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Identification While Drilling of Drill-string Dynamic Model for Diagnostics and Optimization

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Abstract

The main objective of this paper is to improve drilling performance by obtaining a representative dynamic model of a drilling system: top-drive, controls, drill-pipe and bottom hole assembly (BHA). High-fidelity simulations with a representative analytical model are a goal necessary to optimize controller-settings while or before drilling. Goals such as `lowest sensitivity to torque disturbance at the bit' or 'best reaction to stick-slip events' can be pursued while guarding stability limits of the full system.

The method is based on spectral correlation between at least two signals: a broad-band signal with frequencies in the relevant band (0.05Hz to 5Hz) added to the top-drive's torque command and second: the measured top-drive speed. Mathematical tools from seismic exploration and control-theory are used to determine key parameters of this closed-loop system. Correlation techniques allow identification even during high background noise generated by varying friction and bit-cutting forces in most cases.

Experimental results from a number of wells in Oman, Malaysia, and USA show that the transmission-line based model can be accurately matched at all depths. Besides the eigen frequency, a number of higher modes of the drill sting are found, including their effective damping. The identified response agrees with expected response based on pre-computed mechanical drill-string composition parameters. In one well a substantial increase in friction and bit-inertia was identified at certain depth intervals. Logs taken afterwards showed wash-outs at these depths, suggesting diagnostic potential of this estimation technique.

Novel is the ability to identify a dynamic drill string model without advance information, yielding auto-tuning capability for most stick-slip mitigation technologies such as 'softtorque'. A very welcome benefit is the estimation of the string's characteristic impedance and length but also internal and external friction components along the string and at the bit. Traditionally, these damping terms are often neglected, exaggerated or set to an agreeable value to limit the amplitude of resonances in the calculated model. The presented identification method generates updates of these different damping terms every ten minutes or so. During drilling several wells, the found damping terms are spread over a wide range due to mud-pipe, pipe-wall interaction and bit-formation variability. We conclude that damping terms cannot be ignored without severely compromising the dynamic fidelity of the model. Future diagnostic and drilling optimization tools may be based on this new way of harvesting information from down hole.

Introduction

Before being able to design a solution to anything, understanding the problem is essential. When talking about mitigating stick-slip in a drilling operation, different strategies are applied [1], all using some kind of model of the drill string at hand to calculate or derive suitable controller settings. Which model should be used? Albert Einstein ones said: '*A model should be as simple as possible, but no simpler*'. Applying this quote to the subject of stick-slip mitigation in a drilling operation implies questions such as….. Is the often used lumped string model sufficient? Is knowledge of friction essential? Do torque waves reflect at the ends? May axial movements be ignored? Is the weight distribution in the string of any importance? Can whirl be neglected? In the remainder of this paper these issues will be dealt with.

Dynamic Models

A valid dynamic model is a model that can generate essential outputs from measured inputs and predict new outputs from new measured inputs with acceptable accuracy. During the identification process the best parameters are found by optimization that best fits the dynamic relations between measured data, in our case measured topdrive speed ω_{td} and measured top drive torque, or better the topdrive torque setpoint T_{com}.

Top drive model

Figure 1 shows the simplest dynamic model of the topdrive system: a machine with variable frequency drive (VFD), together acting as a source of torque with high bandwidth condensed in D. Effective inertia J_{td}(kgm^2). The topdrive sub-system inputs are T_{com}, T_{string} and its output is topdrive speed ω_{td} . The driller's reference speed ω_{set} is assumed slow changing or constant. The effective speed controller is A, the speed filter H and always present in the VFD, some torque filter E.

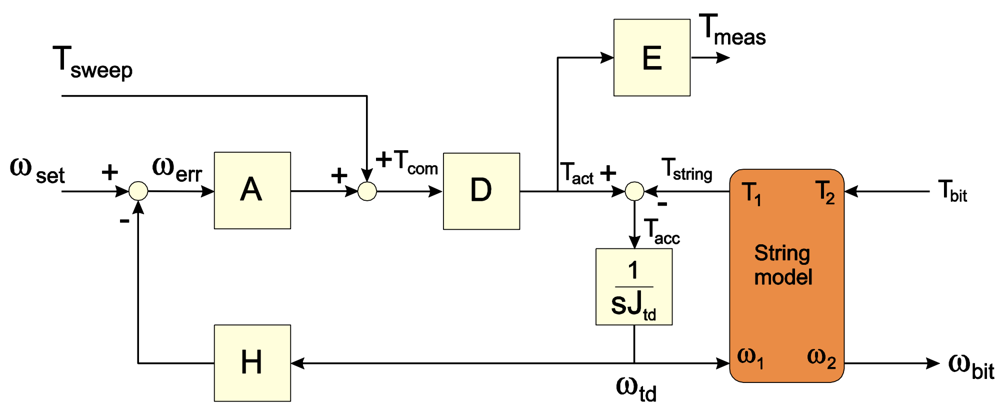

Figure 1: Control structure of topdrive with identification while drilling.

In this paper we will use the transfer from T_{sweep} to ω_{td} and call this the command mobility in (rad/Nms). No measured torque is required.

Drill string models

Lumped models

In many simplified string models, the so called 'lumped model' is used [1]. In a lumped string model, the hole string is simplified to just one torsional spring with spring constant K_s (Nm/rad) and one effective down hole inertia J_{bha} (kgm^2), as shown in top graph in Figure 2. Such a model neither exhibits any travel time of torsional waves nor higher modes, it only represents the fundamental resonance frequency to a reasonable extent. The bottom graph in Figure 2 incorporates damping terms and is a more realistic one. This same graph however is a full model of a small fraction of any drill-string. Stacking a high number of such fractions (we often use several hundred to get to a realistic model) can be done like in Figure 3. It may be useful to the reader to think of a string fraction in terms of an electrical equivalent circuit.

