Preface

Vibrations in mechanical systems are oscillations occurring without being intentionally provoked. They often have detrimental effects on the system performance and may cause premature wear of the system components, underperforming processes, and could even involve security problems, such is the case in aircraft wings; which in the worst case scenario, excessive vibration causes the aircraft to crash.

In oilwell drillstring systems, vibrations constitute an important source of economic losses; drill bit wear, pipes disconnection, borehole disruption and prolonged drilling time, are only some examples of consequences associated with drilling vibrations.

Extensive research effort on the modeling and control of drilling systems has been conducted in the last century. Before the sixties, investigations were focused on material strength of the drillstring components, but the trends have since changed to emphasize on its dynamic behavior [136]. In 1960, Bailey and Finnie of *Shell Development Company* conducted the first analytical and experimental study on torsional and axial drilling vibrations [20].

Since then, numerous approaches for modeling and control have been proposed. The most popular control techniques are listed below:

- *Steering torque feedback system* [127]. The underlying idea of the torque feedback method is to adjust the velocity provided by the rotary table according to torque variations; hence, propagating waves are dampened at the top extremity instead of being reflected back to the drillstring. The major shortcoming of this strategy is that it requires an accurate measurement of the torque, which, in practice, can be difficult to obtain.
- *Soft Torque Rotary System* (*STRS*) [138]. This method is an improved version of the feedback torque technique. It avoids the task of measuring the drill string torque by computing it through the motor current. A proper tuning of the controller allows reducing drillstring vibrations.

- *Proportional-Integral-Derivative* (*PID*)*-control* [225]. This is a simple strategy to avoid the stick-slip phenomenon. PID controller gains are obtained through an appropriate stability analysis. A drawback of this technique is that the drillstring vibrations are not sufficiently damped to guarantee an optimal drilling performance.
- $\mathscr{H}_\infty$*-controller* [265]. Results obtained with experimental prototypes have shown that torsional drilling oscillations are reduced by means of an $\mathscr{H}_\infty$ control law which is linear, time-invariant and has robust qualities. However, in order to get a proper control performance, a very accurate model is required. Another disadvantage of this method is that saturation constraints are not well-handled.
- *Active vibration damper* [137]. The basic idea of this method consists in increasing the viscous damping at the bottom end to avoid drillstring vibrations. The damping coefficient is modified via a magnetorheological fluid which allows manipulating the viscous properties of the drilling mud. This strategy allows attenuating the stick-slip vibrations, however an optimal drilling operation requires additional control accions.
- *Sliding mode control* [212]. This control strategy, introduced in [209] and discussed and modified in [212], is based on the bifurcation analysis of a lumped parameter model describing the torsional drilling dynamics developed in [210]. The stick-slip phenomenon can be mathematically seen as a sliding motion, which occurs when the bit velocity is zero. The existence of this sliding motion depends on the weight on the bit and the torque applied by the surface motor. Such a regime is the main cause of bit sticking problems. The sliding mode control consists in introducing another discontinuity surface and forcing the system to evolve along it. On the new surface, the bit speed will follow the top-rotary-system speed after reasonable time, avoiding the bit sticking phenomena. This strategy does not represent an automatic controller, but it should be understood as an off-line safe parameters selection method which helps the driller operators avoiding bit sticking problems.
- *D-OSKIL* [50]. D-OSKIL is a short word for drilling oscillation killer. This method uses the weight on bit as an additional control variable. The control proposal is based on the fact that a large enough weight on bit is required to guarantee a satisfactory rate of penetration, and if it reaches higher values, drilling vibrations may arise. An optimal trade-off between the weight on bit and the rate of penetration has to be found. Experimental implementation of such a mechanism, in a laboratory testbed, is reported in [188]. One disadvantage of this method is that its implementation may require the repetitive addition and removal of drill collar sections to properly adjust the control law, which may result infeasible and could induce axial vibrations.

Despite the development of numerous methods for eliminating drilling vibrations, nowadays such phenomena still greatly affects perforation processes. This is mainly due to the lack of proper understanding of the system's dynamics; in fact, most of the proposed techniques are based on simplified lumped parameter models that disregard the distributed nature of the system, and only consider the torsional drilling behavior.

This monograph compiles research findings and approaches on the modeling and control of vertical rotary oilwell drilling systems. The problem of suppressing drillstring vibrations is addressed within the control theory framework using the wave equation model to describe small amplitude vibrations of the rod. Diverse techniques based on the system stability are proposed and evaluated through numerical analyses. Even though this volume does not presents experimental results, computational analyses are carried out considering parameters that reflect typical operating conditions of a real oil platform. It should be stressed that the description of the actual behavior of the system in all its practical phases of operation is a complex task which can hardly be carried out by models restricted to vibrations of small amplitude motions. Nevertheless, the models presented here give us a general idea of the phenomena occurring during the drilling process and allow us to taking action into this matter.

The aim of this book is threefold. First, the modeling problem is addressed; to fully understand the underlying phenomena giving rise to drilling vibrations, a reliable mathematical model must be conceived. To this end, some theoretical background on the friction laws derived from tribological studies are reviewed. Furthermore, in order to comprehensively characterize the system's dynamics, an infinite-dimensional model, expressed by a set of partial differential equations coupled to nonlinear boundary conditions, which describes the coupled axial and torsional drillstring trajectories is considered. For practical purposes, the proposed model is transformed through the d'Alembert method into a pair of neutral-type time-delay equations. Second, a deeper analysis of the drilling system is provided through a time-delay approach which allows analyzing its stability properties and determining its qualitative dynamic response. Third, the vibration control problem is tackled; several classical control approaches are revisited and some novel techniques based on the dynamic behavior analysis of the system are proposed. The performance of the control proposals is highlighted through simulations of the system which show an effective elimination of coupled drilling vibrations.

