2
Literature review

Oil exploration challenges have motivated several works lately. It has been very difficult to overcome field troubles in all domains of the process. The drilling process has not changed substantially over the years and still is a source of many papers and thesis.

Aiming the best efficiency of this process, researchers spend time on this subject to meet the needs of the industry. Part of them propose solutions in order to avoid and/or mitigate these problems. The other part is interested in understanding the phenomena involved. Also, there exist numerical/theoretical and experimental works. Surely, both have great contributions to the academic and industrial environments to optimize process, save time and money.

Herein this chapter presents some relevant works that approach and illustrate the drilling problems, some solutions and conclusions are presented. These works had contributed to guide this thesis in its development.

2.1
Modeling of drilling system dynamics

The modeling of the system, by itself, is a complicated part of the process to understand (or even try to) the phenomena. This modeling should not be too complex to the point of being unsolvable, nor too simple so that the phenomena involved loses its representation. Many researchers had documented their contributions by modeling and analyzing drilling systems, theoretically and/or experimentally.

In 2007, Sampaio *et al.* [45] presented a study of coupled axial-torsional vibrations taking into account geometric nonlinearities in order to show its influence on the system response. They modeled a vertical slender beam under axial and torsional motions by finite element method with 24 elements using linear shape functions for both motion directions. At the lower end, it is applied a time-invariant reaction in axial direction and the resistive torque is modeled by smooth approximation of Coulomb friction law. At the upper end, it is imposed a prescribed movement - constant rotary speed. The authors illustrated that torsional vibration amplitudes are greater when the system is

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coupled. Also, due to this coupling, torsional displacements induce an increase of axial vibration amplitudes.

Kreuzer *et al.* [46], in 2009, described a model order reduction of a drilling system of 2000 m. The high-dimension model consists of 51 bodies, one body to model the rotary table, another one to model the Bottom-Hole Assembly (BHA) comprising the drill-collars and the drill-bit. The string is modeled by the 49 bodies, and it is considered only rotational motion. The authors reduced the model by Karhunen-Loève transformation and Galerkin projection using angular velocity data of all 51 bodies. The equations of motion are projected on the first two characteristic functions. They performed a comparison between original and reduced model using the kinetic energy between these models. An interesting point is that the initial conditions of velocity do not seem the same. Afterward, the authors described a linear stability analysis around the desired angular velocity of 10 rad/s for both original and reduced model. In this analysis, the moment of inertia is varied from 25 kgm^2 up to 1000 kgm^2 for both models. A new comparison between the poles diagrams of each model is performed. The conclusion is that both numerical models possess similar behaviors, thus, the reduced model is validated and may describe a drilling system.

In order to mitigate torsional vibration, Vigué *et al.* (2009) [47] modeled a 2-DOF drill-string experimental set-up described by Mihajlović [43, 44, 48] with a Nonlinear Energy Sink (NES). The authors aimed to change stability equilibria and limit cycle orbits by introducing an added nonlinear system: linear damper and cubic stiffness. Therewith, they varied the parameter sets (3 sets) and analyzed the bifurcation diagrams, numerically. The results presented a changing of Hopf bifurcation points, which increases the equilibrium solution range, and decrease of the amplitudes of the remaining limit cycle orbits. Also, the basin of attraction analysis showed that stable limit cycle orbits may still coexist with stable equilibrium points at a given input voltage.

In 2010, Franca [49] presented the modeling of a three cone roller bit based on experimental results. The author provided a relation between the weight-on-bit,torque-on-bit, rate of penetration and angular velocity in order to investigate the drilling response of the bit. He described the torque in terms of cutting and friction, and the weight in terms of cutting, friction and indentation of the tricone bit. The model is based on energy balance of, at least, one revolution of the bit. Subsequently, Franca presented experimental data from a test bench that provides a rate of penetration from $0.01\,mm/s$ to $100\,mm/s$. At the lower part, the set-up presents a drive mechanism that rotates the rock samples at a controlled angular velocity. The system is cleaned by a dust

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collector and compressed air. The experimental results were in agreement with model results showing that the drilling response of the roller-cone bits can be depicted by the proposed drill-bit model.