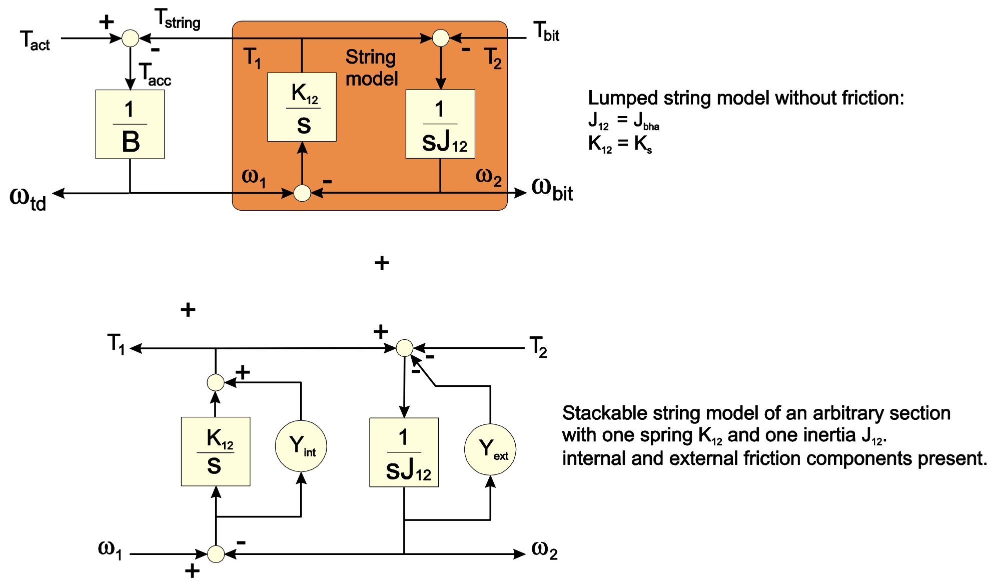

Figure 2: Lumped string model without friction and below: stackable section of arbitrary length.

An important assumption is that all components are assumed to be linear, hence only the effective ‘small-signal’ friction can and will be identified. Neither Coulomb friction (steady torque only depending on the direction of movement) nor ‘Stribeck friction’ a torque that decreases with increasing speed (effectively acting as a destabilizing negative small-signal friction) and is regarded to be the driving force in persisting stick-slip oscillations during unfavorable settings of the top drive controller can be represented in linear models like the ones in this paper. In figure 2 the block diagram of a stackable string fraction model is shown. Its electrical equivalent circuit is shown in the bottom graph in Figure 3.

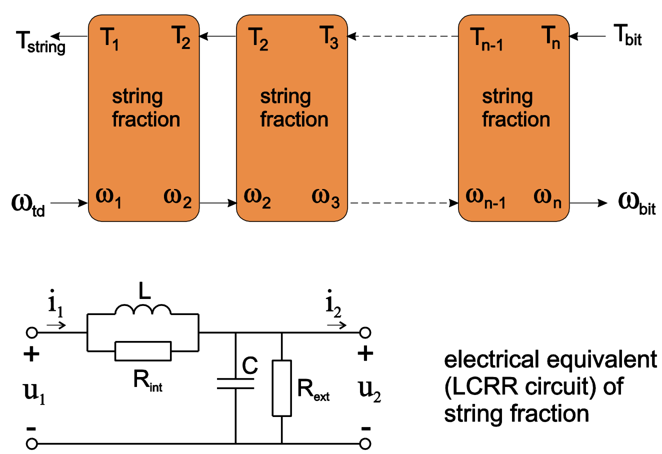

Figure 3: Full string composed of many fractions, below: electrical equivalent circuit of one fraction.

The following equations describe the equivalence when angular speed is equivalent to voltage and torque is equivalent to current admittance Y [A/V] and impedance or resistance [V/A] are reciprocal:

$$u_1 = \omega_1, u_2 = \omega_2$$
$$i_1 = T_1, i_2 = T_2$$
$$L = \frac{1}{K_{12}}$$
$$C = J_{12}$$
$$R_{int} = \frac{1}{Y_{int}}$$
$$R_{ext} = \frac{1}{Y_{ext}}$$

Transmission line models

As discussed a realistic string model can be built by using many dozens or even hundreds of fractions, each consisting of four parameters and two states (local speed and torque). Such a model looks like a traditional ladder network used in transmission line models in electronics.
The main difference however is the R_{int} being parallel to the inductor L. In the electrical world the copper resistance is in series with the per length inductance, not in parallel as here in a mechanical string model. It can be simply shown why this is the case: Suppose in Figure 4 the topdrive being stuck (ω_{td}=0, u_1=0), now suppose a torque on the bit (T_{bit}>0). After waiting for a long time, the string will become wound up and the speed of the bit will become zero as well…the torque in all fractions will become identical to T_{bit} after all waves have died out. The circuit in Figure 4 will do just that, any series resistance in the L-L-L chain would cause a non-zero final voltage, which is not according to physics. A coax cable being shorted on one side and being fed by a current source on the other side does show a final non-zero voltage linearly decreasing with position.
Another point is the often ignored R_{ext} in the electrical cable models. The torsional viscous friction exerted by the mud and other wall friction is very substantial and should be incorporated in the string model. The usually excellent isolation properties of the dielectric material in coaxial cables allow engineers to ignore this component without sacrifice. Hence we can conclude that the standard electrical equivalent circuit of a transmission line needs to be modified to be applicable to model a drillstring.

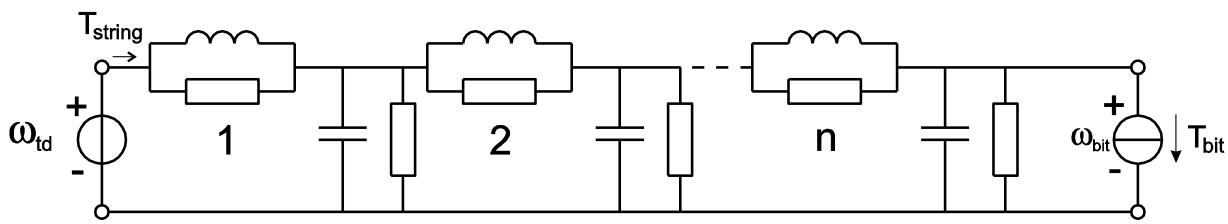

Figure 4: electrical equivalent of ladder-network transmission line model.

A model such as shown in Figure 4 would create a very large number of parameters to be identified. Fortunately the circuit in Figure 4 can be written in the frequency domain for the limit case where n goes to infinity as will be shown in the next paragraph.

