Literature survey on torsional drillstring vibrations

Citation for published version (APA):
Leine, R. I. (1997). *Literature survey on torsional drillstring vibrations*. (DCT rapporten; Vol. 1997.069). Technische Universiteit Eindhoven.

Document status and date:
Published: 01/01/1997

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

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Literature Survey on Torsional Drillstring Vibrations

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Report number: WFW 97.069

Internal Report

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September 1997

Introduction

Drillstring vibrations are an important cause of premature failure of drillstring components and drilling inefficiency. Extensive research on this subject has been conducted for the last four decades. The literature available on the subject can largely be divided in publications focused on axial vibrations, torsional vibrations or lateral vibrations. The current literature survey will give an overview on publications which are related to torsional stick-slip vibrations in drillstrings. Although axial, torsional and lateral vibrations are coupled, mainly publications about torsional vibrations will be studied, as stick-slip in drillstrings is in essence a torsional phenomenon.

Previous literature surveys about drillstring vibrations can be found in Payne [1992], Dykstra [1996] and Van den Steen [1997] about stick-slip control.

Torsional Vibrations

Bailey and Finnie of Shell Development Company [1960] were one of the very first to model drillstring vibration. They gave an analytical treatment of longitudinal and torsional vibrations starting from the wave equation. A surface measurement package was developed and placed beneath the rotary table to measure torque, axial force, rotation and axial displacement while drilling. They examined the contents of the signals and compared predicted natural frequencies to those measured. From this they discovered that for torsional vibrations the boundary conditions were free at the bit (which is a good approximation for pure slipping motion) and fixed at the surface.

Deily et al. [1968] of Esso Research Company reported on using a downhole recording tool to measure downhole forces and motions. The tool could measure axial, torsional and bending forces and moments; axial, lateral and angular accelerations; internal and external pressure. Large Weight On Bit fluctuations were measured. The Weight On Bit even dropped to zero in some cases, which implied that the bit had lifted off the bottom; they termed this *bitbounce*. Weight On Bit and Torque On Bit interactions were identified. Exciting mechanisms such as a 30 Hz signal were attributed to the rows of teeth on tri-cone bits. Negative torques were reported. A strong frequency component at three times the rotary speed was observed.

Cunningham of Hughes Tool Company [1968] analysed additional data from the Esso downhole tool. The author confirmed the 3x rotary speed excitation, reported by Deily et al., and addressed it to the generation of a cammed bottom hole surface (the so called *three lobbed pattern*). If an axial natural frequency corresponds to three times the rotary speed, then small vertical motion of the bit will be amplified due to resonance. Ultimately a cam on the hole will be established, which in turn will feed the vibrations.

Cunningham reported an "angular beating phenomenon" found in the angular acceleration signal. His observation of "The bending traces indicate the bit was rotating rapidly at a maximum of about 92 rpm during part of the time, and was practically still during part of the time" was likely the first observation of the stick-slip phenomenon in drillstrings. The physical mechanism for the "beating phenomenon" or stick-slip was not reported. He also mentioned that 'beats' are more likely to occur at lower rotary speeds than at higher rotary speeds which preluded the current concept of critical rotary speeds for stick-slip vibrations.

Miller and Rollins [1968] reviewed the data of Deily and Cunningham. They showed raw relationships between Torque On Bit and surface rotation speed for different formations. The surface torque seemed to be independent on the surface rotation speed as they only covered 30 - 120 RPM.

Belokobyl'skii and Prokopov [1981]of the Leningrad Polytechnic Institute presented one of the first analytical treatments of stick-slip vibrations in drillstrings. A large part of this treatment was based on earlier analytical results found by research on stick-slip in general. Nevertheless, the authors introduced the subject of friction induced torsional drillstring vibrations.

Besaisow et al. [1985,1986,1990] described the Advanced Drillstring Analysis and Measurement System (ADAMS) which only measures surface data. The surface measurements had a large spectral content , and the authors provided a variety of explanations for the peaks that were observed.

Halsey et al. [1986] of Rogaland Research Inst. presented a method to calculate the torsional resonant frequencies in a drillstring by means of Fourier analysis. The effect of tooljoints was incorporated by a correction factor for the wavenumber. This correction was found to be valid for frequencies below 40 Hz. They compared experimental surface data with the predicted resonant frequencies and found them in good agreement. The torsional resonances were not affected by rotation rate or Weight On Bit. The field data were recorded in a nearly vertical well (Ullrigg, Rogaland).