Stability analysis in drilling system is not very applied. This is because the friction model used to represent the resistive torque acting on the drill-bit is not so easy to describe analytically. Rudat *et al.* [50] (2011) performed a stability analysis observing the energies provided by the non-conservative efforts - torque on bit and damping. In fact, the authors proposed a model-based stick-slip control system. They have used a torsional pendulum of one degree of freedom with a prescribed angular velocity. The authors used a data set containing 150 seconds of the 200 Hz downhole measured angular velocity of a nearly vertical hole with a PDC bit. The Extended Kalman Filter in order to online parameter identification: natural angular frequency, damping ratio and mass moment of inertia. Also, the friction parameters presented variation over time, and so it is necessary that they be estimated online. Although the quite simple model, the simulated results were in accordance with field data measurements. The authors also illustrated the variation of the stability map for two given times of the process.

Saldivar *et al.* [28], 2011, described a drilling system by a torsional beam. The viscous and structural damping was taken into account. The BHA was modeled as a lumped inertia at the bottom end. Also, the system was subjected to a resistive torque which includes a viscous damping term, and a dry friction term. The authors proposed a solution using D'Alembert method and described a neutral type expression to perform a formal stability analysis. Afterwards, they described three strategies to reduce stick-slip by surface-controlled parameters. These strategies are manipulation of the weight on bit, manipulation of the damping at the bottom end, and application of a control law that ensures the dissipation of the system. For each of the strategies, they illustrated simulation results in order to prove its efficiency.

In 2012, Kreuzer *et al.* [34] approached the torsional vibration problems by decomposition method. The goal of this paper is to control torsional vibration by traveling waves. They do not use the top drive dynamics and the desired angular velocity is provided via simple proportional control law. The nonlinear friction torque is given by a piecewise function with several empirical input parameters. The model is governed by the wave equation and discretized in 200 degrees of freedom. They divided the analysis in different scenarios: first, without friction torque at the string and with friction at the string node 175 (closer to the drill-bit). The D'Alembert solution is used to approach the problem. They inserted the propagation time between two

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specific points into the solution and show that the angular velocities may be determined by time delay terms of measurements points. The traveling wave in direction of the actuator is absorbed by the actuator, extracting energy from the system and avoiding reflection at the top end. The control strategy lead to a good mitigation in the results of the numerical model across a specific frequency range for both friction scenarios. The experimental results also presented satisfactory responses when the control strategy is applied. The friction-induced vibration was applied via AC motor at the lower end of the experimental set-up.

Divenyi *et al.* (2012) [51] analyzed a non-smooth system with axial-torsional coupling. Actually, the model was proposed by Christoforou and Yigit [52] in 2003 and it included lateral, torsional and axial vibration modes. Divenyi *et al.* used the axial-torsional coupling in a 2-DOF system to observe the dynamics of the drill-string system under non-smooth excitation. The coupling between both modes is through contact with formation, where an axial force is necessary to generate torque: the formation presented a stiffness. Thereby, the stick-slip and bit-bounce phenomena were observed and, also, a parametric analysis was performed. A stiffness was associated with the formation, and the drill-pipe equivalent mass, fluid added mass were concentrated and combined with the BHA mass to make up the axial mass. The authors performed a smoothening of the equations by arctangent function and sign of the angular velocity. The contact/non-contact non-smoothness was treated by dividing the governing equations into two situations: with and without contact. The transition between these situations had a linear variation. The numerical results were divided into four cases: normal operation, stick-slip, bit-bounce and stick-slip/bit-bounce. In normal operation, the system has shown torsional and axial vibrations but without bit-bounce and stick-slip. Thereafter, the input parameters were changed in order to observe stick-slip phenomenon and the relationship with axial mode. Divenyi *et al.* illustrated the stick-slip behavior via phase space. Also, the axial phase space was depicted showing an *intricate steady state behavior* and concluding the large influence of the torsional dynamics on the axial dynamics. A new set of parameters were inserted to observe bit-bounce: the phase space for axial and torsional vibrations were depicted and the amplitude of axial displacement reached 40 mm showing that the contact had been lost. In this case, there is no stick-slip but the phase space illustrated a different torsional behavior. The authors state that the discontinuity of the axial mode may be seen in the torsional phase space due to two different regions showing a large influence of the non-smooth axial behavior on the torsional mode. In the last case, the friction