Mathematical foundation

Relation of stackable drill string element with α and β, using ρ for specific mass [kg/m^3], G for shear modulus of steel [N/m^2], kappa for specific viscous wall damping [Ns/m^4], delta for specific viscous damping originating in material hysteresis [Ns/m^2] and Laplace operator s.
Define:

$$\alpha = \rho s + kappa \quad [\text{Ns/m}^4] \quad \ldots\ldots(1)$$
$$\beta = \frac{G}{s} + delta \quad [\text{Ns/m}^2] \quad \ldots\ldots(2)$$

Then we can write dynamic properties of a drill string element of length dx [m] and cross sectional polar moment IP [m^4]:

- Inertia and wall damping: $\alpha \cdot IP \cdot dx = \underbrace{\rho \cdot s \cdot IP \cdot dx}_{inertia} + \underbrace{kappa \cdot IP \cdot dx}_{damping}$ [Nms/rad] …… (3)
- Stiffness and material damping: $\beta \cdot \frac{IP}{dx} = \frac{G \cdot IP}{\underbrace{s \cdot dx}_{stiffness}} + \frac{delta \cdot IP}{\underbrace{dx}_{material\ damping}}$ [Nms/rad] ……..……….(4)

Resulting transfer matrix properties:

1. Propagation coefficient (γ): $\gamma = \sqrt{\frac{\alpha \cdot IP \cdot dx}{\beta \cdot IP / dx}} = \sqrt{\frac{\alpha}{\beta}} \cdot dx$ [-]
2. Characteristic admittance (Y_0): $Y_0 = IP\sqrt{\alpha \cdot \beta}$ [Nms/rad]
3. Characteristic impedance (Z_0): $Z_0 = \frac{1}{Y_0} = \frac{1}{IP\sqrt{\alpha \cdot \beta}}$ [rad/Nms]

And in case of infinite series of elements for pipe with length L: $n = \frac{L}{dx} \rightarrow \infty$ it can be proven that (Ref 1):

$$\begin{bmatrix} \omega_1 \\ T_1 \end{bmatrix} = \begin{bmatrix} \cosh(\gamma L) & Z_0 \sinh(\gamma L) \\ Y_0 \sinh(\gamma L) & \cosh(\gamma L) \end{bmatrix} \cdot \begin{bmatrix} \omega_2 \\ T_2 \end{bmatrix} \quad \ldots\ldots(5)$$

Equation (5) can easily calculate in the spectral domain the behavior of a uniform string of any length in combination with the dynamic parts connected to either side of it. This description is our preferred form to match to measured spectral data. The resulting model to be identified can now be *as simple as possible* with only 8 parameters as shown in Figure 5.
For non-linear time simulations, the found parameters can be directly used to generate a time-model with a reasonable amount of fractions to simulate things like stick-slip in a very realistic fashion.

Complete model

Combining the topdrive model in Figure 1 with the string model in Figure 4 results in the complete model in Figure 5. It shows a variable frequency drive (VFD) and a soft torque system (EPST) that communicates bidirectional to the VFD as shown in Figure 1. The identification software (ID) is inside the EPST computer. A key parameter for all dynamic properties of the string is the polar moment IP = $\pi/32 * (OD^4 - ID^4)$ [m^4], only depending on sizes outer diameter (OD) and inner diameter (ID). No knowledge of these sizes is needed during identification, but the found IP can be used to verify the validity of the estimation.

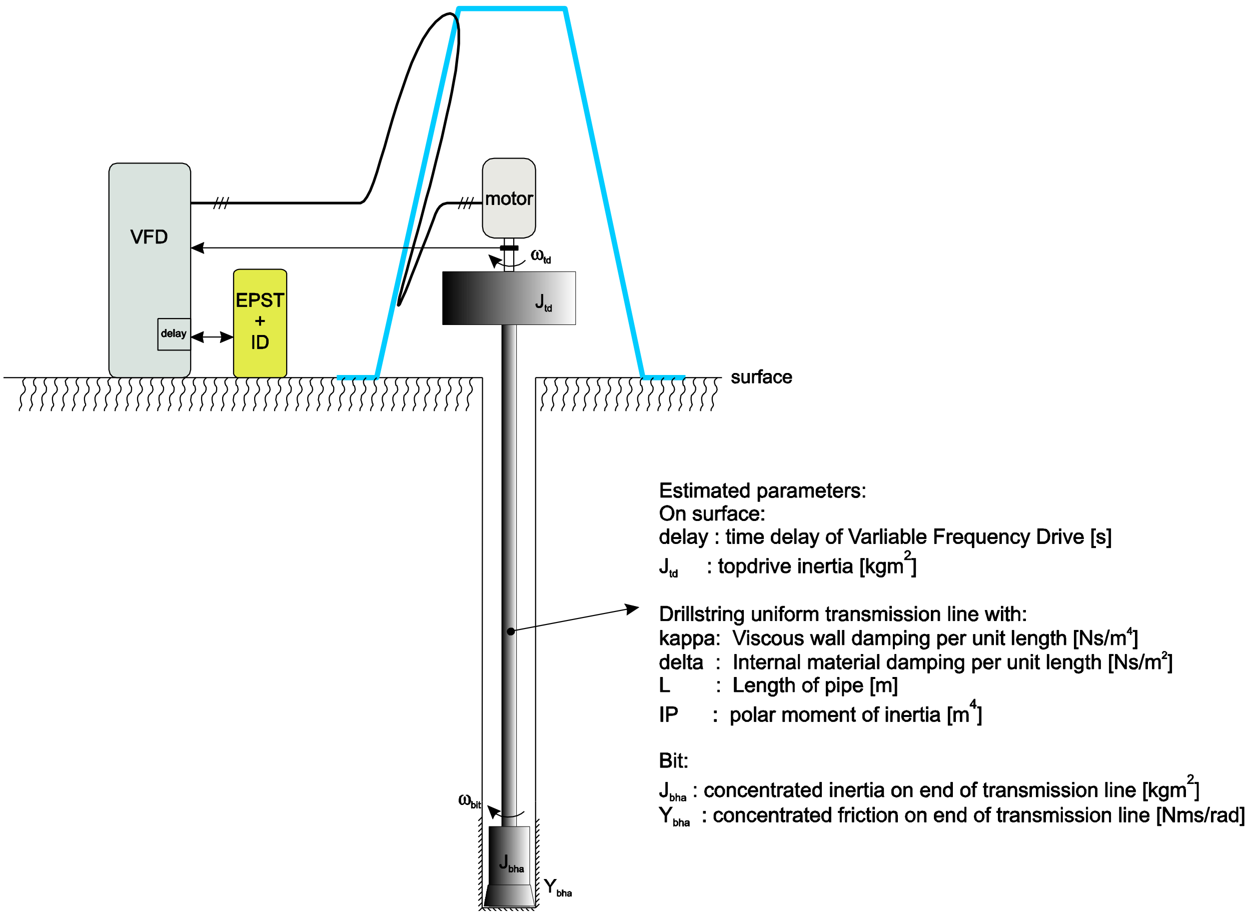

Figure 5: Simplified drill system model.

