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LABORATORY SIMULATION OF DRILL BIT DYNAMICS USING A MODEL-BASED SERVO-HYDRUALIC CONTROLLER

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ABSTRACT

Drilling costs are significantly influenced by bit performance when drilling in off-shore formations. Retrieving and replacing damaged downhole tools is an extraordinarily expensive and time-intensive process, easily costing several hundred thousand dollars of off-shore rig time plus the cost of damaged components. Dynamic behavior of the drillstring can be particularly problematic when drilling high strength rock where the risk of bit failure increases dramatically. Many of these dysfunctions arise due to the interaction between the forces developed at the bit-rock interface and the modes of vibration of the drillstring. Although existing testing facilities are adequate for characterizing bit performance in various formations and operating conditions, they lack the necessary drillstring attributes to characterize the interaction between the bit and the bottom hole assembly (BHA). A facility that includes drillstring compliance and yet allows real rock/bit interaction would provide an advanced, practical understanding of the influence of drillstring dynamics on bit life and performance. Such a facility can be used to develop new bit designs and cutter materials, qualify downhole component reliability, and thus mitigate the harmful effects of vibration. It can also serve as a platform for investigating process-related parameters which influence drilling performance and bit-induced vibration to develop improved practices for drilling operators.

Sandia National Laboratories is pursuing the development of an advanced laboratory simulation capability which allows the dynamic properties of a BHA to be reproduced in the laboratory. This simulated BHA is used to support an actual drill bit while conducting drilling tests in representative rocks in the laboratory. The advanced system can be used to model the response of more complex representations of a drillstring with multiple modes of vibration. Application of the system to field drilling data is also addressed.

THE DRILL BIT VIBRATIONS PROBLEM

The drilling industry has developed comprehensive test facilities to characterize bit performance for the challenging environments encountered downhole. These facilities have resulted in improved understanding of the physical interaction between the bit cutting elements, the rock, and even wellbore hydraulics. These laboratory-based characterizations have given birth to high performance bits that can effectively drill soft to hard rock formations under precisely controlled operating conditions.

However, field drilling conditions can result in downhole conditions that are drastically different from the preferred operating conditions typically encountered in the laboratory. The bit can interact in a complex way with the constraints of the formation and the bottom hole assembly (BHA), resulting in a range of vibration modes being excited in the drillstring. In harder formations, these vibrations can cause cutter damage and even complete failure of the bit cutting structure. This bit damage is often accompanied by significant economic losses due to the non-productive time incurred while tripping out of the hole to replace the bit. The vibration problem becomes especially frequent in deeper and harder formations. Hence, drill bit dynamics are limiting factors in the use of high performance bits and related tools for drilling hard rock formations.

The phenomena of drillstring vibrations and their effect on drilling performance have been the subject of extensive analytical and field investigation for almost 50 years. The development of analytical representations of drillstring axial and torsional vibrations to identify critical modes was initially pursued by researchers (Bailey and Finnie, 1960; Dareing and Livesay, 1968). Over the years drillstring vibration models were expanded to include numerous additional physical behaviors including lateral vibrations (whirl) and mode coupling (Elsayed and Dareing, 1994; Christoforou and Yigit, 1997; Leine et al, 2002). Many other researchers developed models designed to quantify vibrational instability regimes arising from coupling of rock/bit interaction and vibration of the drillstring (Dareing et al, 1989; Elsayed et al, 1994; Abbassian and Dunayevsky, 1998).

Over the years, many field investigations measuring drillstring vibrations at the surface have also been conducted (Finnie and Bailey, 1960; Van Diver et al, 1990). More involved efforts have also been completed using downhole instruments to measure vibration near the drill bit in order to validate vibration models (Jogi et al, 2002). Unfortunately, field testing does not necessarily provide the most efficient venue for providing the experimental data to corroborate the massive amount of study that has been devoted to understanding the influence of vibration on drilling. In particular, field investigation tends to be very expensive because of the high operating costs associated with drilling a hole that can be many miles deep. Moreover, the environment presents many uncontrolled variables such as lithological uncertainty associated with the complex geologies encountered as well as other unknowns associated with the application. What is desirable is to somehow shrink the multiple thousands of feet of drillstring and other BHA components into a laboratory-scale rig in order to provide a more controllable environment in which to study the multiple modes of vibration and their impact on the drilling process. This capability does not currently exist. Consequently, present day bits are not dynamically robust enough for the impact conditions they encounter in the field, simply because they haven't been proven for these loads in their development process. Given the complex nature of bit cutting structures in use throughout the industry, a laboratory simulation capability is needed to reproduce the dynamic behavior of field drillstrings in the laboratory. It is the purpose of this work to outline the critical elements required to develop this capability as well as report a series of proof-of-concept experiments that have been performed to demonstrate its viability.

LABORATORY SIMULATION

Objectives

The purpose of this drilling simulation is to represent the dynamic motion of the drillstring in a controlled laboratory setting accurately reflecting field drilling conditions so that the bit response may be monitored, characterized, and improved before committing the bit and drilling tools to expensive field drilling operations. Ideally, one desires to simulate the properties of any drillstring in the laboratory and evaluate the response of a candidate bit in a representative rock sample. This approach, illustrated in Figure 1, would allow a bit to drill the formation and respond as if it is drilling at depth. There are several motivations for development of this capability. It will allow the drilling industry to:

- ***Develop an advanced, practical understanding of the influence of drillstring dynamics*** on bit performance and life that will be used to improve and optimize bit designs***;***
- ***Identify deficiencies in drill bit material properties and designs*** as representative impact loadings that occur in the field can be reproduced in the laboratory;
- ***Validate development of hardware and methodologies*** that can be used to introduce stability to the drilling process to eliminate drillstring dynamic dysfunctions; and
- Use the capability as a proving ground to ***determine best practices*** to properly handle dynamic dysfunctions when they occur.