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coefficients were changed in order to observe both stick-slip and bit-bounce phenomena: the authors depicted both bit-bounce due to two distinct regions, highlighting the non-smoothness, and also the stick-slip due to the null value of the angular velocity. Finally, the authors performed a sensitivity analysis of the parameters involved, such as drill-pipe length, weight-on-bit, and frequency excitation. Also, they depicted the sensitive dependence to initial conditions and the "*multi-stability characteristics related to the co-existence of attractors*".

Patil and Teodoriu [53], 2013, have made a comparative review of modeling and control of torsional vibrations, including experimentation using laboratory set-ups. Their objective was to highlight relevant papers in order to perform their analysis. Several theoretical works were based on control strategies in order to mitigate vibrations. Resistive torque models were studied in order to understand their influence on the dynamics of the system. On the other hand, experimental works tried to represent a drilling system in reduced scale. Torsional, lateral and axial vibration were studied in different works. They concluded that laboratory studies did not represent all possible factors which affect drill-string dynamics and an adaptive control strategy would achieve better results for mitigating the torsional vibration while drilling and optimize the rate of penetration. Still in 2013, Patil *et al.* [32] performed an investigation of the influence of systems properties (as stiffness and inertia) and drilling parameters such as rotation per minute (RPM) and weight-on-bit (WOB). They also performed analysis of the influence of the rock strength over the rate of penetration using a model with two degrees of freedom. An interesting fact in this model was that the increase of the length of drill-pipes during drilling, while the length of the BHA remains constant. The WOB was considered oscillating harmonically. According to the authors, the results were in accordance with field data.

In 2015, Kapitaniak *et al.* [54] investigate all types of vibrations in an experimental rig. This experimental set-up permits reduced scale drill-bits and rock samples to reproduce the dynamical behavior of the drill-string. They propose models which were validated based on the experimental set-up observation. Water is used to clean and cool down at drill-bit and rock. PDC and tricone drill bits were used to cut the rock samples. Also, the rate of penetration is measured by a displacement transducer placed in the BHA. Lateral motions are measured by a non-contacting eddy current probes and voltage signal at the electric motor is acquired and controlled by a LabVIEW interface. The authors performed a bit-rock interaction modeling isolating the phenomenon via a replacement of the low-stiffness shaft by a rigid shaft, as a result the system rotates with no torsional dynamics and

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the torque on bit as a function of angular speed was observed. The finite element modeling was used to investigate the drill-string and BHA via the commercial software ABAQUS and the bit-rock interaction was inserted in the software. Thereafter, the authors proposed a low-dimensional model of the system based on torsional pendulum physical model (as seen in [20, 55–57]). In this second model, there was no lateral and axial dynamics, being analyzed only torsional vibrations. The excitation at the surface was constant velocity in addition with a sinusoidal component. Comparison between experimental, FE and low-dimensional models were performed: phase-portrait and time responses of the models presented very similar results. Due to simplicity of the torsional pendulum, the system did not present quasi-periodic solutions that were observed in the experimental and FE models. The last simulation using FE model was to investigate buckling phenomenon but not compared with experimental data.

Lian *et al.* (2015) [58] performed a numerical and experimental analysis of a drill-string dynamics in gas drilling of horizontal wells. The authors explained that gas drilling is a drilling technique using nitrogen or natural gas as circulating medium. Following the authors, this kind of drilling provides advantages such as rate of penetration improvement and formation protection. However, *some problems related to friction and vibration* have been reported in gas drilling of horizontal wells. They described a finite element model for 200 m drill-string system with lateral, axial and torsional modes. The experimental set-up had $25\,m$ drill-string length inside the wellbore with a cone bit. Thereafter, the authors performed a parametric analysis observing the effect of the rotary speed and weight-on-bit (WOB) on the experimental results. Therewith, they estimated values WOB and rotary speed values in the FE model. Buckling and contact of the drill-string were analyzed: based on the FE model, they stated that the bending deformation of the drill-string was caused by friction, axial forces, and *other factors*. After $10\,s$ of simulation, they concluded that a sinusoidal buckling happened at near of the drill-bit while helical buckling happens "*away*" from bit.