Having a complete model including the (speed or torque) controller as shown in Figure 5, the topdrive motor and inertia and accurate drillstring description based on transmission line models, the full system behavior can be analyzed in detail off-line or on-line. Experiments can be conducted in simulation and sensitivities can be predicted. Since physical drilling happens mainly at the bit, the mechanical characteristics at the bit (unobservable from the surface) should be most important to the drilling supervisor. When a constant bit speed is the ultimate goal, the bit-mobility (bit speed per torque on bit) expressed in rad/Nms should be minimized as to lower the chance of stick-slip. Only a valid representative model description allows such optimization. Lumped string models are too simple for this purpose, they do not show any higher modes, and predict a much lower mobility than what is happening in the real world. Transmission line models however, do incorporate an unlimited amount of higher modes all having some influence on the bit speed as a function of time or frequency. In practice the behavior between 0...2Hz can be influenced by the top-drive controller, for higher frequencies the bit-mobility is determined by the string-parameters of mainly the BHA and lower part of the string, the topdrive control makes no difference any more.

System Identification

A well designed excitation signal T_{sweep} is added to the torque setpoint, as can be seen in Figure 1. The effect of this injection is transferred to measured speed, depending on all system parameters, including the dynamic properties of the string itself. An example spectrogram (spectrum as a function of time) is depicted in Figure 6, all frequencies between 0.05Hz and 4.0Hz are injected to the torque setpoint (left plot) and the response in the measured speed is visible in the right plot. Due to the torques exerted to the BHA by drilling, the string modes appear as horizontal lines around 0.4Hz, 0.7Hz, 1.4Hz etc, mainly in the speed signal.

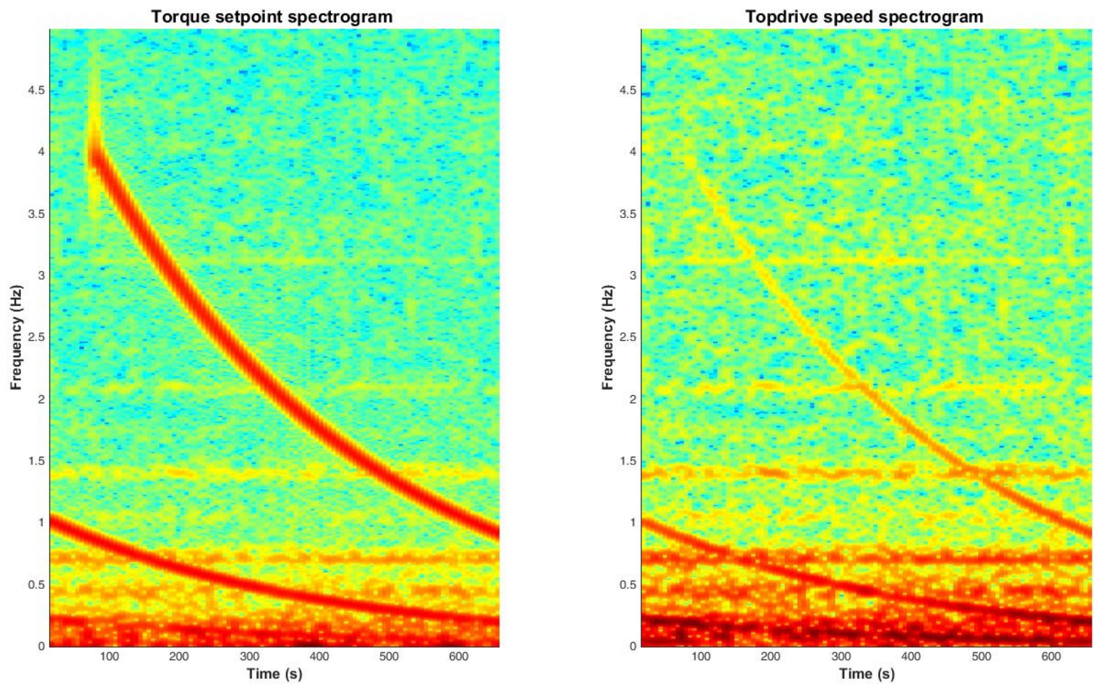

Figure 6: Spectrograms of torque and speed, basis for identification while drilling. The string modes show up as horizontal lines, the injected sweep consists of three simultaneous exponential frequency components covering all relevant frequencies.

A linear system is assumed. During severe stick-slip one could imagine that two distinct models; a bit-stuck model and a bit-slipping model take turns.

Passive

No input signal is available when doing passive identification. The spontaneous noise that excites the system will originate mainly at the drill bit. Often the frequency content of available noise is not sufficient to do proper identification.

Active

Injection of relevant frequencies is very beneficial for enhancing the coherence and the accuracy of the representative dynamic model. White noise is often used in literature; however a chirp or sweep signal requires less amplitude and power to reach similar coherence and allows detection of non-linear distortion and aliasing effects. A sophisticated sweep signal was developed that provides full exposure over three orders of magnitude of frequency providing good coherence even in conditions while drilling.

Field data results

The system was tested on a number of drilling rigs during normal drilling. In Figure 7 up to Figure 13 data is presented from drilling a particular vertical well in both 12 ¼" hole (up to ~3000m) and 8 3/8" hole (from ~3000m and higher). Figure 7 (measured) and figure 8 (estimated) shows a series of typical command mobility results over frequency (labeled A through F, six successive recordings of 10min) together with a stacked result. Clearly five drill string modes can be recognized. Once the drill string model has been derived any system transfer function may be evaluated (see bit mobility in lower graph of figure 8.

In case these results are plotted over depth, drill string damping properties may be monitored. In one particular depth interval the signature of the command mobility was completely different from other depth ranges, indicating unexpected high damping. The caliper log taken after drilling showed clear washouts over this interval indicating that the high damping might be diagnostic for drilling trouble zones (Figure 9 through 13 around ~3100m).

