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1
General introduction

Oil and its derivative products are still very present nowadays. Daily, we find these products in our kitchens, vehicles and works, such as natural gas, fuels (gasoline, diesel, jet fuel, and others), air conditioner refrigerants, lubricants of motors, asphalt, cosmetic products and so on. Before entering into the discussion on renewable and clean energy, these products may provide conducive environment to the life in big commercial cities. As a primary source of global energy, the oil exploitation is still extremely important for human life.

Despite the plunge of the oil prices, resulting in "*one of the most dramatic declines of the oil prices in recent history*" [1], the world total production and consumption have increased over the last ten years. The prices dropped down from US$114 in June 2014 to US$28 in February 2016 [1], but the consumption and production did not present any decreasing whatsoever, as shown in Figure 1.1.

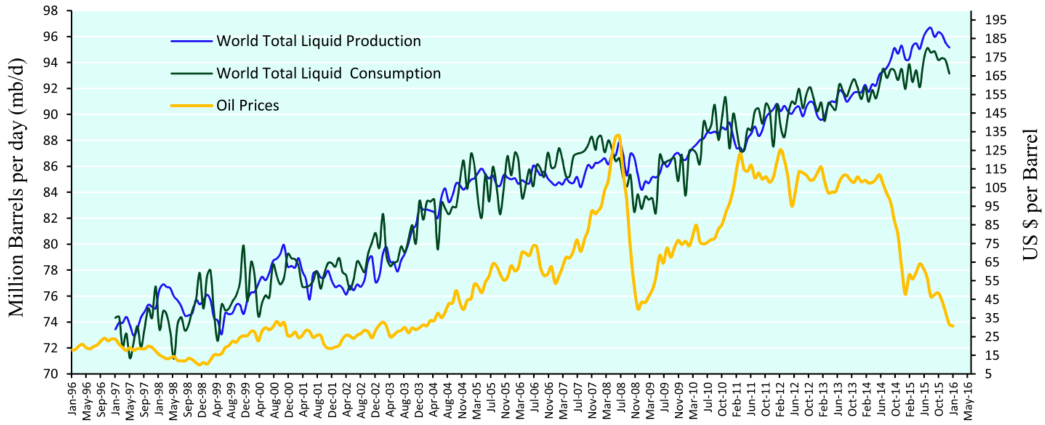

Figure 1.1: Oil prices vs supply/demand [1].

Even with a current great appeal for renewable and clean energy, the oil demand is still related to economic activity. By comparing the Brazilian oil consumption with the other South American countries, it is possible to state that Brazil consumes 3 times more than Argentina (Figure 1.2), whereas China quadruples the oil consumption of Brazil (Figure 1.3). Besides, in a world rank, Brazil is the 11th country of oil consumption with 2 029 000 *bbl*/*day* (barrel per day). In the top of the rank, the United States present (19 150 000 bbl/day), China (9 400 000 bbl/day) and Japan (4 452 000 bbl/day) [2].

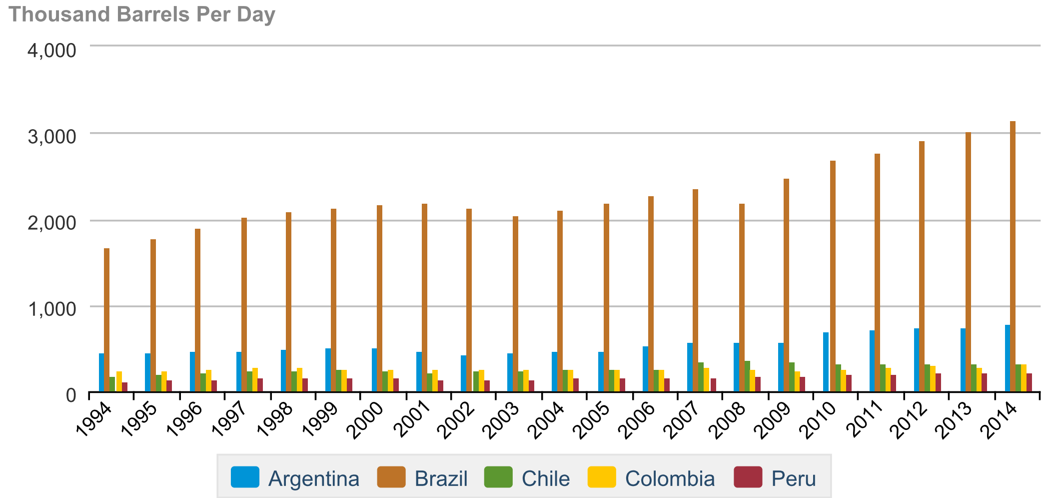

Figure 1.2: Total petroleum consumption of some South American countries [2].