This present volume is self-contained and provides operational guidelines and control solutions to deal with drilling vibrations. Since the modeling and control techniques presented here can be generalized to treat diverse engineering problems, it constitutes a useful resource for researchers and specialists working in both control engineering and petroleum engineering area. Furthermore, this monograph can be considered as a complementary tool for teaching the fundamentals of dynamic systems; concepts like modeling, transformation of hyperbolic PDE to delay systems, friction forces between contact surfaces, bifurcation analysis, stability theory, among others are explained in detail and can be easily understood due to the practical application under study.

How to Read the Book?

Three parts compose this contribution.

Part I Modeling

This part provides a summary of the main classical modeling strategies to reproduce the drillstring behavior. Lumped parameter models which have been used to describe torsional and axial drilling dynamics are reviewed. Distributed parameter models allowing a more reliable system representation are next presented. Propagating waves arising from drilling vibrations can be modeled by the standard wave equation; an appropriate choice of boundary conditions allows approximating the phenomena observed at both extremities of the drillstring. The complexity of this modeling strategy is overcome through a direct transformation based on the d'Alembert method which allows deriving a more handleable system representation: a neutral-type time-delay equation.

Since the frictional torque arising from the bit-rock interaction is a crucial aspect of the system, the modeling part of the book includes one chapter entirely devoted to the mathematical description of the friction forces leading to harmful vibrations. Classical friction laws derived from tribological research, including the stiction and the Coulomb, Stribeck, Karnopp, Armstrong, Dahl and LuGre friction models, are briefly discussed.

The first part of the book also presents a set of distributed parameter equations which comprehensively models a vertical oilwell drilling system. The upper extremity modeling includes a description of the actuators' dynamics. The bottom extremity description considers a bit-rock interface model which allows taking into consideration the drilling surface characteristics and the bit geometry.

Part II Analysis

This part of the book provides some basic theoretical tools for analyzing the drilling system dynamics described by time-delay equations of neutral-type. It is worthy of mention that time-delay equations, also known as Delay Differential Equations (DDE), belong to the class of Functional Differential Equations (FDE) which are infinite-dimensional, as opposed to Ordinary Differential Equations (ODE). Time-delay systems are classified into three distinct types: when the rate of change of the state depends on the present and past values of the system state, the model is said to be of *retarded-type*; when the rate of change of the state depends not only on the present and past values of the system state but also on the earlier value of the state rate change, the corresponding equation is of *neutral-type*; when the rate of change of state is determined by future values of the state, the model of *advanced-type*, this last one is rarely encountered in practical applications. This part of the book present an overview on the most important concepts of the general theory of neutral delay differential equations such as the existence and uniqueness of solutions, spectral properties and stability concepts both in frequency-domain and time-domain analysis framework.

A bifurcation analysis of the drilling system is also provided in the second part of the book. By using some tools of the center manifold and normal forms theory, a simplified description of the system is obtained. The reduced model, obtained through spectral projections, allows characterizing the qualitative dynamic response of the system.

Part III Control

Several methodologies are proposed to tackle coupled axial-torsional drilling vibrations; the stick-slip and bit-bounce phenomena are effectively suppressed via stabilizing controllers.

The third part of the book presents a detailed description of the different types of drilling vibrations; detection guidelines, detrimental consequences and empirical control solutions are discussed. Through drilling system simulations, the main practical strategies to suppress the stick-slip phenomenon are evaluated.

Furthermore, a summary of important industrial aspects of the drilling process are presented. These include a review of the different devices absorbing energy to reduce vibrations as well as the different methods used for acquiring, monitoring and transmitting data from the downhole to the surface, and the innovative automated systems that improve the perforation process.

More sophisticated control techniques involving feedback actions are discussed. Low order control schemes to reduce coupled torsional-axial drilling behavior are developed; a pair of delayed proportional and delayed PID feedback controllers are shown to be able to reduce drillstring vibrations.

A different control strategy is designed by exploiting the differential flatness property of the drilling system. This property refers to the ability of a system to be exactly linearized via endogenous feedback. The main attribute of flat systems is that the state and input variables can be directly expressed without integrating any differential equation, in terms of one particular set of variables and a finite number of its derivatives, which helps to tackle, in a simple way, trajectory tracking problems. The design of a pair of nonlinear controllers aimed at steering the drill string trajectories to prescribed paths gives rise to the suppression of coupled drilling vibrations.

Several feedback controllers based on Lyapunov techniques are also presented; asymptotic, exponential and practical stability of the drilling system is achieved. The obtained stability conditions are stated in terms of Linear and Bilinear Matrix Inequalities (LMI, BMI).

The book ends with a comparative/contrastive study that highlights the benefits and vulnerabilities of the different control methods presented here.

It is worthy of mention that the three parts of the book are independent each-other as much as possible. Nevertheless, certain results are required for a proper understanding of the theoretical developments.

Each chapter ends with a section named *Notes and References* which highlights particular aspects of the developments and also includes conclusions, comments and additional reference literature.

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