In a further work, Kapitaniak *et al.* (2016) [59], after validations provided by [54], analyzed torsional vibration of drill-string, numerically and experimentally, with the aim to develop a numerical model that must be calibrated based on experimental data on a latter case: helical buckling. The authors proposed an orthotropic material in order to form the stress-strain matrix relation. Thereafter, they used the stick-slip of the experimental set-up as the initial pre-buckling condition. According to the authors, the slight differences between the sticking interval and amplitude of the numerical and

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experimental model were caused by the *simplification of cutting process* in friction approach. Nevertheless, it presented a very good match in a period. Kapitaniak *et al.* depicted a top and front views of the numerical and experimental model under helical buckling. Different from the [58] (and also different parameter sets), the helical buckling happened along of all test bench.

Stochastic approaches have been used in order to predict behaviors of the drilling system. There exist some works, as Ritto (2010) [21,60] and Cunha Jr (2015) [14,61] that provided understanding about the uncertainties involved in drilling processes. Ritto modeled a vertical drill-string with lateral, axial and torsional coupled dynamics. Also, the possibility of impacts from the lateral dynamics was taken into account and the bit-rock interaction was modeled with uncertainties. Cunha Jr modeled the horizontal part of a drill-string dynamics as well. In this configuration the weight of the drill-string forces the contact with borehole wall at the beginning of the motion. The mud fluid also was present in the modeling. Ritto *et al.*, in 2012 and 2013, modeled a drill-string system with uncertainties in the imposed speed and bit-rock parameters [62] and a horizontal drill-string with uncertainty in the frictional force due to contact with the borehole-wall [63]. This latter, only the axial motion discretized by finite elements was considered.

In terms of stability, bifurcation, and chaos, Wei *et al.* [64], in 2016, proposed a dynamic model which consists of a combination of pad tangential motion and disc torsional motion to reduce the vibration and noise of brake system coupled with a friction. The authors state that the motion of the disk is rotational while the pad's motion corresponds to the translation. It is chosen the lumped parameter method and Stribeck friction model in order to model the system. In order to avoid discontinuity, which makes stability analysis complicated, the authors have chosen a smoothing method to smooth the friction model - which is adding a hyperbolic tangent function with a smooth factor constant to transform the friction model into a continuously differentiable function throughout the relative velocity range. Similar to the torsional diagrams in drill-string experimental problems [15, 19–21], they plotted a diagram $F_n \; vs \; \omega$ (normal force versus rad/s) differing stable and unstable zone. The Hopf bifurcation is identified when the angular velocity decreases. Also, period-doubling bifurcation and chaos occur in function of the friction parameters.

Aarsnes and Aamo (2016) [65] performed a prediction of occurrence of self-excited vibrations during drilling via linear stability analysis. Their model consists of torsional and longitudinal dynamics with an unstable equilibrium. The authors approached the analysis in frequency domain, dealing with the

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delay equation and infinite dimensional nature of the drill-string dynamics. The authors note that the decrease of the torque on bit at increasing angular velocity is "*likely to be the result of complex drill-string dynamics rather than an intrinsic property of the bit-rock interaction*" [66] (*apud* [65]) and that "*the apparent decrease of the mean torque with the angular velocity responsible for the growth of the amplitude of the torsional vibrations is a consequence of the axial vibrations*" [67] (*apud* [65]). Following the authors, a heuristic was proposed to state which terms may cause instability: axial ou torsional one.