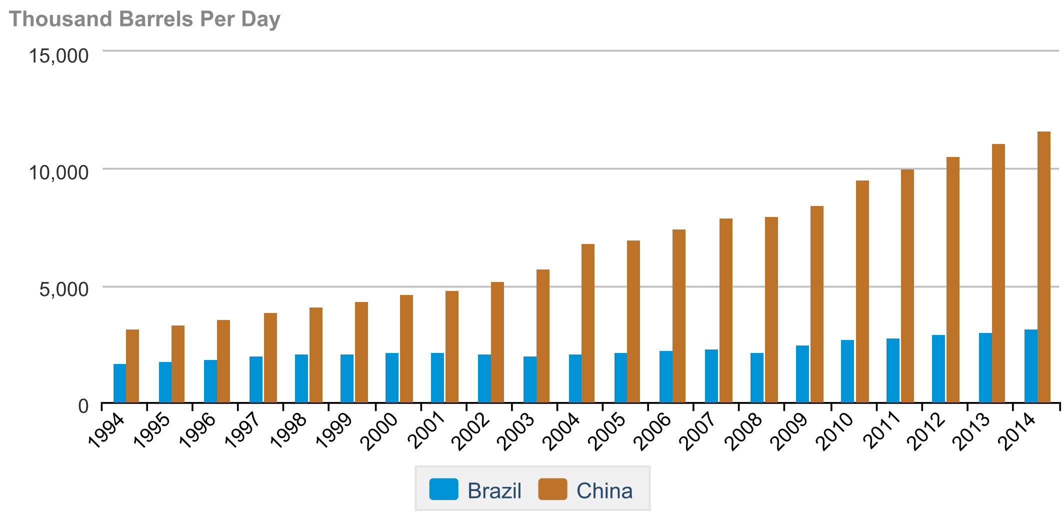

Figure 1.3: Brazil and China total petroleum consumption [2].

In terms of production, Brazil is also the 11th world economy with 2 652 000 bbl/day, behind Saudi Arabia (1st - 11 730 000 bbl/day), United States (2nd - 11 110 000 bbl/day) and Russia (3rd - 10 440 000 bbl/day). According to Petroleum National Agency (ANP - portuguese acronym) [3], the oil barrel production has increased over the last 17 years, as depicted in Figure 1.4. In 2016, the total production of the year reached almost 919 million of barrels [3].

Still according to ANP, Brazil possesses 29 basins with a 7 175 km^2 area to explore, known as pre-salt polygon (see Figure 1.5). This area is located in the coast of five states: Santa Catarina, Paraná, São Paulo, Rio de Janeiro

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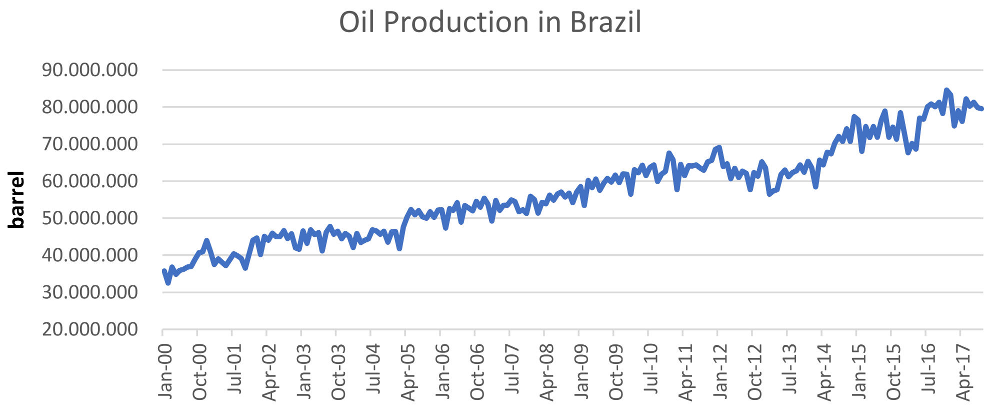

Figure 1.4: Brazil oil production history. Source: author based on [3].

and Espírito Santo [4]. Only a small percentage of this area already has an exploitation grant. In September 2017 and March 2018, the Agency promoted bid rounds for exploration and production of oil and natural gas with a total fund collection of R$3.842 and R$8.014 billions, respectively, and other bid rounds are scheduled for 2019. Also in June 2018, ANP shall promote the 4th bid round for shared production in pre-salt [3]. In this scenario, it is possible to state that the oil prospecting activity in Brazil will soon be intense again.

