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Introduction

1.1 Motivation of the Thesis

The drilling of an oil well is responsible for most of the costs of obtaining oil from deep reservoirs [30]. The overall process costs up to a million dollars a day, and it is also a very sensitive operation in the matter of risks. Despite the use of modern techniques to discover what to expect during the drilling, it is not unusual to experiment some non-predicted situations that can end up in a major accident. There are still many open challenges involving the modeling of the complex dynamics of a drill string.

In a general way, the drilling system (fig. 1.1) consists of a motor, usually electric, but some older are hydraulic, located at the top end position, which imposes rotational motion in the drilling system. The torsional movement can be transmitted to the drill string through two different sources, the Kelly drive or the top drive. Kelly uses a powered rotary table with a polygonal hole, where an equal polygonal section shaft passes. This system is being abandoned over the top drive, as this last can manage larger section drill stings. A rotary table type rig can only drill 30-foot sections of drill pipe. The top drive can drill 60-90-foot pipes (double and triple drill pipe), depending on the drilling rig size. Handling longer sections of drill pipe enables a drilling rig to make greater daily progress, thus requiring fewer connections of drill pipes. Another advantage of top drive systems is time efficiency.

The bottom end position comprises the Bottom Hole Assembly (BHA), a section of the drill string that uses sections of thick walled pipes (heavy weight drill pipes) that are heavier than the common drill pipes, and the drill bit. Between these ends the top-down torque transmitting element called drill string (connection of a series of 30 foot pipes) is situated. At the top, the top drive rotates with a constant angular speed (Surface RPM - SRPM). The normal force that pressures the bit to the rock is provided by the weight of the column, mainly by the heavy weight drill pipes. This normal force, known as weight on bit (WOB) can be controlled in given boundaries, by the system that supports the top drive on the rig. This combination of WOB and SRPM provides the needed Torque On Bit (TOB) to induce rock failures (crushing, shearing or grinding). These failures depend on the drill bit used in the rotary

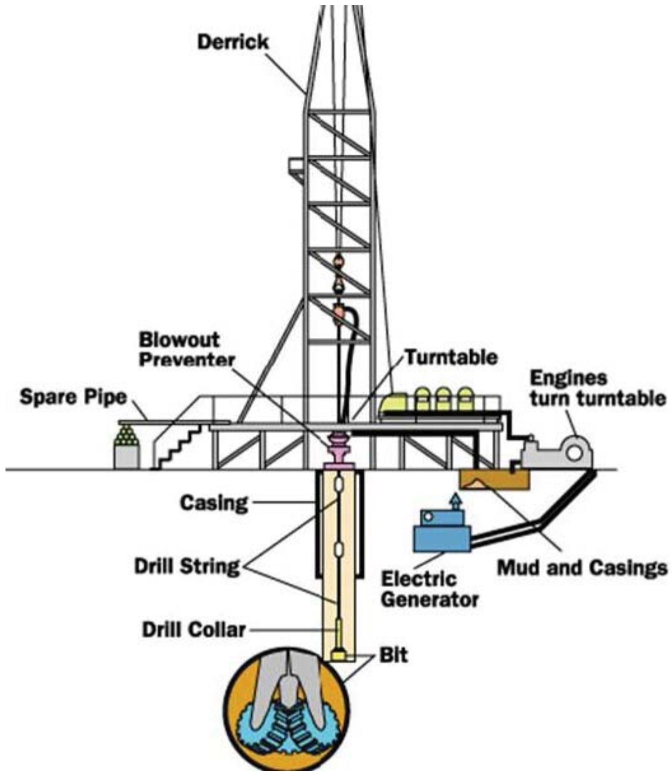

Figure 1.1: Drilling rig - *Image from Fox Oil Drilling Company*

drilling process.

Drill bits are the main source of friction on the drilling setup, therefore they have a big influence on torsional vibrations of the drill string. Figure 1.2 shows the two more common bits, the tricone and the polycrystalline diamond compact (PDC). The PDC cuts the rock by shearing, therefore it imposes bigger torque on the drill pipes.

Many mechanical phenomena occur at the same time, and very little information is actually measured on the drill string and drill bit during the process. Therefore, if one pretends to optimize drilling it is mandatory to consider non modeled phenomena.

In the last years, modeling and simulation of nonlinear dynamics of a drill-string including uncertainty modeling has been intensively studied [33, 34, 37, 33, 38, 36].