In 2017, Pereira [29] performed a numerical control analysis with the aim of creating a methodology of surface control analysis for a full scale drill-string. The author used a 2-DOF torsional pendulum with a DC-motor providing the angular velocity at the top. He tested PI (proportional and integral), PID (proportional, integral and derivative), MPC (Model predict control) and a combination of MPC and PID. Pereira *et al.* [68] tested this methodology on an experimental set-up model in order to investigate the influence of PI controller. In this experimental model, an intermediate resistive torque may be applied. They observed that the PI controller is effective in a restricted zone. They concluded that this limitation may be associated with the fixed value of the proportional and integral constants.

Ritto *et al.* (2017) [69] proposed a lumped parameter model for torsional vibration of a drill-string, with a friction torque modeling the bit-rock interaction. Field data, with 50 Hz sample rate, were used to fit the bit-rock interaction curve. Afterward, the time responses of the bit were compared with field data which presented good match. The proposed bit-rock interaction model was composed of linear and cubic functions, and then compared with another very common model (a hyperbolic tangent model): the stability map presented different stability regions. The proposed model was in agreement with the field data.

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2.2
Friction-induced vibrations

Friction has been present in human's life since the first step. Dry-friction appears in several systems and may be desired or undesired. An example of desired friction is the vehicle brake systems. On the other hand, this phenomenon appears in drilling processes, gear systems, and may cause premature wear, loss of energy, and increase process costs.

Thomsen presents several studies about friction-induced oscillations. In 1999, he published an application of high-frequency external excitation in a damping-spring-mass system on a belt which moves with constant velocity

[70]. The adopted friction between mass and belt is a negative-slope friction and the external excitation is modeled as an unbalanced mass running with an angular speed. Firstly, with no external excitation the mass present self-excited oscillations. Hence adding high-frequency harmonic excitation of small amplitude, he concluded the prevention of self-excited oscillations. The author states that the "*presence of fast vibrations effectively smoothen out the discontinuity of the dry friction*", tending to cancel negative slope of friction characteristic.

Awrejcewiz *et al.* (2007) [71] investigated experimentally a 2-DOF mechanical system. As before in [70], the mass on a belt is studied. However, the system presents a variation of the normal force during displacement. The authors proposed a friction model and then performed measurement and identification of the involved parameters. The phase plane showed that the trajectory of the numerical model describes the experimental trajectory only in the beginning of the movement. Awrejcewiz *et al.* justified this behavior as micro-stick and -slip conditions prevailing in real contact and to non-symmetric experimental set-up.

Kang *et al.* [72], in 2009, studied the stick-sip limit cycle of a classical 1-DOF oscillator on a belt with the friction law presenting a negative slope and, following, the mass two contact area with the belt. They state that "*the slope of the friction curve is crucial to the stability*" of the equilibrium solution and limit cycle. They analyzed the influence of the system parameters on the oscillation modes (merged and separated) via root loci, phase plane, and bifurcation diagrams.

In 2010, Meziane [73] studied numerically and experimentally friction-induced vibration of two beams in contact. They stated that the instability is characterized by self-sustained vibration, stick-slip, and separation of contact surfaces. Both influence of the relative velocity between two surfaces and the contact angle were investigated. The authors concluded that the contact geometry is an important parameter for friction-induced instability. The proposed numerical model matches with experimental frequency spectrum and time-responses.

Behrendt *et al.* (2011) [74] investigated stick-slip motion of a brake pad under constant load and constant velocity via finite elements. The friction curve was assumed as velocity-dependent friction. Stick-slip motion and slip-separation were observed as function of relative velocity. Also, the micro motion was depicted using short time scale and compared to overall behavior (macroscopically). They stated that the macroscopic sliding is generated by a set of "*microscopic relaxation slipping events*" and, to the brake pad model,

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they concluded that the macroscopic stick-slip motion may appear only under a "*mutual excitation and interaction*" between macro and micro dynamics.