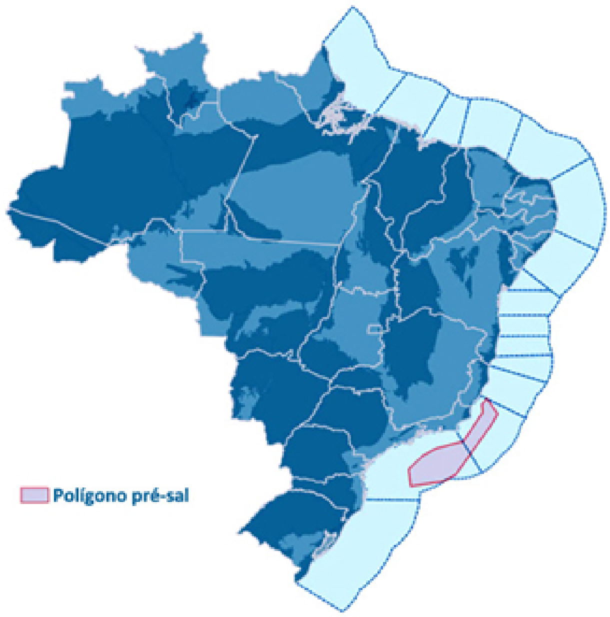

Figure 1.5: Pre-salt area in Brazilian coast [3].

However, the exploitation of these hydrocarbons presents a myriad of precaution requirements. The drilling process involves many factors to be controlled, such as drilling mud weight, weight-on-bit, surface speed, lithology,

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among others. The time is another important factor: the rig rate is around one million dollars per day. According to [5], onshore drilling costs comprises about 30-40% of total well costs, whereas offshore drilling process comprises 70% of the total well costs. Besides, it is extremely valuable to avoid accidents of oil leakage in all domains of the process which may lead to irreversible environmental damages to the ecosystem, large fines and loss of extraction grant. Silvestre (2017) [6] exemplifies an accident in 1989: Exxon Valdez Company spilled 37000 *tons* of crude oil off the Alaskan coast, causing the death of thousands of birds and sea animals. In Brazil, in 2011, Chevron Brazil was fined R$50 million (US$ 28 million) for about 8,000 barrels of oil leaked off the coast of Rio de Janeiro, in Frade field. Therefore, drilling systems remain with great complexity challenges on each oil well drilling.

1.1 Drilling systems

Drilling systems consist of a set of equipment (surface and downhole) capable to create holes in the earth sub-surface for oil and/or natural gas extractions [7, 8]. The equipment may be located onshore or offshore. In the 1860s, Cel. Drake discovered an onshore well, only 21 m deep in Pennsylvania. Following this event, the commercial exploitation has started in United States and the by-products of the petroleum distillation replaced kerosene and whale oil with a large profit [9]. Until the 1900s, the drilling process was performed via the percussive method and then, Anthony Lucas (oil explorer) drilled and found oil via rotary drilling method in 341 m well depth. Since then, the rotary drilling process gained ground and gradually replaced the percussive drilling method. From 1950s, intensive marine incursions (offshore wells) [9] have occurred using rotary drilling. Nowadays, in Brazilian pre-salt, there exist rigs in 2500 m deep water depth and reservoir targets in 7000 m [10].

Most of oil wells are vertically placed, but there also exist inclined and/or even horizontal configurations [11]. It often happens in order to overcome some constraints that a vertical well may present, such as, *blowout* well control via relief wells, that they hit reservoir targets, which are located under inaccessible locations (ex: rivers, cities, etc.), to contour geological accidents (ex: salt and rock failures), among others [8, 9]. The directional and vertical oil well configurations are illustrated in Figure 1.6, whereas Figure 1.7 depicts an example of an onshore directional well reaching a reservoir target. Also, directional drilling technique provides a larger contact area between well and oil reservoir which may enhance oil extraction, since these reservoirs often present a larger horizontal dimension than its vertical dimension [12]. Nonetheless, this

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well configuration needs more navigation equipment to conduct the borehole, presenting a complex dynamic behavior, and more susceptible to fatigue damage than that of a vertical well [13].