Due to the recent low oil prices and more strict ambiental issues, there is a constant need to optimize the drilling process by reducing the failures, optimizing the penetration rate and the lifetime of the components, and reducing incidents.

Although being a very complex engineering problem and involving high risks and a lot of money, drilling is still today a process very much guided by

Figure 1.2: Drill bit types - *Image from Petroleum online*

trial and error, a process that relies a lot on the expertise and knowledge of the drilling operator that has the responsibility to conduct the process relying on very few and imprecise information about the rocks he is drilling, the coordinates of the well and vibrations and loads on the drill assembly. As it is known in engineering, putting a big part of the responsibility to control a complex process in human hands, frequently can lead to errors, so it is desirable to research how to make this process more safe and efficient by understanding its characteristics.

The subject of drillstring vibration is an ongoing challenge for drillers in oil fields and researchers in this area. Drillstring vibrations are assumed as the main cause of drillstring components failure, bit failure, deterioration of the well trajectory, excessive bit and stabilizer wear, lower penetration rate, reduced accuracy of Measurement While Drilling (MWD) tools and decreased efficiency [9].

Unwanted vibrations of the drillstring dissipate part of the energy that is intended to be delivered to the bit, and, among other technical problems, are said to increase the drilling cost by 10% [21], which in a competitive business as oil prospection, can be decisive to the economical viability of a well.

The vibration of the drillstring can be divided into three primary modes: axial, lateral (also referred to as transverse, or bending), and torsional modes, where each one of these being responsible for different failures on the drilling system.

The drillstring is a low torsional stiffness structure, which is easily excited during operation. These torsional oscillations mostly have its origin in the contact between bit and rock and are transmitted through the drillstring up to the surface. Torsional vibrations occur more often in hard formations [5] and are excited by the friction force between the bit and rock or even between the drillstring itself and the bore hole.

Torsional vibration causes an irregular, non constant bit rotation speed, which causes, among other problems, fatigue failure of the drill collar connections, damage to the bit and slows the overall drilling process. Generally, torsional vibrations can be detected by the drilling operator at the surface, by fluctuations in the torque applied by the top drive to maintain a constant rotation speed, i.e. the operator sets a desired RPM on the motor controller and monitors the measured reactive torque applied on the motor [48].

In recent years, the development of Measurement While Drilling (MWD) devices - systems that are positioned on the BHA and send almost real time informations to the surface - provided drilling operators with a more complete set of information about what is happening down hole, such as, inclination, trajectory, vibration levels, etc.

The most severe case of torsional vibration of the drillstring is the Stick-slip. It is characterized by the presence of periodic fluctuations in the bit rotational speed, going from zero RPM to more than twice the surface rotary speed [14]. In some specific cases the BHA can even rotate in the other direction during some time.

Control is probably one of the areas of engineering that has shown the biggest advancements over the last decades. Many of its base theorems and assumptions are based on well known mathematical theorems, but the recent increase in the power of computers and its widespread use allows engineers to implement very complex algorithms in control hardwares, as well as simulate with high precision the behavior of a given system with a given control law.

1.2 Objectives

This thesis aims to study the torsional dynamics of a reduced scale drillstring model and to propose control laws to avoid stick-slip behavior in this system. In order to understand the stick-slip behavior and test the control laws in a simple system, the analysis begins with a simple mass-spring-damper model with induced stick-slip.

After this investigation, the stick-slip of a reduced scale drillstring is analyzed and then some control strategies for this model are proposed, and results of simulations are presented.

The focus of the control is to apply the L_1 adaptive controller to eliminate stick-slip and reduce torsional vibrations. This work begins by applying this controller on a simple translational mass-spring-damper system, analyzing the results, and afterwards applying the L_1 adaptive controller to the reduced scale drillstring model.

In order to further analyze the stick-slip in a reduced scale drillstring, an experimental setup was developed and the results of tests are presented. It is also shown a method that eliminates the stick-slip behavior in the experimental setup by applying a torque directly on the bit.

1.3 Literature review

A variety of models have been used to study torsional vibration of drillstrings. The most prevalent model, which has been widely used for many years, implements a torsional pendulum. In this model, the BHA is assumed as a rigid body and the pipes are assumed inertialess compared to the rotary table and the collars [26] [45]. The effects of dry friction on the torsional vibrations of the drillstring were studied in [26], among a series of other publications.