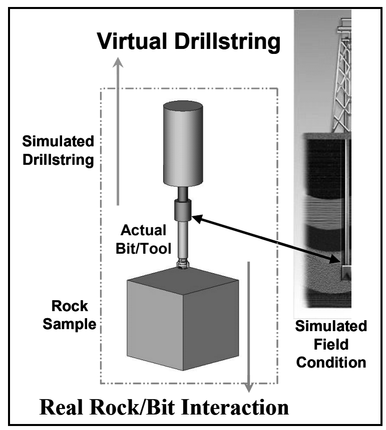

Figure 1. Laboratory simulation of drilling dynamics.

The dynamic range where the complications occur must be identified for these drillstring representations to be meaningful. Drillstrings vary dramatically in their properties depending upon their geometry, depth, well profile, and surface support. Consequently, drillstring modes of vibration exist in broad ranges. Zamudio (1987) shows fundamental modes of vibration in the sub-hertz level to tens of Hz for a 7200 ft model of a drillstring. Jogi (2002) measured vibrations in the 0-100 Hz range for a relatively shallow depth. Sandia has measured similar vibrations using downhole diagnostics. These vibrations are observed at the bit in the longitudinal, rotational, and lateral axes. The present work addresses modes of vibration up to 100 Hz. The larger frequency modes will typically have smaller amplitudes and accordingly less energy. To accurately reflect reality, vibration modes should be included in all axes. However, for the purposes of this paper, the scope is limited to the representation of the axial mode of the drillstring. If a realistic simulation can be accomplished in the laboratory, obtaining these objectives will be of significant benefit to the drilling industry.

Mechanical Analog versus Model-Based Control

To understand how a drill bit specified for a given drillstring application will respond in a particular formation requires a capability to reproduce a broad range of drillstring attributes. The properties of a field drillstring can be simulated in the laboratory using either a mechanical analog or model-based control. These two approaches are illustrated schematically in Figure 2. In the mechanical analog approach, drillstring vibration is introduced using a mechanical system that has a dynamic response simulating simplistic models of a drillstring. For example, a single degree of freedom spring-mass-damper, or a system of spring-mass-dampers, that replicates the dynamic response of the desired system in narrow frequency bands.

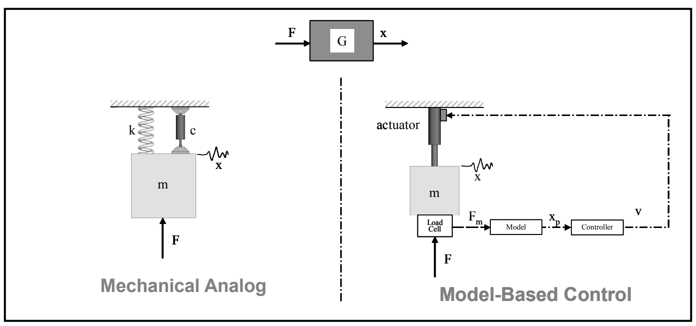

Figure 2. Mechanical Analog versus Model-Based Control.

In the model-based control approach, motion of the drillstring corresponding to a bit force is predicted using a computational model and replicated using a system of actuators. The model could represent a simple mechanical analog, an advanced representation based upon a complex model, or even reproduce measured data taken in the field. The model used to control the response is not limited to computational models but more generally a prescribed relationship between the input force and the resulting response. Research using these two approaches is summarized in this paper. If a system can be produced that models a drillstring in the laboratory, then real rock-bit interaction can be used to observe how drillstring vibration affects the response of the bit. Such a system can be used to address the influence of various effects characteristic of complex drillstring behavior that are observed in the field.

SIMULATION BY MECHANICAL ANALOG

Approach

Sandia National Laboratories maintains a laboratory-based drill rig for the purpose of evaluating candidate drilling technologies. The facility, shown in Figure 3, consists of a hydraulically-driven vertically traversing frame that supports a rotary top drive system. A movable platform is used to locate and hold a 3 ft rock cube which is clamped during drilling tests, although it does not have any pressurized confinement. Water is used as a drilling fluid and is fed through a swivel located above the top drive. The rig is fully instrumented to measure rate of penetration (ROP), weight on bit (WOB), rotary speed, torque, and acceleration in several locations, along with bit longitudinal and rotational displacements. A 25 hp hydraulic power unit is used to rotate the drillstring using a belt drive system connected to a positive displacement motor; the unit also powers the long stroke hydraulic cylinders used to move the vertically traversing frame. The three inch diameter drillstring accommodates the 3-1/4 inch diameter coring bit shown in the inset of Figure 3. Three half-inch diameter PDC cutters are circumferentially spaced around the periphery of the bit. Other bits could also be used. A desktop computer is used for data acquisition and control of the proportional valves that move the long stroke hydraulic cylinders that support the vertically traversing frame. This facility, as pictured, is used for testing a spring-mass mechanical analog.