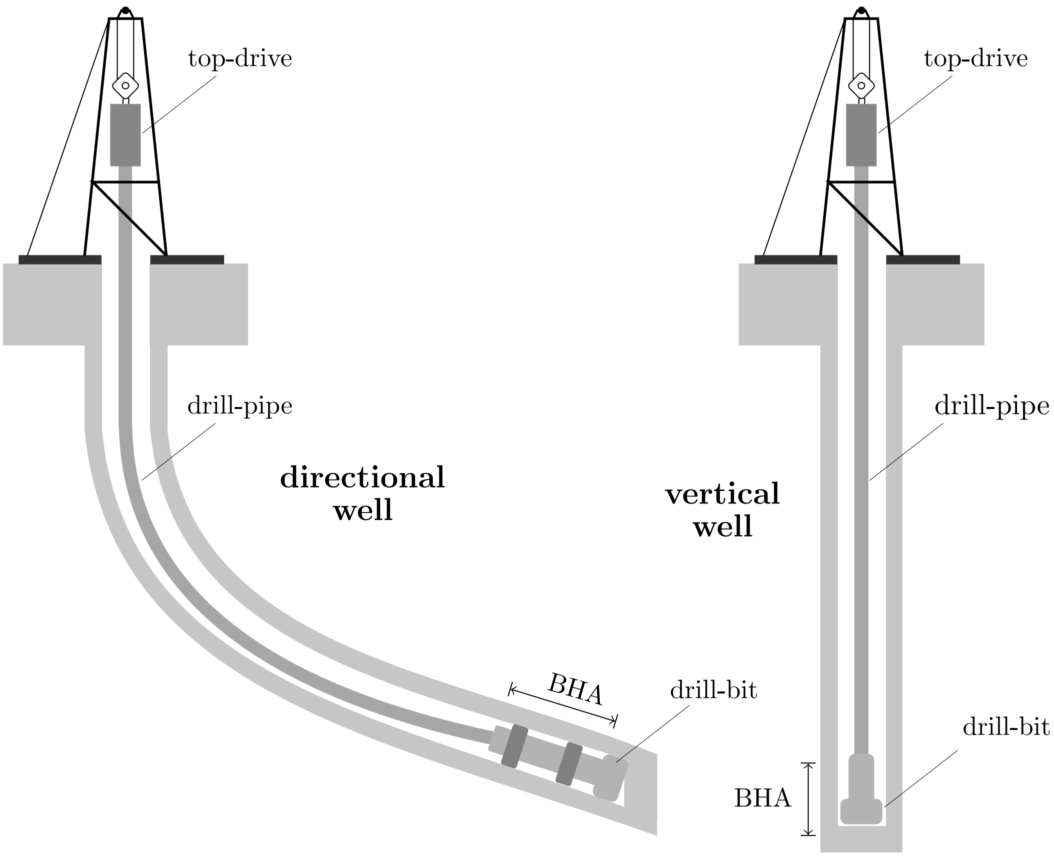

Figure 1.6: Directional and vertical oil well configuration. Adapted from [14].

Basically, the drilling system consists of a motor (electric or hydraulic) located at the top end position which imposes rotational motion in the drilling system. The bottom end part is named the Bottom-Hole Assembly (BHA), which comprises *heavyweight drill-pipes* and *drill-collars* that are responsible to transmit the necessary weight to drill without buckling. Also in the bottom there is a cut tool named *drill-bit* responsible to gouge the rock. Between these extremities, there is a torque-transmitting element called *drill-string* (connection of a series of pipes). At the top end, the top-drive imposes an angular velocity (surface RPM - SRPM). Thereafter, an axial force called weight-on-bit (WOB) is imposed, and this combination of WOB and SRPM provides the needed torque on bit (TOB) to induce rock failures (crushing, shearing or grinding) [15]. These failures depend on the drill-bit used in the rotary drilling process which on its turn, depends on the rock formation [8]. The system operation is more thoroughly described in references [8, 16–21].