Aarrestad and Kyllingstad [1986] of Rogaland Research Inst. analysed the coupling between bit torque and axial load at the bit for tri-cone bits drilling a bottomhole with a three lobbed pattern. The authors studied downhole data measured at the Ullrigg test rig with a hardwire MWD tool (which is now named as the Trafor system). Frequency spectra of downhole measurements were often found to contain the 3x rotary speed frequency. The spectra also very often contain higher harmonics of this fundamental "3x" frequency and the authors attribute this to nonlinear coupling between torsional and axial vibrations. Small side lobes near dominate frequencies were reported and explained by modulation theory.

Peltier et al. [1987] proposed a linear relationship between Torque On Bit and Weight On Bit. The authors verified that the torque can be related to bearing wear of the bit.

Dawson, Lin and Spanos [1987] investigated torsional stick-slip oscillations in drillstrings semi-analytically. They assumed a piecewise linear friction curve in the slip phase and applied this to a one degree of freedom model. Comparison with experimental results showed good agreement. The field measurements were obtained from a deep low-angle directional well. The theoretical investigations showed that amplitude increased with rotary speed and the frequency increased slowly with rotary speed. The model also predicted a critical rotary speed above which stick-slip oscillations would not occur. This was also observed in the field. They suggested that the oscillations could be reduced by lowering the static friction coefficient.

Kyllingstad and Halsey [1988] treated the drillstring as a simple torsional pendulum and assumed a signum friction model with static point. This simple one degree of freedom model made it possible to give analytical expressions for stick and slip time. It was indicated that a one degree of freedom model with constant rotation of the rotary table overestimated the Bottom Hole Assembly motion. The model predicts a stick-slip frequency slightly lower than the first torsional natural frequency. Torque control via feedback at the surface was identified as a possible way to eliminate stick-slip.

Halsey, Kyllingstad and Kylling [1988] investigated torque feedback to cure stick-slip motion. A conventional speed controller for the rotary drive is designed to keep the rotary speed as constant as possible, independent of the torque load. The idea behind the torque feedback concept is to allow the rotary table speed to respond to dynamic torque oscillations in such a way that the rotary table absorbs or dampens the vibrations. The aim of the control algorithm of Halsey et al. was to make the mechanical impedance of the rotary drive equal to the drillstring's characteristic impedance as to establish zero reflection. The system incorporated a torque and a velocity sensor mounted on the drillstring. The signals were processed in a computer-based feedback system and used to control the drive's speed. This system was the first controller to avoid stick-slip oscillations in drillstrings. However, the sensor package proved to be vulnerable and expensive.

Close, Owens and Macpherson of Exploration Logging [1988] reported stick-slip vibrations during reaming. The results were measured with downhole measurements system located in a Measurement While Drilling tool (MWD tool). The accelerometers in the MWD tool failed after prolonged operation.

Cook et al. [1989] presented the first real-time downhole Root Mean Square (RMS) measurements of forces, accelerations and fluid pressures. The quantities as RMS values were transmitted to surface using mudpulse telemetry. The authors mentioned increased RMS bending moments as the steerable assembly passed through local dog-legs.

Lin and Wang [1990,1991] investigated stick-slip oscillations in drillstrings numerically and came to conclusions already drawn in papers about stick-slip in general. The amplitude of stick-slip vibration increases as rotary speed increases, but the vibration will vanish when the rotary speed passes through the critical speed.

In 1986 Elf Aquitaine started the DYNAFOR research project with the purpose of improving drilling performance through a better knowledge of dynamic phenomena. A surface measurement device called the "Dynamètre" was developed enabling measurement of tension, torque and accelerations in three directions at the top of the drillstring. Several thousand hours of drilling were recorded on different rigs and with numerous drillstrings.

Clayer, Vandiver and Lee [1990], a joint effort of Elf Aquitaine and M.I.T., studied the effect of surface and downhole boundary conditions on the vibration of drillstrings. The authors investigated DYNAFOR surface measurements of a nearly straight well drilled in 1989-1990. Theoretical transfer functions were compared with measured transfer functions both for axial and for torsional vibrations. The bottom boundary condition in torsion could be approximately modelled as a free end (as Bailey and Finnie experienced). The bottom boundary condition in axial vibration depends on drilling conditions, as well as time and frequency. The surface boundary condition in torsion can be modelled as a simple spring-inertia-dashpot only as a first approximation, because the impedance is effected by the hydraulic power swivel. Surface boundary conditions in axial vibration are well modelled if the mass and spring properties of the drawworks are taken into account.