Navarro-Lopez and Cortes [29] developed a lumped parameter model to investigate the influence of sliding motion on self-excited stick-slip oscillations and bit sticking phenomena. Hopf bifurcations were used to investigate the range of rotary speeds where undesired torsional vibrations of the drillstring happen.

In a recent study, Arjun Patiland [32] developed an uncoupled 2DOF torsional vibration model of the drillstring. A parametric study is conducted on the effect of rotary speed, WOB and drillstring stiffness on the stick-slip motion of the drillstring. It also considers the effect of rock strength on the rate of penetration and verified that the results are in line with the field trials.

Several researches focused on the problem of analyzing the coupled vibration modes that included torsional vibrations. Among these, we can highlight [41] where a nonlinear finite element analysis was presented to analyze axial-torsional coupled vibrations of the drillstring. Energy variational methods were used to generate the equations, assuming both linear and non linear strain energy, as well as considering the effect of structural damping.

Recent master dissertations from PUC-Rio dynamics lab have addressed the theme of stick-slip phenomenon and investigated some of its causes, proposing the use of reduced mathematical models and presenting numerical and experimental results with the use of the same test setup that was used in this thesis. Although not focused on the control of the modeled drill string, these works were of great use for the dynamics and experimental development of the drill string test bench on PUC-Rio.

Santos dissertation [42] has a very complete analysis of the friction coefficients of the test bench braking system parts. In his dissertation several experimental investigations are made to properly quantify the friction models and coefficients of the PUC-Rio dynamics lab horizontal drilling test bench.

Andrade [3] presents a numerical and experimental analysis of the torsional vibrations of drillstring dynamics, the dissertation uses a nonlinear friction model aiming to induce stick-slip, where the friction model is based on dry friction imposed by a brake device on the test bench. The nonlinear behavior of the experimental apparatus is analyzed and the numerical model is validated comparing experimental and numerical bifurcation diagrams.

Ritto et. al. [35] analyze the dynamics of a horizontal drill-string modeling an uncertainty on the frictional force and how uncertainties on the frictional forces propagate through the system. A stochastic field with exponential correlation function is used to model the frictional coefficient.

Ritto et. al. [39] show a computational model, proposed to model uncertainties in the bit-rock interaction model. To do so, a nonparametric probabilistic approach is used, witch is developed to consider model uncertainties in the bit-rock nonlinear interaction model. The nonlinear Timoshenko beam theory is used and the nonlinear dynamical equations are discretized by means of the finite element method.

Lima and Sampaio [24] study the dynamics of a mechanical system composed of a mass-spring oscillator over a moving belt. The contact between the mass and the belt is modeled with dry friction, and the movement of the belt is modeled as stochastic with velocity modeled as a Poisson process. The objective is to characterize using Monte Carlo simulations, the response of the dry-friction oscillator composed by a sequence of stick and slip-modes.

Also, Lima and Sampaio [25] study the same mechanical mass-spring oscillator over a moving belt to determine how the statistics and histograms vary with the system parameters, i.e., to make a parametric analysis of the statistical model of the stick-slip process. In the stochastic parametric analysis, the influence of two system parameters were analyzed, the base motion and the friction coefficient. The stick phase of the movement is analyzed in its duration in relation to the variation of the model parameters, such as the friction coefficient.

Under some recent researches aboard the theme of control strategies for flexible shaft driven systems, the one from Svejda [28] demonstrates the output tracking of the linear single-input and single-output (SISO) controlled system represented by the DC motor with a flexible shaft. The main aim of the output tracking of the DC motor with a flexible shaft described in this paper is to ensure that the angular position of the flexible shaft will follow the desired angular position. The proposed output tracking controller is based on the transformation of the controlled system to the so-called normal form. This transformation is the application of the partial feedback linearization of the nonlinear control systems. A state-space model is proposed for the problem and a simulink model is created for the simulations but it is shown that in the presence of the uncertainties actuating on the flexible shaft the proposed method fails as is expected for a PI type controller.

Al-Hiddabi et al. [2] stated that linear controllers are not effective in suppressing the vibrations of the drillstring and suggested a nonlinear controller for damping the lateral and torsional vibrations of the drillstring. Results show that the controller was more effective in damping torsional vibrations than lateral vibrations.

Yigit and Christoforou [49] developed a linear quadratic regulator (LQR) controller based on a linearized model to control stick-slip vibrations. Use of the controller reduced the occurrence of stick-slip, while exciting some lateral vibration modes for certain operational parameters.