Based on the resulting model parameters, curves for the bit mobility over frequency can be calculated. Bit mobility is a measure for bit/dhm (down hole motor) speed responsiveness to torque disturbances to the bit/dhm.

There are different ways to represent the established bit mobility (in [rad/Nms]). One is as a transfer function over frequency whereas another is a step response in time, each focusing on different aspects of bit mobility. Although the impulse- and step-responses are each other's integral/derivative, the step response is preferred over the impulse response because the impulse response does not clearly show how long it takes to 'digest' a structural change of bit torque.

It is assumed that best drilling circumstances are achieved when bit rotational speed is as constant as possible, together with a minimum chance to let the bit stall. Stalling may happen when bit/dhm speed drops temporarily below a threshold value from where it cannot recover anymore because of the higher friction at (very) low speeds. This is frequently explained by the well known 'Stribeck' curve.

The bit mobility over frequency provides insight in the presence and intensity of higher modes and the limited effect of any topdrive control on higher modes. The bit mobility over time (step response) provides insight in reflection time and effectiveness of applied softtorque method in terms of decay time and amount of undershoot after a stick to slip transition that may occur.

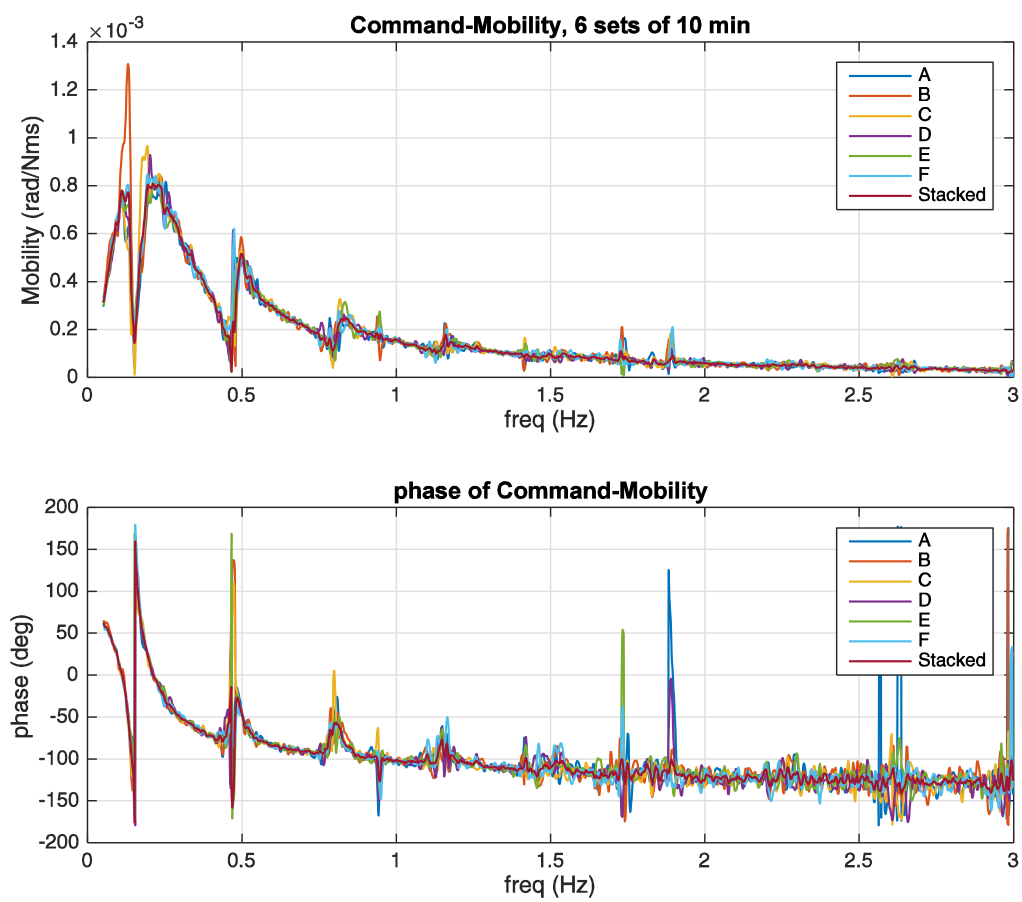

Figure 7: While drilling, estimated transfer functions of command-mobility (rad/Nms), quality of the data shows from the low spread.

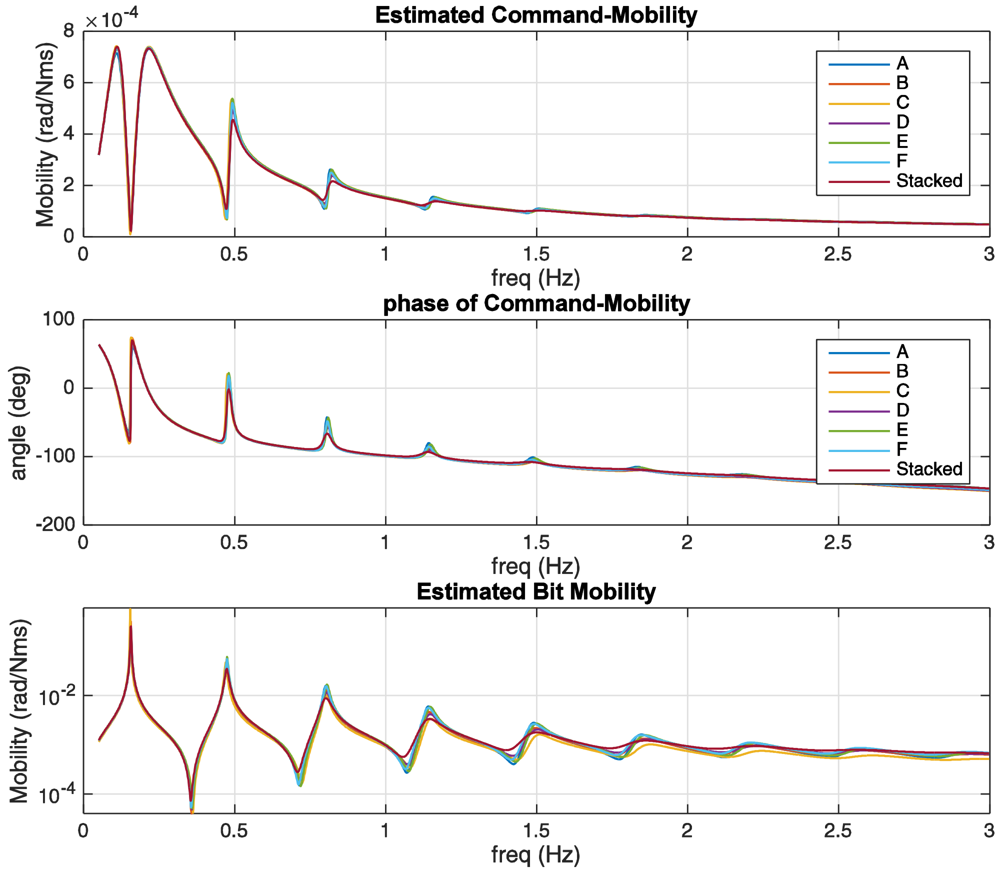

Figure 8: Estimated command-mobility functions from successive measurements. Bit Mobility is calculated based on locked top-drive to only show the string characteristics. Some variation in damping is observed, frequencies and modes are almost identical.

