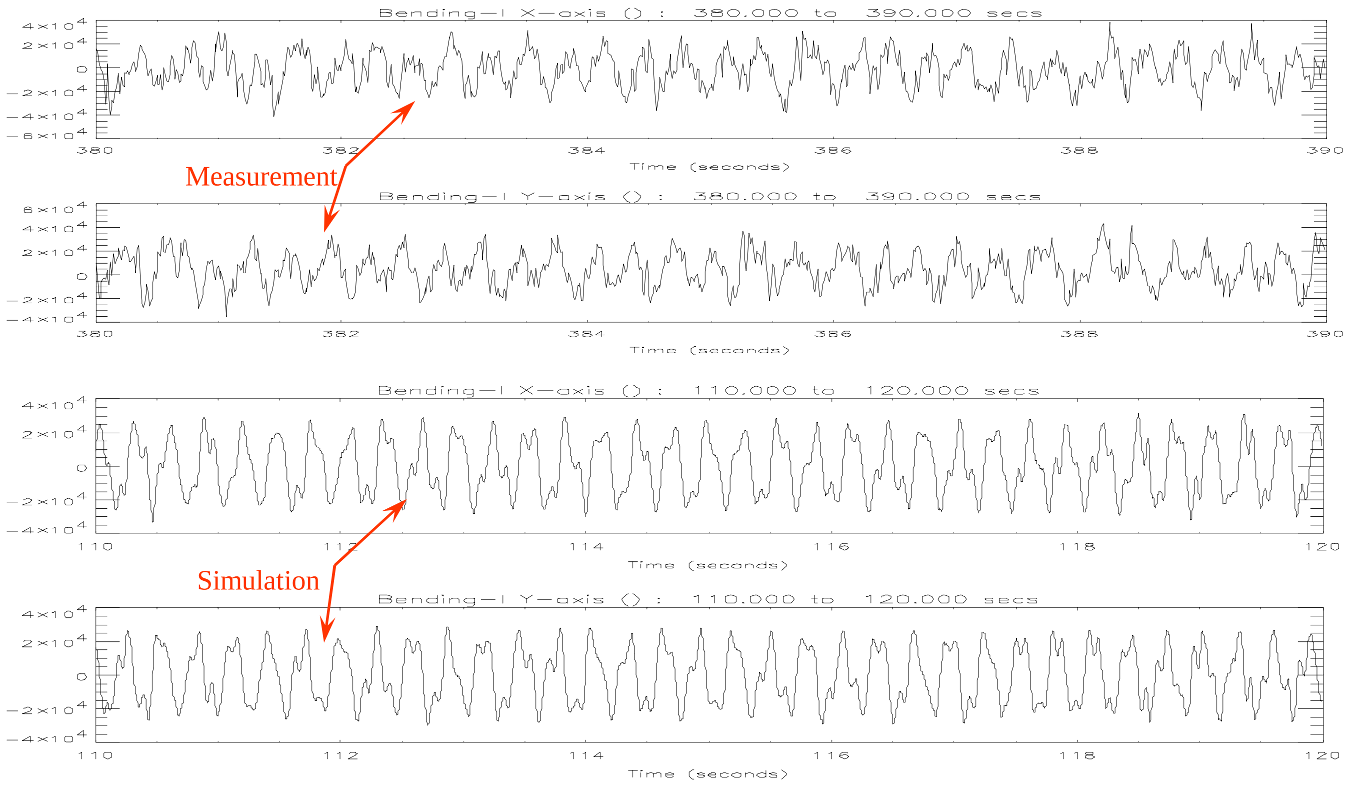

**Fig. 16 – BHASYS TD validation by Copilot data at BETA; 80rpm, run12 with backward whirl**