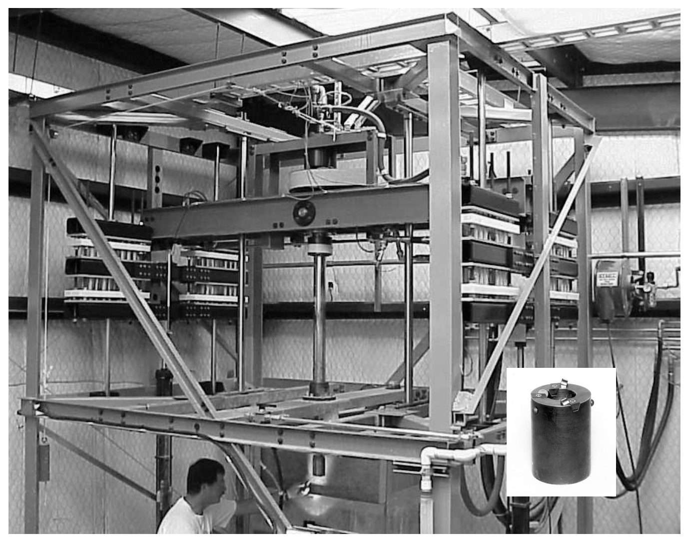

Figure 3. Sandia's drilling facility with a mechanical analog of a drillstring. The inset shows the bit used for the drilling tests.

System Design

The dynamics of a field drillstring have been simulated in this facility by using a spring suspension system to support the vertically traversing beam, or load head, which consists of heavy structural steel channel that sits on the bit. The long-stroke hydraulic cylinders are used to support this spring-mass system and regulate the weight on bit. The system is likened to field drilling in that as a driller pulls up on the drillstring to regulate WOB, pushing up on the spring suspension system with the long-stroke cylinders allows WOB to be regulated in the laboratory drilling facility. The load head is constrained to axial motion by guide shafts within the frame. The axial compliance for this laboratory representation is determined by the spring-suite comprising the suspension system, consisting of

96 compression springs with individual spring constants of 27 lb/in. The weight of the load head with the top drive is approximately 1610 lb. Hence, the system has a fundamental mode of vibration of approximately 4 Hz. (Rotational, or torsional, compliance has also been added to this system using two counter-wound power springs inside the shell of the belt-driven pulley. However, the rotational compliance is removed for the present testing.)

Drilling Tests with a Mechanical Analog

Drilling tests were conducted by rotating the bit at constant speed and easing the bit into the rock until an average WOB was obtained. Drilling parameters were controlled and the bit response was monitored. The drilling test in Figure 4 was conducted using a Sierra White Granite rock sample, a nominal WOB of 800 Lb (nominally 800/3 Lb per cutter) and rotational speed of 140 RPM. This figure shows the bit motion plotted with respect to the local rock surface. When the bit motion becomes positive, indicating that the bit is above the rock surface, the bit force (WOB) is released, rendering it equal to zero. The bit bounces above the local rock surface and, as it returns into the rock, high impact loads are applied to the cutters. The WOB in this plot was measured using a strain-gage based measurement sensor located just above the bit. It is apparent from this figure that this condition resulted in severe bit bounce, with impact loading at the bit exceeding 5000 Lbs, more than six times the applied WOB.

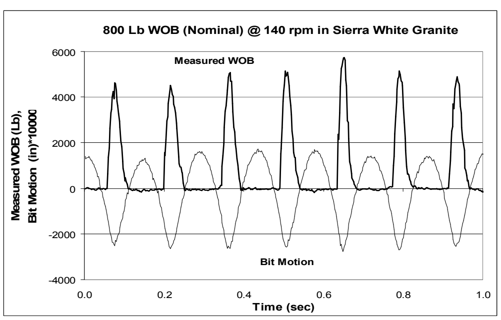

Figure 4. Bit motion and measured WOB from drilling tests with a mechanical analog.

This testing was repeated using a variety of operating conditions. The results show there are combinations of WOB and rotary speed that are preferred to reduce the severity of bit bounce. Figure 5 shows the peak bit motion measured as the rotary speed is varied from 140-260 RPM. This figure also superimposes the rate of penetration over the bit displacement using a semi-log scale. One sees that increased bit vibration at 200 RPM leads to a tremendous loss in the ROP, i.e., practically no drilling is taking place. The importance of this condition to loss of penetration rate and likelihood of cutter bit damage is apparent. This work with fixed-compliance has been described in greater detail in Elsayed & Raymond (2000, 2002) wherein the effect of coupling between axial and rotational vibrations due to the presence of rotational compliance is also addressed.

Although the potential for adverse behavior due to the influence of operating conditions, drillstring characteristics and bit characteristics is generally acknowledged within the industry, the aforementioned research quantitatively demonstrates the impact of vibration on drilling performance. It also provides the opportunity to quantify the effect of the interaction between the different drilling parameters. There are, however, numerous limitations to laboratory simulation using a mechanical analog. The mechanical analog is a single point representation that is not amenable to emulating the varying properties of the drillstring over time, such as the increase in length and compliance as more pipe is inserted into the hole. Mechanical analogs also tend to be very time consuming to exchange in the setup and have obvious cost implications with respect to maintaining the hardware necessary for a large range of compliance conditions Furthermore, since the damping is inherent in the type of analog used, it is difficult to precisely control the level of damping present in the system. For these reasons, simulation of the drillstring properties using model-based control is desired.

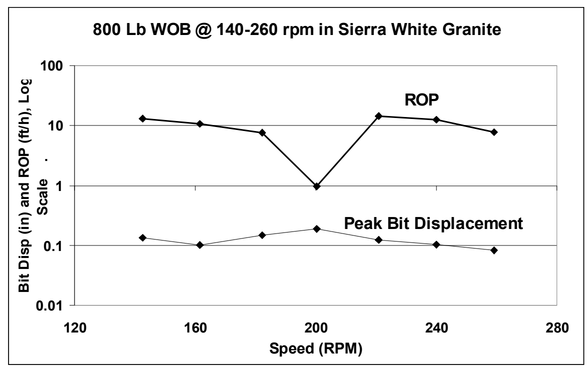

Figure 5. Effect of drillstring dynamics on bit response and resulting rate of penetration.