measurement	kappa(Ns/m^4)	delta(Ns/m^2)	L(m)	IP(m^4)	T_{delay}(s)	J_{td}(kgm^2)	Y_{bha}(Nms/rad)	J_{bha}(kgm^2)
A	217	2.354e+08	4455	1.633e-05	0.03899	1104	2.141e-13	85.98
B	4.235	3.717e+08	4460	1.67e-05	0.04036	1123	0.03716	84.43
C	1.011e-10	3.92e+08	4400	1.689e-05	0.0426	1093	7.565e-05	103.90
D	2.559e-14	4.23e+08	4443	1.571e-05	0.0417	1098	3.593	81.58
E	80.09	2.749e+08	4430	1.562e-05	0.03916	1093	9.571e-13	82.15
F	76.18	3.191e+08	4472	1.601e-05	0.04075	1112	4.704e-15	77.62
Stacked	0.05795	6.348e+08	4488	1.575e-05	0.03895	1113	2.264e-13	75.20

Table 1: Example set of parameters from the estimator referring to data from Figure 8.

The data in Table 1 shows that kappa, delta and Y_{bha} show the largest variability. It can be shown that the value of kappa determines the 'sharpness' in the resonance peaks of the transfer functions and the value of delta reduces the 'peak height' with increasing frequency; suggesting dispersion damping which renders higher drill string vibration modes less important.
The stacked estimation suggests more internal friction and less external friction, which can be explained by the gradual downward movement of higher modes, causing the stacked data to show a broader and lower peaks in the spectral response at higher frequencies, just what a higher delta value does…hence stacking to improve signal to noise should only be done over limited time periods.

Diagnostics

Damping

In well nr 10 a substantial increase in friction and bit-inertia was identified at certain depth intervals. Logs taken afterwards showed wash-outs at these depths, suggesting diagnostic potential of this estimation technique.

Accurate estimations are possible, data of large part of a whole well are shown in Figure 9 to Figure 13: The measured command mobility (speed per injected torque in (rad/Nms), is the basis for our estimation process. All data is gathered while running with soft-torque active, using parameters calculated from models obtained from the on-line estimator.

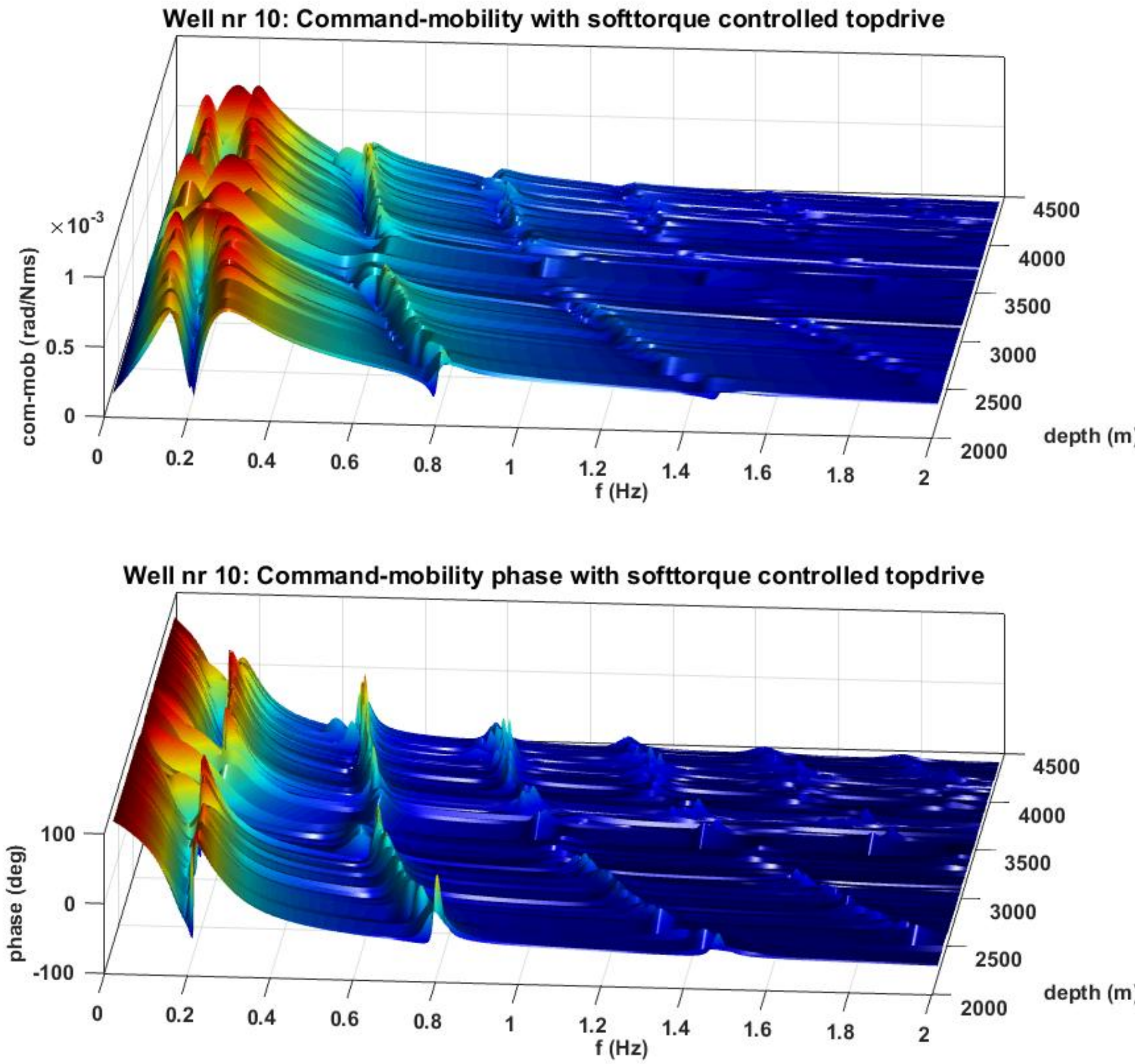

Figure 9: Command-mobility measured and identified. Both amplitude and phase show trend of higher modes very clearly. Absence of deep valley near the string resonance around 0.2Hz in the high damping locations may seem surprising.