Bayliss et al. [10] analyse a basic pole placement controller design for a Single Input Single Output (SISO) linear model of a drilling system, but recursively evaluated based on an online Recursive Least Squares (RLS) identification of the open-loop plant parameters. It presents a discussion on system architecture implications, and the simulation results with and without adaptive stick/slip mitigation method. The presented method on this paper relies on accurate measurements of the speed on Bit.

Rudat et al. [40] present an innovative model based stick-slip control system using a lumped parameters model with parameters identified from real world applications trough Newton Gauss method and extended Kalman filter. The key idea of this paper is to run simulations on an embedded system down hole and transmit the updated model parameters in a lower bitrate trough mud pulses, an established technology. It shows that lumped masses model can reproduce nonlinar dynamics of drilling and shows, with experiments done in field tests, the effectiveness of the proposed approach.

On the area of adaptive control, most of the research focuses on aircraft stabilization and guidance, and robotic manipulators. Some of the topics where adaptive control was used on drilling problems are, managed pressure drilling (MPD) and trajectory control problems. Sun et al. [44] have an implementation of an adaptive L_1 controller to control the trajectory of a drilling considering downhole directional drilling systems in the presence of unexpected variations in steering force, input delays, measurement noise and measurement delays, where L_1 control theory shows a good advantage over more common theories.

Mahdianfar [27] presents a modification to L_1 adaptive control that allows for disturbances entering at the output and application of this control strategy to Managed Pressure Drilling with harmonic disturbances representing the heave motion of a floating drilling rig. In this paper a control system design approach is proposed and applied for disturbance attenuation and set-point regulation in the so-called heave problem in oil well drilling. Furthermore it is tested in a medium size experimental test facility. The results demonstrate that the proposed regulator efficiently regulates the down-hole pressure to the desired set-point, with significant attenuation of periodic disturbances. The control system methodology is a modification to L_1 adaptive control that allows for disturbances entering at the plant output.

In the area of L_1 controller filter optimization, the most important work is Hamidreza et al. [20]. This paper proposes a systematic analysis and synthesis method for optimal design of filter for L_1 adaptive output feedback controllers. The key challenge in establishing a satisfactory trade-off scheme between performance and robustness in L_1 adaptive control architecture is the non-convex nature of the underlying optimization problem for filter design.

1.4 Organization of the Thesis

The Thesis is organized as follows. In Chapter 2, the mathematical formulations of the problem are presented. Models used in this thesis are described as well as the friction laws used to characterize the contact between moving bodies. Subsection 2.2 introduces the stick-slip phenomenon and shows in 2.2.1 a brief simulation of a simple mass-spring-damper system with stick-slip to exemplify the stick-slip on a simple system. Following, section 2.3 presents the stick-slip in a torsional slender system.

Chapter 3 initially presents an overview of what the control laws are intended to do, then a brief explanation of the PID control. Section 3.2 begins with a bibliographic review of adaptive control, presenting its development, the main articles that use L_1 adaptive control, a discussion about the articles that criticizes this new adaptive controller and if these critics are applied to the problems analyzed in this thesis. Section 3.3 presents the formulation of the MRAC control, this architecture is presented in a way to show the differences between it and the L_1 control, therefore, no simulations or deep discussions are made about MRAC in this thesis.

Sections 3.4 and 3.5 introduce the structure and formulations of the L_1 controller, followed by the results of simulations performed with this control applied to two problems. The first is a cart-sping-damper system over a moving belt that is presented to test the implementation of L_1 control and compare it with problems from literature. The second one is a torsional slender system that simulates the simplified torsional dynamics of a drillstring. In the end, the use of a L_1 adaptive controller together with a PID is analyzed as well as a method to optimize the design of the controller.

Chapter 4 describes the experimental setup of the torsional slender system, the characterization of its mechanical properties, and a qualitative comparison between two types of sensors used to measure rotational speed.

Section 4.3 presents a strategy to reduce stick-slip vibrations by using a second motor on the torsional slender system. Results from simulations and experiments are presented for this method.

Section 4.4 shows an experimental analysis of how the rotational speed of the torsional slender system can affect the characteristics of the stick-slip.

Finally, in Chapter 5, the results are summarized and compared. Chapter 6 proposes future works following the themes of this thesis.

Appendix A presents the Simulink block diagram of the L_1 adaptive controller used in this thesis.