Brett [1991] studied torsional stick-slip oscillations with PDC bits on a laboratory test drilling machine, on a full scale test rig and theoretically. Friction curves relating Torque On Bit versus angular velocity of the bit were obtained experimentally in the laboratory with a sharp and a dull PDC bit. The obtained friction curves showed a smoothly decreasing torque with increasing speed but the number of data points used was too small especially at low speeds thus no information about the static friction torque was obtained. The experiments did reveal that the Torque On Bit was proportional with the Weight On Bit for all observed bit speeds. The dull bit showed a higher rate of decline in the friction curve as compared to a sharp bit and is thus more prone to stick-slip. Brett attributed this difference to the increasing difficulty in cleaning the bottom of the hole when the bit drills with a crushing mechanism. A sharp bit can clean the hole much better mechanically and drills more by shearing than by a crushing action.

Brett used a smoothed friction curve for the numerical investigations. The model predictions matched quite good with the field measurements conducted in a nearly vertical well in Wyoming. It was pointed out that backward rotation is highly detrimental to a PDC bit. The author noted that in the field stick-slip is reduced by decreasing Weight On Bit and/or increasing rotary speed, but suggested that increased speed can excite other forms of vibration.

Dufeute and Henneuse of Elf Aquitaine [1991] investigated the data of the DYNAFOR project between 1988 and 1990. Stick-slip oscillations were present during 50% of the time and were found to be highly detrimental to bits, drilling tools and drillpipe. Observed tearing off of cutters suggested the existence of backward rotation. An empirical law was established stating that the period of oscillation is 2 seconds per 1000 m of 5" drillpipe. The existence of a critical rotary speed above which stick-slip does not occur and below which it appears was confirmed. The critical rotary speed varies considerably according to the equipment and conditions in the well. As so many parameters come into play, they were unable to calculate this speed. As Weight On Bit increases, thereby increasing stabiliser and contact loads, stick-slip is more likely and severe. Studies of the influence of mud type on stick-slip were inconclusive. Lithology was considered to be the prime factor on the stick-slip phenomenon. During drilling of a highly stratified formation, torsional waves developed when the near-bit stabiliser crossed a zone of more clayey intercalations. The authors verified the possible elimination of stick-slip oscillations using torque feed-back. Lubricant tests were successful in eliminating stick-slip. As the lubricant passed the Bottom Hole Assembly the friction characteristic was changed which eliminated stick-slip vibrations. The average torque diminished with 16%. Stick-slip was prevalent with downhole mudmotors due to the practice of slowly rotating drillstring during these operations. This observation was confirmed numerically by Leine[1996]. Comparison of runs with and without stick-slip in similar conditions led to the conclusion that stick-slip decreases the Rate Of Penetration.

Henneuse [1992] made an overview on the research conducted by Elf Aquitaine from 1960 upto 1992, including the DYNAFOR project. Some new ideas are introduced:

- A stick-slip detection algorithm is mentioned that alarms the operator at various levels (green, orange, red).
- The "audiodrill" is introduced : bit noise on the signals is made audible by an audio amplifier. The ear is thus used as an 'time/frequency analyser' which can identify several dysfunctions of the bit. The audiodrill finds its application in non-stationary signals such as shocks.
- A delay study can be used to locate the origin of an excitation in the drillstring. As axial and torsional propagation in steel are different, there will be a time delay between these signals when received at surface. The time delay is proportional to the depth of the excitation.

Henneuse suggests that the occurrence of stick-slip is closely related with the operational mode of the bit : cutting or abrasion (a suggestion also made by Brett).

Dubinsky, Henneuse and Kirkman [1992] give a historical overview of Russian, European and American research in surface monitoring of downhole vibrations. In Russia and Europe the science evolved as a way to identify lithology changes and for drilling optimisation. The Russians aimed their attention in the 1970s on optimising the performance of turbines. A method was developed to detect stick-slip vibrations while using a turbine by inspecting the auto-spectral density of the surface axial accelerations. In the United states the goal was to reduce drillstring failures. The authors suggest that downhole dysfunctions are always observable at surface.