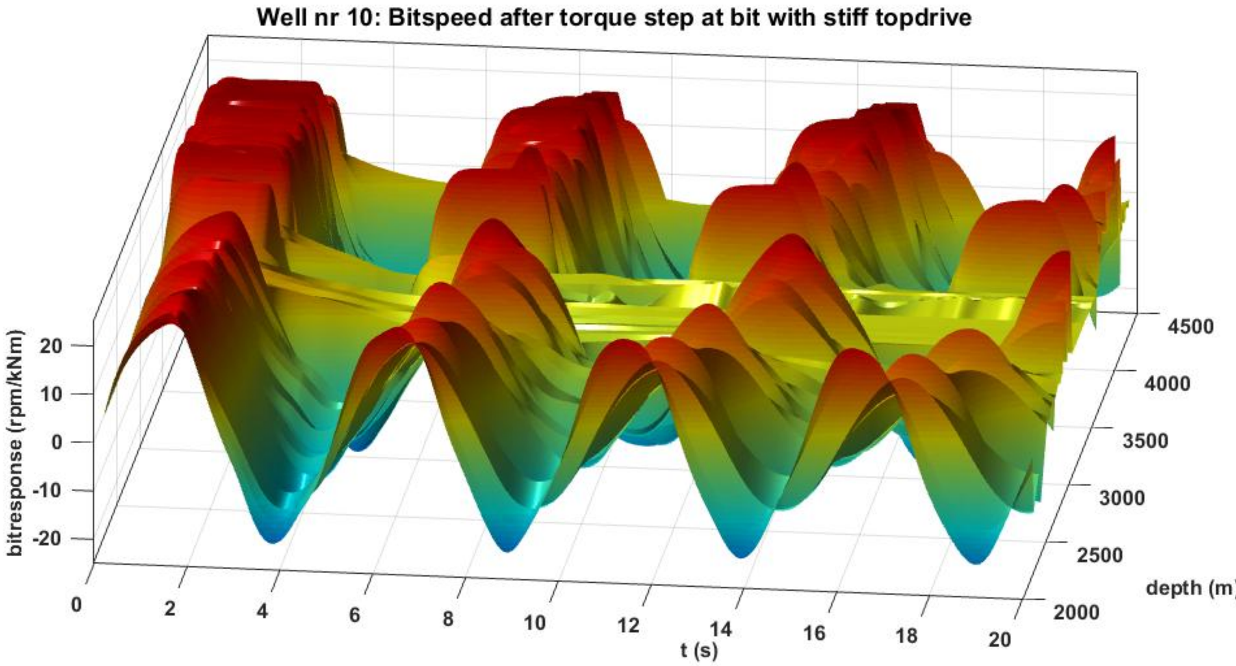

Figure 10: Well 10: Response of bit speed to a torque step at the bit in case the top of the string is clamped (stiff topdrive). The two different string types are quite clear just as a part with heavy damping. Very slow decay of reflected energy is noticed.

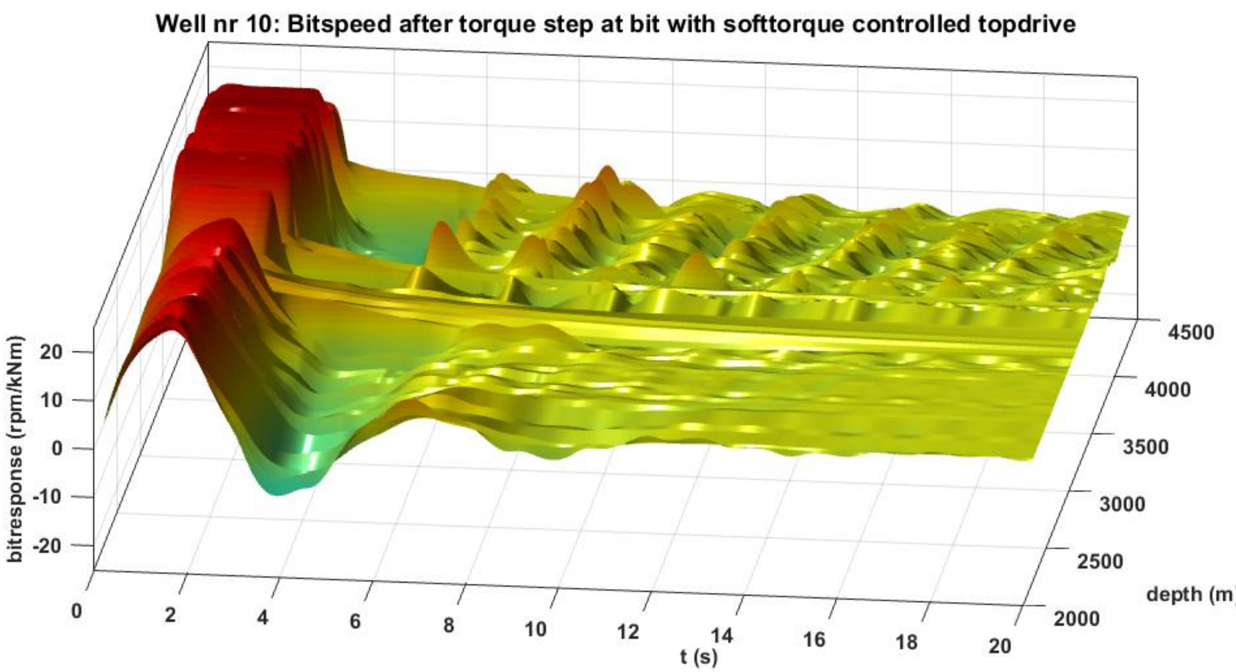

Figure 11: Well 10, Response of bit speed to a torque step at the bit, with used parameters of soft torque controlled topdrive. Two string types and depths with high damping are eye-catching.