SIMULATION BY MODEL-BASED CONTROL

Approach

The intent of simulation using model-based control is to reproduce the dynamic properties of potentially any drillstring without the limitations of a mechanical fixture, as described above. The approach is to computationally model the drillstring and allow real-rock bit interaction to generate the forces to be used as input to this model and then predict, or prescribe, how the system should respond to these forces. It then becomes a matter of enforcing the correct displacement at the interface between the bit and BHA using fast-acting actuators such that the bit “feels” as if it’s in the hole at depth. The drilling function is performed by an actual bit in a representative rock sample, yet the bit will behave as though it were attached to a long, flexible drillstring specified at the user’s discretion. A schematic of the approach is shown in Figure 6.

The former drilling facility was modified and used to demonstrate a prototype system using this approach. As in the mechanical analog, model-based control comprises two primary equipment subsystems: a drilling simulator and a dynamics simulator. The drilling simulator consists of the drill rig gantry with the vertically traversing frame. The dynamics simulator supports the drill bit (and possibly a BHA tool in future implementations) and produces the dynamic compliance of the drillstring at the bit using fast-acting actuators that are controlled by a model of the drillstring. The vertically traversing frame is used to support the dynamics simulator, analogous to how fixed-compliance was accommodated in the mechanical analog.

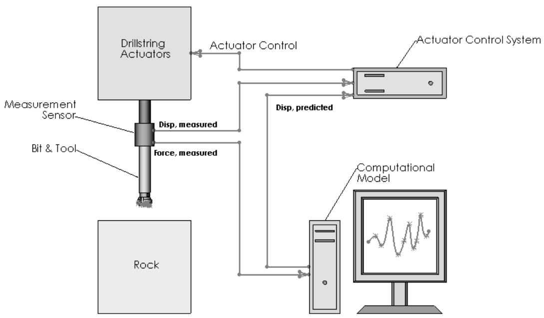

Figure 6. Model-Based Control Approach.

System Development

To develop a competent simulation using model-based control requires attention to several areas. These include:

- *Simulation Requirements Definition*
- *Predictor Development*
- *Dynamics Simulator Development*
- *Servo-Hydraulic System Selection*
- *Controller Development*

Each of these items will be addressed separately along with the approach to implementation of these in a prototype system. These topics are coupled and their appropriate integration results in a system that meets the performance objectives.

Simulation Requirements Definition

The relationship between the forces applied to a particular drillstring and its displacement response must be understood to define performance requirements for the system. In the context of Figure 2, the Frequency Response Function, 'G', of the drillstring must be known, so its response can be predicted when it is subject to an arbitrary bit force. The relationship could be determined from a computational model consisting of simple formulations or a complex representation of a drillstring, depending upon the fidelity of response required. Field data of representative configurations can also be evaluated to understand these requirements. The displacement response should be characterized as a function of the bandwidth of the system. The initial objective for a prototype system was to reproduce the response seen in the mechanical analog fixture. This required a peak displacement of approximately 0.5 inch from static to 5 Hz.

Predictor Development

The drillstring model is the driver in the drilling dynamics simulator. When the bit encounters a reactive force from contact with the formation, the model predicts how the drillstring would respond to that force. It can be a computational model or any rule-based method that specifies the response based upon input parameters.

Some available computational modeling approaches for a predictor include transfer function representations, finite element analysis methods, wave propagation formulations, and normal modes analysis. With selection of a reasonable time increment for numerical integration in these models, desktop computers can predict future displacements very quickly enabling real-time updating of the actuator controllers. The complexity of the model utilized is primarily limited by the computational ability to provide a solution in time to update the controller. The appropriate level of spatial discretization necessary to reasonably reflect the vibrational behavior of the drillstring can be determined through sensitivity analysis which can also be utilized to optimize time discretization for control purposes. Preliminary work in this area indicates that fairly simplistic representations can be used to capture the dominant modes of vibration. A normal modes solution has been incorporated for a predictor and is presented in further detail later in this paper.

Field data can also be used as a predictive driver. This would allow vibrations encountered in production drilling operations to be reproduced. Using measurements of bit forces and the resulting response, the Systems Identification method could be used to develop frequency response functions for the drillstring. Systems Identification is a linear regression technique used in controls theory. It allows a representative model of the system to be developed by assuming a model order and using regression analysis to solve for the algebraic coefficients in the model. The order of the system is verified by reducing the least squares error between fit and actual data in the regression analysis.

In a real drillstring, the relationship between input and output variables can easily manifest itself as a non-linear relationship. The versatility of the model-based control approach is that it allows the predictor to be chosen to represent any user-specified drillstring and then addresses the ensuing response using the physical simulation.

Dynamics Simulator Development

To simulate the dynamic response on a particular axis of a drillstring requires that the laboratory system be configured with actuators that can produce dynamic displacements on that axis with amplitudes mandated by the predictor. The development of the dynamics simulator must address the mechanical design of the drilling equipment, the configuration of the actuators to produce the required dynamic response, the rock containment system, and the sensors used to monitor the mechanical response of the system. The mechanical design of the prototype system was a modification to the drilling system described above with the fixed-compliance system removed. To achieve the required system response, the dynamic mass of the top drive system had to be reduced by decoupling it from the load head. The top drive sits on a 12” wide structural steel channel. The 8” wide channel was slotted to allow for relative motion of the top drive system. This reduced the effective mass of the system and allowed axial motion of a lighter mass to be introduced. The system could have been configured with a lighter top drive to extend the frequency response, but the complexity of the system would have required a large system rebuild. As shown in Figure 7, the actuators are configured within the load path between the load head and the power head beams to enforce the required displacement of the bit relative to the rock.