Dykstra et al. [1994] conducted laboratory and field experiments to investigate the dynamics of the drill bit and drillstring. Simultaneous surface and downhole measurements were made. The tests were performed in an extremely shallow and vertical well (max. 700 ft.) with only drill collars. Surface measurements were found to be inconclusive with respect to downhole behaviour. The published data is quite raw but decreasing Torque On Bit for increasing rotation speed can be easily be observed both for roller cone and PDC bits.

In the late 1980s the Institute Français du Pétrole designed the Trafor system, a research tool to improve knowledge about drilling and how to model it. The Trafor system consists of a downhole measurement sub, called the Télévigile, and a surface measurement device known as the Survigile. The signals of the Télévigile and Survigile are gathered by a computer and synchronised. The Télévigile is connected to the surface equipment through an electric wire. Downhole Weight On Bit, Torque On Bit, accelerations in three directions and bending moments in two directions are measured. Torque, tension and rotary speed are measured at surface. The great merit of the Trafor system is the ability to measure both downhole and surface data at real-time.

Pavone and Desplans [1994] give a description of the Trafor system and some experimental results. The most remarkable result is the relation between Torque On Bit and bit rotary speed. The characteristic is clearly showing a stick phase and lower torques for higher speeds (a negative slope). The measured torque of the Télévigile was corrected with the torque induced by the inertia below the Télévigile and corrected with the torque induced by the wall friction. This corrected measured torque thus yields the Torque On Bit. The authors suggest that the torque decreases when the speed is increased but remains constant when the speed decreases. This relationship between torque and rotary speed would thus involve a hysteresis. A high correlation between hookload and torque lost by friction along the wellbore wall is reported. The Torque On Bit is found to be dependent on the Weight On Bit to the power of 1.1 according to field measurements. The authors proposed PID control and the use of an anti stick-slip tool to prevent stick-slip. This yet not existing anti stick-slip tool should increase the viscous friction downhole.

Shell Research in Rijswijk, The Netherlands, focused their research since 1990 on the improvement of the torque feedback system developed by Halsey et al. at Rogalandforskning Institute. They found that the system of Halsey had two shortcomings:

1. The sensor package for the measurement of torque and rotary speed proved to be vulnerable.
2. The control algorithm, based on zero reflection, was not satisfying.

A system was developed which obtained the information of speed and torque directly from the voltage and current measured at the motor terminals. This system was called the Soft Torque Rotary System (STR-system). Javanmardi and Gaspard [1992] tested the STR-system on off-shore wells. The effect of the STR-system on reducing torque fluctuations and stick-slip conditions of a directional well was significant. Much attention was paid to the proper tuning of the STR-system (Jansen [1993]; Jansen, Van den Steen and Zachariassen [1994]; Jansen and Van den Steen [1995]; Van den Steen [1997]). Jansen [1993] considered the fundamental torsional mode and modelled the drive system. Optimal tuning was obtained by requiring two coinciding poles. The reduction of inertia of the rotary drive was found to improve the performance of the STR-system. The suggestion was made to investigate the effect of the system on tapered drillstrings. A tapered drillstring will have a pronounced second mode beside the fundamental mode.

Sananikone, Kamoshima and White of Sedco-Forex [1992] developed a similar system. The system also used the motor current as a measure of torque but obtained the speed from a rotational accelerometer mounted on the motor shaft. The system features partial cancellation of the inertia of the rotary table, but the control algorithm (based on zero reflection) does not fully take advantage of this. The authors compared motor current feedback with direct torque feedback and found the latter to perform better though more expensive.

Fear and Abbassian [1994] described ho monitoring torsional oscillations can improve drilling performance. They modified mud logging sensors to print continuous surface torque, rotary speed, stand pipe pressure and hook load. Also tests with downhole motors were conducted showing complex behaviour of the drillstring and a possible coupling with fluid and axial oscillations.