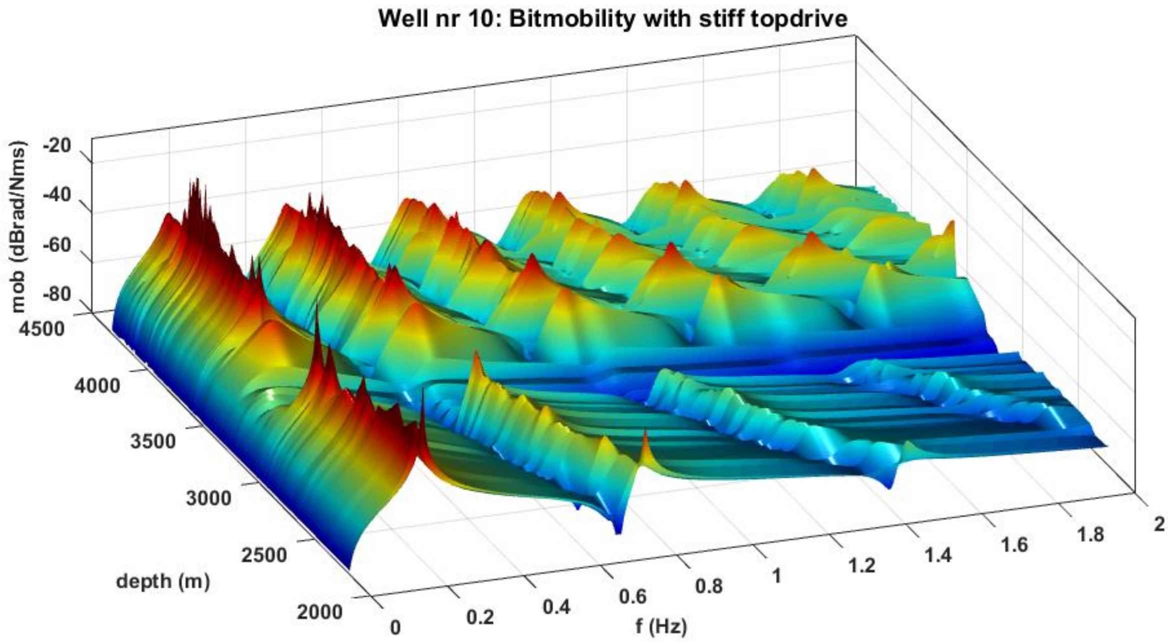

Figure 12: Frequency domain representation of bit mobility with stiff topdrive, equivalent to Figure 5.

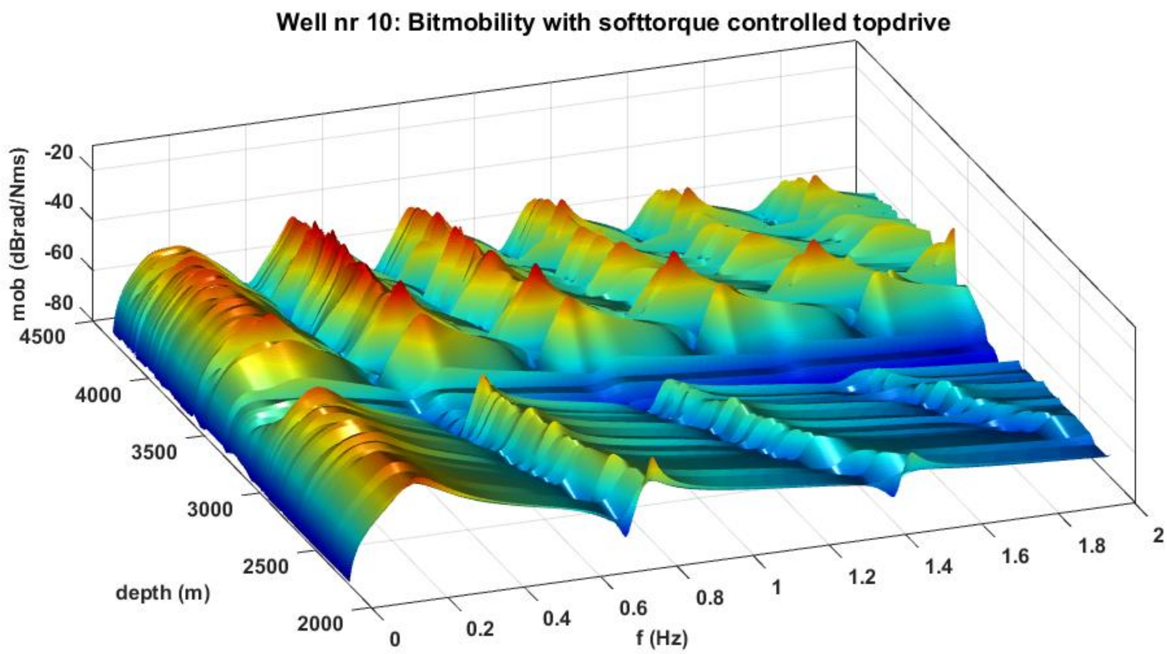

Figure 13: Frequency domain representation of bit mobility with softtorque controlled topdrive, equivalent to Figure 11.

Conclusions

- Adding an excitation signal to the topdrive torque which is rich in a spectral sense, very good identification of the mechanical top drive, controller and drillstring dynamics is possible, yielding a realistic model fit for simulation and optimization.
- Knowledge of mechanical string parameters provide a model with reasonable location of resonance frequencies, however the effective damping terms prove impossible to predict. The proposed transmission line based

identification method does provide effective internal, external and bit viscous damping terms (all linear).

- A transmission line based model can describe the full mechanical behavior of the drill string in great detail with only 8 relevant parameters and 10 minutes worth of measurement data.
- Higher modes are more pronounced in 8 3/8" hole drilling than in 12 ¼" drilling. Main difference is the relative heavier BHA in the 12 ¼" drilling case resulting in a smoother and more sinusoidal step response (Figure 10 and 11).
- Standard softtorque control mainly reduces the mobility of the bit at the fundamental frequency of the string (compare Figure 12 with Figure 13), the first higher mode is slightly improved, but second and higher modes are almost insensitive to controller settings: the top-drive's inertia dominates everything else at these frequencies.

Acknowledgements

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