Figure 6 shows a measurement sensor at the interface between the bit and the dynamics simulator. It measures both the reaction force transmitted from the bit and the displacement response. The force measurements are input to the predictor to determine the required response of the drilling system to the drilling load. In the prototype system, the measurement sensor is integral to the actuators (described below). The actuators feature an integral strain-gage based load cell and an embedded displacement sensor (LVDT). The measured displacement can be used as input to the controller to assess the accuracy of the response relative to predictor requirements.

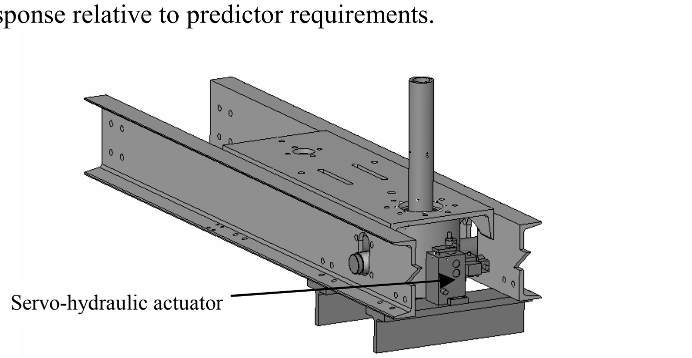

Figure 7. Dynamics simulator for model-based control.

The rock sample must be properly restrained so that is does not have any additional compliance that feeds back into the response of the bit. In the drilling facility, the rock is clamped at its base on a structural steel pallet that is clamped in place against an overhead plate. If pressurized containment is used, then the seal friction on the drillstring must be accounted for in the dynamic response of the simulator.

Servo-Hydraulic System Selection

The appropriate motive force technology must be identified to motivate the dynamics simulator with a bandwidth consistent with the output of the predictor. Servo-hydraulic actuators are the only motive-force technology available to accommodate the forces and displacement bandwidth applicable to this problem (Dorf & Bishop, 1998). However, these motions are subject to the additional overhead in mass and friction imposed by the mechanical system that supports the bit and top drive. Hence, the actuators must be selected to be an integral part of the overall system. The actuators have both static and dynamic force requirements since they operate in series with the load path.

Xcite Systems servo-hydraulic actuators were chosen for the prototype system consisting of an 1107-4-T/C Exciter Head with an 1104-MOD4 Master Controller. These actuators are powered by a 30 hp hydraulic power unit. They are typically used for modal excitation analysis on large structures. They are compact and easily integrated into the drilling fixture, as shown in Figure 7, to accomplish the dynamics simulation. These specific actuators produce 1000 lb across a dynamic range of static to 100 Hz. The actuators force and displacement capability versus bandwidth is shown in Figure 8. The actuators are able to reproduce any transient signal that lies beneath these envelopes.

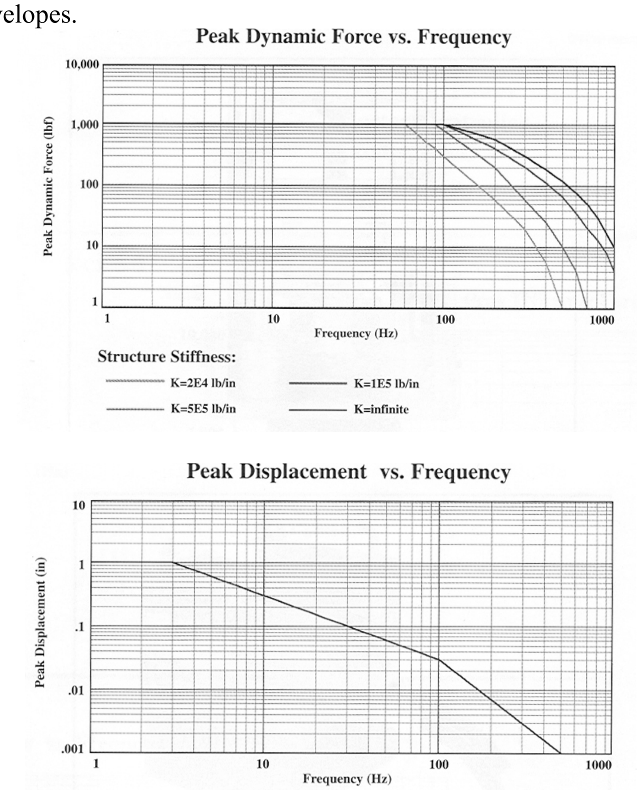

Figure 8. Force capacity and displacement response for servo-hydraulic actuators used in simulation (Xcite Systems 2000).

Controller Development

The development of the overall system must also address the development of the controllers that drive the actuators in the dynamics simulator to produce the response mandated by the predictor. The actuators must accelerate the mass of the top drive and also drive the bit against the rock in response to the required model dynamics. The actuators are operated in stroke control mode, since a displacement is enforced based upon the output from the predictor. The approach to integrate the controller that drives the dynamic simulator was to have a system run in parallel completely autonomous from the drilling function performed by the drilling simulator. This is synonymous with how drilling takes place in the field, i.e., the drillstring responds based upon its dynamics properties regardless of how the drilling system is controlled. This autonomous system samples the force measurements from the measurement sensor, sends them to the predictor, transmits the predicted command to the controller, and the controller sends a command signal to the actuators.