Drinčić *et al.* (2012) [75] performed an investigation on the Stribeck effect. They developed a compressed bristle model: the body was in contact with a row of bristle. The bristles were modeled as frictionless roller, a spring, and damping. The body presented a slanted from vertical. The force friction was the sum of the all horizontal components of the forces exerted by the bristles. In the vertical direction, the forces exerted by the bristles affect the vertical motion of the body. The authors simulated a spring-mass system in contact with a surface: the friction was the proposed one. They observed stick-slip and oscillation in vertical direction. The velocity/friction-force curve presented a loop: dynamic Stribeck effect. Afterward, they proposed a simplified bristle model, which presented similar results with LuGre model. The authors concluded that the Stribeck effect was caused by the vertical motion of the body. Drinčić [76], in his thesis, studied several friction models with hysteresis, stick-slip and Stribeck effect, and their influence on the dynamics of the spring-mass system.

In 2015, Saha *et al.* [77] proposed an investigation about two different friction-induced vibration models. Firstly, the authors developed a friction model based on a modification of the LuGre friction model [78] (as Yanada *et al.* [79]) and compared this model with a Dankowicz model [80] (*apud* Saha *et al.* [77]). Both friction models are investigated by examining the response of a damped single degree of freedom on a moving belt exhibiting friction-induced vibrations. According to the authors, the LuGre friction model can only predict counterclockwise hysteretic loop in the pure sliding regime, meanwhile, a modified LuGre model was developed to capture both clockwise and counterclockwise hysteretic loops in the pure sliding regime. The authors added an internal damping term to the friction force in the LuGre friction model in order to avoid undamped oscillations in the bristle deflection. They justified heuristically this term. Following the authors analyzed the influence of the different friction parameters on the system and the friction force. They concluded that both friction models change the stability of the steady-state of the system via Hopf bifurcations.

Lima and Sampaio [81], 2017, developed a statistical model for dynamics of base-driven stick-slip oscillator. The goal of this paper is to understand and characterize the dry-friction oscillator over its stick and slip phases under a statistical point of view. The system consists of spring-mass on a rough surface base with stochastic motion. The base velocity is modeled as a Poisson process. Interesting conclusions are the duration of stick and slip modes: they

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are identically distributed and independent random variables, i.e., they have almost the same mean for duration time of stick $D_1 = D_2 = ... = D_{S_T}$ and for duration time of slip $H_1 = H_2 = ... = H_{S_L}$. In following, 2017, the authors performed a parametric analysis of the statistical model described before [82]. The constant rate λ, that represents the expected value of number of changes per unit of time of the bang-bang motion of the base, and the friction coefficient μ are the parameters chosen to this analysis. They concluded that the increasing λ decreases the stick duration time. Also, they verified that for a $\lambda \in [0.5, 3.8]$ $1/s$ the increase of number of stick provides an increasing of the total time of stick, even for lower stick duration, and after $\lambda > 3.8$ $1/s$ the total time of stick decreases. In terms of μ, the total time of stick grows as μ increases. For this system and values of μ up to 1.5, the total time of stick varies linearly, and then $\mu > 1.5$ the total time varies as a negative exponential growth.

2.3 Summary

Several works have been published in drilling system dynamics, and probably much more are coming. It is a very complex process and involves a myriad of phenomena. Also, friction models still generate great discussions due to complex micro and macro dynamics, as well as their interactions.

In this literature review, there are complex models to investigate vibrations (coupled and/or uncoupled), buckling, horizontal and vertical drill-string, numerical and experimental works. At the conclusions of all these works, others questions are made due to complexity and richness of problems to solve. An interesting fact is that few papers include the top-drive dynamics. Some authors suppose a torque source strong enough to keep a constant velocity at the top. Other authors model this velocity with a sinusoidal perturbation or with uncertainties. In fact, there are regions where these assumptions may be taken, but there is also space for much more investigations on this subject.

In addition, systems with friction-induced vibrations remain as a source of great investigation. The nonsmooth dynamics impose great challenges on the friction modeling. Some authors state friction as a macroscopic phenomenon arising from molecular interaction. There is great interest in the precise description of the behavior of a system under friction. Herein, the literature review on friction-induced vibration was mainly to better understand the phenomenon and try to model the friction acting on the test rig of this thesis.

Hereafter, the drill-string experimental set-up is described and dry friction-induced vibration is observed numerically and experimentally. Also,

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the DC-motor dynamics is included, since oscillations in its angular velocity are observed.

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