Van den Steen [1997] conducted a comprehensive study on the STR-system (and variants) restricted to the hyperstability condition. Safe operation of the system under all possible conditions was a main concern. Hyperstability or passivity of the controller will ensure this. The author gave a detailed model of the drive system and presented a model of the drillstring in the form of transmission matrices. A constant Torque On Bit was assumed in the slip phase. The resulting nonlinear model was thus linear in both stick and slip phase. This allowed fast numerical computation of stick-slip cycles by making use of fundamental solution matrices. It was assumed however that the bit speed would always be zero or positive. The term *marginal stick-slip* was introduced being the limit cycle which is on the verge of instability. A closed analytical solution was found for the period of oscillation of a one degree of freedom system at marginal stick-slip. The author studied different optimal control criteria for the STR system:

- Maximised minimum damping
  This criterion ensures coinciding poles (Jansen [1993]) and gives an optimal damping if the excitation at the bit is white noise. The optimal tuning parameters can be deduced analytically. The optimal tuning parameters for this criterion only depend on the structure and not on the friction downhole.
- Minimum power of the BHA velocity spectrum
  The mean square response of the rotational velocity is tuned to be minimal. This criterion coincides with a criterion used for dynamic vibration dampers mention by Den Hartog [1934] (Leine [1996]). The optimal tuning parameters can be deduced analytically, only depend on the structure and not on the friction downhole.
- Maximum suppression of stick-slip oscillations.
  The threshold value of the rotary table speed is tuned to be minimal. The optimal tuning parameters can only be found numerically and do depend on the friction.

The author also studied higher modes of oscillation and mode reduction. It was concluded that the ratio of BHA inertia relative to the inertia of the rotary table is the prime factor to the attainable damping. A self-tuning STR-system was suggested.

An implementation for a hydraulic drive was implemented by Jansen, Van den Steen and Zachariassen [1994].

Serrarens [1997] developed an H_∞ controller as an alternative for the STR-system. The author concludes that the H_∞ controller performs better than the STR-system. However, the system has a few drawbacks as compared to the STR-system:

- The controller does not satisfy hyperstability.
- No closed analytical solution has not yet been found for the optimal weighting functions (tuning parameters).
- The physical mechanism of the STR-system is well understood while that of the H_∞ controller is difficult to interpret.

The author suggests to investigate the influence of building a simple dynamic attractor to phase out the oscillations instead of the STR-system.

Conclusion

A large amount of research on torsional drillstring vibrations has been conducted in the last few decades. However, there seems to be a time lag between developments in tribology and developments in drillstring dynamics. Stick-slip vibrations of a block-on-belt mechanism were identified experimentally and theoretically by Bowden and Leben in 1939. The stick-slip vibrations were addressed to a drop in friction as velocity increased and the general mechanism was thus well understood.

Cunningham actually experienced stick-slip vibrations in drillstrings in 1968 but was unable to see the relationship with the results found by tribologists and named it an 'angular beating phenomenon'. The insight that the vibrations were friction induced did not came before the 1980's around the time that Belokobyl'skii and Prokopov published their theoretical paper in 1981.

A number field measurement were conducted but all suffered from shortcomings:

1. Most of the field measurements only contain surface data. Stick-slip can indeed be detected from surface, at least in a straight well, but detailed information about the mechanism downhole can not be obtained. This partly explains why it took so long to discover stick-slip in drillstrings.
2. Most of the measurement devices, especially the downhole devices, were prone to fail. The failing of one of the transducers made the whole test often unusable. Calibration proved to be difficult and the experiments were often regarded as unreliable.
3. All of the downhole measurements were taken in nearly vertical wells. The authors concluded that the vibrations downhole can be observed at surface. Calculated natural frequencies were in good agreement with the experimental results. However, directional drilling is common in today's drilling practice. It is not evident that the pendulum mode is still dominant in a deviated well. A pronounced higher mode would require different tuning for the STR-system.

The above shortcomings make the useful amount of data very limited.

While tribologists studied the frictional characteristic of various materials extensively, which is the cause of stick-slip, this approach was totally absent in drilling research. Most researchers published a guess of what they thought the frictional characteristic of a bit would look like and used it in simulations. Hardly any attempt was made to measure the relationship between torque and rotation speed of bit (or Bottom Hole Assembly). Only Pavone did publish one friction curve of the bit but used highly filtered data which can cause the observed hysteresis phenomenon. Really no attempt was made to discover which bit types are prone to stick-slip when drilled on different rock types and how to alter the bit to cure stick-slip motion. It is the opinion of the author that progress begins with getting a clear view of the obstacles.

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