System Configuration

The basic system configuration consists of the servo-hydraulic actuators with the companion analog controller that drives the spool valve on the actuator, and the desktop computer equipped with National Instruments' LabView that is used for data acquisition and control. A National Instruments data acquisition card is used to monitor the force and displacement measurements from the embedded sensors on the actuators. A LabView application monitors the forces from the load cell, inputs these to the predictor model, and then uses the predicted displacement values to output a voltage to drive the displacement of the actuators in stroke control mode. A sampling rate of 5000 Hz is used resulting in a solution time average of 200 microseconds per step. The output signal is sent to the analog controllers which in turn control the response of the actuators. The voltage to drive the actuators to get the required displacement must be specified. A transfer function is required for the actuators so they can be input the proper control signal to achieve the desired response. Testing was conducted to characterize the frequency response of the actuators when they are used to drive inertial masses that represent the dynamic mass of the top drive.

Some dynamic mass must be moved to accomplish the simulation. This mass includes the top drive, rotating drillstring, bit, and other components comprising the dynamics simulator. The displacement-bandwidth relationship for the overall system is a function of this mass. Too much dynamic mass in the system will limit the ability to meet the requirements for the simulation.

Testing was also conducted to characterize the frequency response of the actuators when they act against an elastic foundation. As the bit enters the rock, it is decelerated by the rock penetration reaction. The bit is driven by the actuators which are in stroke control mode, so the actuator force must be large enough to allow the bit to penetrate the rock in accordance with model predictions.

Overall System Transfer Function

Shake testing was conducted on weights representing the dynamics simulator to develop a transfer function for the overall system that can be used to control the actuators. A typical displacement-time history response is shown in Figure 9. A chirp input signal was provided to the actuator controller and the response of the system was observed. This information was used to develop a transfer function for the dynamic simulator when motivated by the servo-hydraulic system. For a 212 lb mass, the response of the system starts to fall off after about 8 Hz.

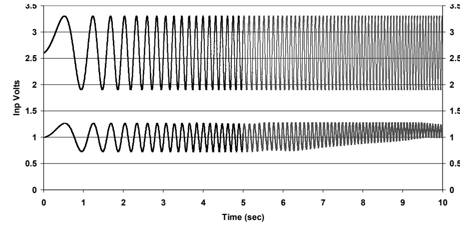

Figure 9. Input voltage (top) to actuator controller and actuator displacement response (bottom).

A transfer function for the displacement of the servo-hydraulic actuators as a function of driving voltage was derived using Matlab's System Identification module. The resulting function is shown in Figure 10. This was derived from the data in Figure 9 for 0-4 seconds (before the system response starts to drop off) corresponding to a frequency range of 0-10 Hz.

However, the inverse of this transfer function is needed to get the actual driving voltage applied to the actuator to enforce the correct displacement response. The inverse transfer function is required to determine the controller voltage based upon the desired displacement. The block diagram shown in Figure 11 is used to produce the inverse of the transfer function in Figure 10. This system is input into the National Instruments' LabView controller to control the actuators in stroke-control mode.

$$H(s) = K\left[\frac{1+T_z s}{1+2\zeta T_w s+(T_w s)^2}\right] \text{ [in/v]}$$

$$\text{with } K = 0.38376, \quad T_w = 0.01038, \quad \zeta = 0.7301, \text{ and} \quad T_z = 0.0044012$$

Figure 10. Transfer function for the servo-hydraulic actuator derived using System Identification.

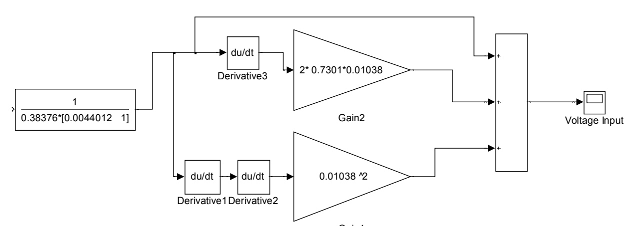

Figure 11. Block diagram to determine control voltage for a given displacement.

PROOF-OF-CONCEPT DEMONSTRATION

With the exception of the predictor, the other components of the system have been prepared for a simulation. A transfer function for the drilling facility equipped with the mechanical analog can be characterized to develop a predictor, or drillstring driver, for a proof-of-concept demonstration using the model-based control approach.

Predictor for the Mechanical Analog

A model for this system (i.e., a frequency response function) was derived by impacting the end of the drillstring (when the mechanical analog was in place) with an instrumented hammer. Time histories of the impact force on the hammer and the resulting displacement of the bit are measured. A frequency response function (FRF) is derived by taking the ratio of these two quantities in the frequency domain. This is shown by the solid lines in Figure 12.

The drilling system with fixed-compliance acts like a simple harmonic oscillator. Accordingly, appropriate values of stiffness, mass, and damping can be expected to form a reasonable characterization. However, when this is done, there is poor agreement between the predicted and measured frequency response functions. The system has extra apparent stiffness in the response of the drillstring due to stiction in the system. Using an artificially higher stiffness (e.g., 5500 lb/in) results in a better fit, as shown in Figure 12. This frequency response function [$1/5500/ (0.0007562s^2 + 0.01s +1)$] will be used to generate results for comparison to the mechanical analog system.

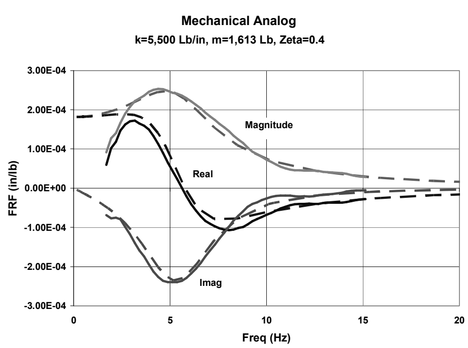

Figure 12. Transfer function for the mechanical analog (Bold lines represent measured data; dashed lines are fit).

Implementation

The foregoing developments are used to conduct a "model-based control simulation" using the frequency response function shown in Figure 12 as a predictive driver. To demonstrate that a model-based control simulation approach can be used to reproduce drill bit dynamics, a proof-of-concept demonstration was conducted in a static load frame prior to integrating it into the drilling function. This required that the actuators be re-configured. One of the actuators was used to generate a WOB force profile by loading it against a rigid frame. This force was measured, the FRF was used to predict the response of the drillstring, the voltage to produce this response was determined and sent to the actuator, the response of that actuator was monitored, and a comparison made to the predicted value from the model. This was done using the National Instruments controller and incorporated the previous control system characterizations. The approach is shown in Figure 13. The only difference from an actual drilling simulation is that the bit force was generated using a secondary actuator as opposed to actually drilling and using bit forces. This allowed the response of the system to be evaluated against a known input.

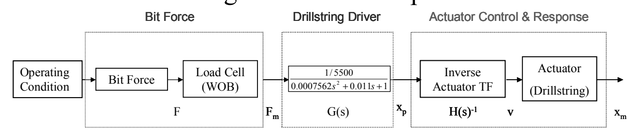

Figure 13. Implementation of the simulator to produce a given response for a drillstring.

The predicted response and the measured response of the actuators are shown in Figure 14. This was done using a chirp as an input. Note that the control algorithm is open loop, i.e., there is no comparison between the displacement results from the servo-hydraulic actuator and the results from the predictor to correct the input signal to the dynamics simulator. Nevertheless, favorable results are obtained. Based upon this success, the proof-of-concept demonstration advanced to a drilling system configuration.

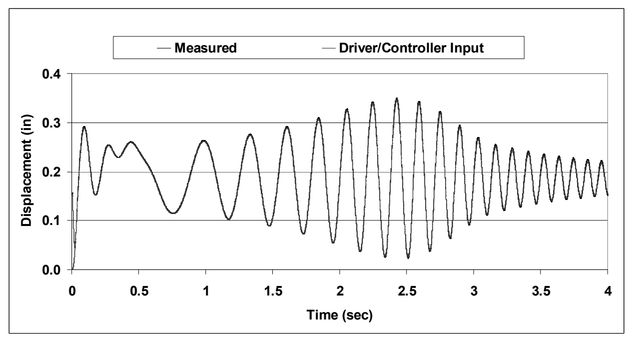

Figure 14. Agreement between predicted and measured displacements for the Proof-of-Concept demonstration.

Drilling Tests

The drilling test follows the same approach used in Figure 13 only instead of forcing the system with another actuator, an actual drilling test was conducted. This approach allowed the fixed-compliance drilling results to be reproduced for a proof-of-concept verification. The displacement response of the bit and its corresponding FFT are shown in Figure 15. The drilling conditions are 275lb WOB at 135 RPM in Sierra White Granite. The dominant mode of vibration at 5 Hz is clearly evident. Notice that there are some other frequencies with weak amplitude that come into play. These other frequencies with small amplitude may be due to excitation of other modes of vibration in the system (e.g., structural vibration modes). This simulation has established the viability of model-based control as an advanced means of studying drill bit dynamics. Unlike the previous approach, model-based control is not limited to simple modes of vibration, damping inherent in the mechanical analog, or single point design constraints. This approach can be used to more thoroughly evaluate bit, drillstring, and rock interactions.

The method is now applied to more advanced representations of a drillstring.

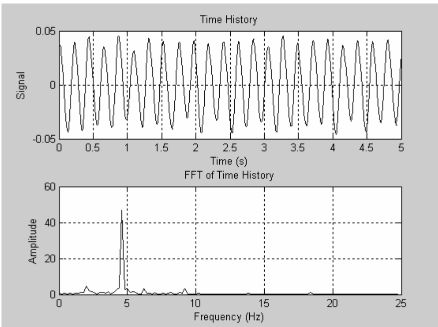

Figure 15. Bit response for the Proof-of-Concept drilling test in the time and frequency domain.

ADVANCED DRILLSTRING REPRESENTATION

Normal Modes Model

A drillstring model that is common in the literature (Zamudio, 1987) is a normal modes characterization of a drillstring comprised of 7200 ft of 4-1/2 inch diameter drill pipe and 780 ft of 6-1/2 inch diameter drill collar. The properties of the rig supporting this drillstring are also modeled at the top of the drillstring. The normal modes model was prepared by discretizing this system into a series of spring mass elements. The traveling block, swivel, and kelly are represented by a mass of 22600 lb, and the draw works cable with spring stiffness of 52500 lb/in. The 7200 ft drill pipe section is modeled using 19 lumped mass components with a mass of 5600 lb and stiffness of 28,000 lb/in. The interface between the drill pipe and drill collar is modeled using a mass of 7720 lb and stiffness of 28,000 lb/in. The drill collar section is modeled using 7 lumped mass components with a mass of 9800 lb each and stiffness of 700,000 lb/in.

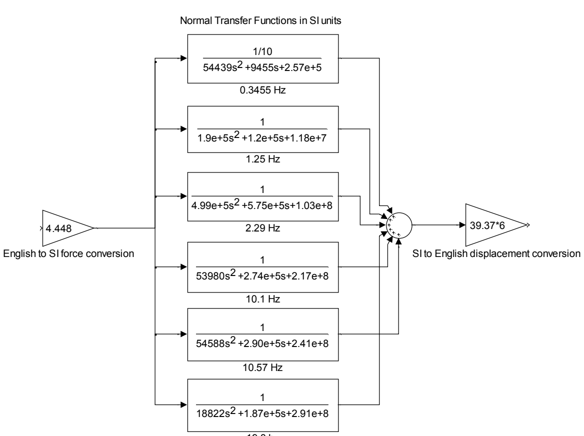

Figure 16. Dominant modes from the normal modes model used in predictor.

Rayleigh damping is used to apply uniform damping throughout the model. The assumption of proportional damping is commonly used in structural applications and facilitates diagonalization of the system of equations. It is also standard in many commercial finite element modal analysis software programs. This normal modes model has been implemented into the model-based control system as a predictive driver. Zamudio indicates the response of the system is dominated by the six most compliant modes in the system. This reduced system, shown in Figure 16, is used as a predictor.

Drilling Tests

Drilling tests were conducted with this normal modes model using the 3-1/4 inch diameter bit shown in the inset of Figure 3 in a sample of Sierra White Granite. A snapshot of the drilling record results obtained at a nominal WOB of approximately 500 lb at 120 RPM is shown in Figure 17. The look and feel of an actual field drilling record is clearly evident and in stark contrast with typical laboratory drilling records. The cyclic nature of the drilling is dominated by the lowest mode of the system. The total force on the system does not exceed the combined static and dynamic force limitation of the servo-hydraulic system, i.e., the system is not force-limited when the bit impacts the rock. The displacement response of the bit is shown in Figure 18 where the FFT magnitude is also shown. The bit response is dominated by the fundamental mode of vibration, despite applying a 1/10 scale factor to this mode. The second mode is slightly apparent in the FFT. The higher modes have significantly greater stiffness resulting in low amplitudes of vibration contributed to the bit response. The higher frequency modes will be reproduced provided their amplitude is consistent with the capabilities of the system. The magnitude of the frequency response function from the normal modes model is shown in Figure 19. It also shows the system is dominated by the more compliant low frequency modes. The similarity between the FFT of Figure 18 and the FRF in Figure 19 attests to the success of the implementation of the advanced drillstring representation using the model-based controller.

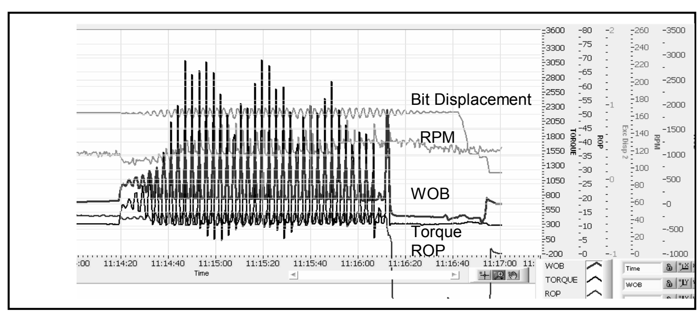

Figure 17. Drilling record from the model-based control simulation using the normal modes predictor.

SUMMARY & CONCLUSIONS

This research has shown that bit/drillstring dynamics can be reproduced in the laboratory using real rock-bit interaction and physical implementations of a drillstring's dynamic response. A mechanical analog has been effective at demonstrating the necessity of addressing integrated bit, drillstring, formation and operating parameter specifications. Simulation using model-based control has been demonstrated to be capable of reproducing realistic drill bit dynamics in the laboratory and has exceeded the capabilities realized by simulations using simple mechanical analogs. Both approaches can be used to address the effect of rock type, bit design, and drillstring properties on the stability of the drilling process.

A favorable response has been obtained using an open loop control system in the model-based controller. Implementation of a feedback control system will allow the bit response to closely track the displacement predicted by drillstring model. Feedback control is more important for producing faster response times characteristic of greater frequencies in the drillstring modes of vibration.

The scope of this paper is limited to the axial mode of the drillstring. This same approach could be extended to all coordinate axes. Future work with a model-based controller should address the interaction of these multiple modes of vibration, the influence of confining pressure on the rock sample, and the nonlinear response of the drillstring. The model-based control approach could also be used to allow the frequency response function of the drillstring to be adjusted to simulate drilling at extended depths.

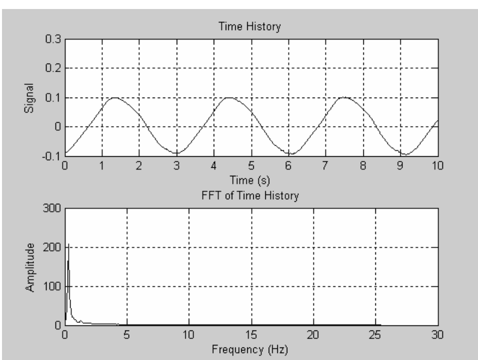

Figure 18. Bit response with the normal modes predictor in the time and frequency domain.

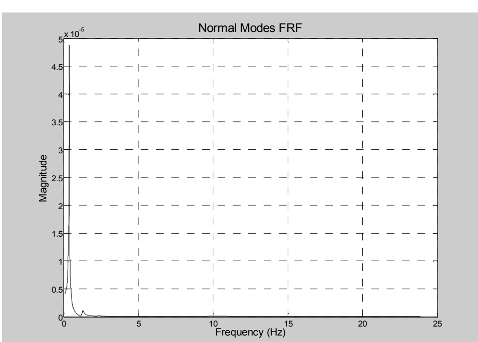

Figure 19. Magnitude of the normal modes model transfer function.

NOMENCLATURE

G(s), Frequency Response Function for the Drillstring [in/lb]
H(s), Transfer Function for the Actuator [in/v]

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