Once established a directional oil well design, it is necessary to provide its type of the directional hole. This configuration depends on the horizontal

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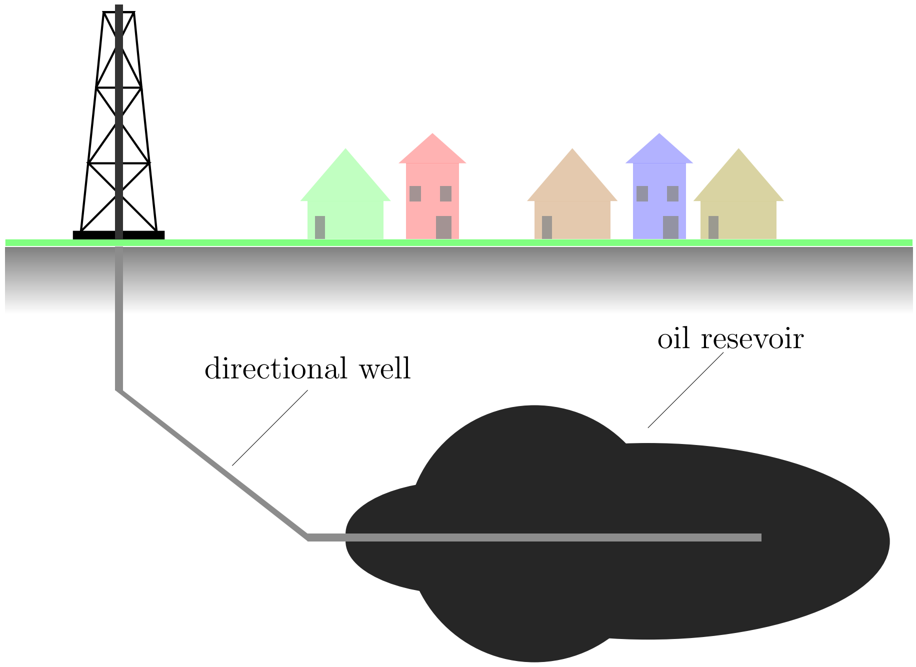

Figure 1.7: Directional drilling to reach oil reservoir targets under a housing area.

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remoteness, depth of the deviation point (*kick-off point*), rig-target location and total vertical depth of the oil well. In Figure 1.8 the types of directional wells are illustrated.

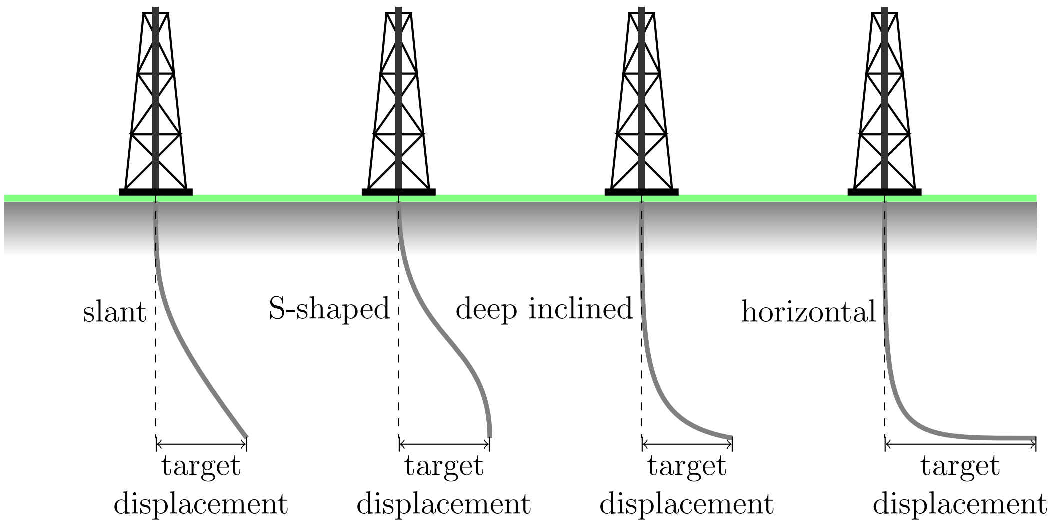

Figure 1.8: Types of directional oil wells. Adapted from [22].

1.1.1 Dynamics of drilling systems

Several phenomena may appear during the drilling process such as axial, lateral and torsional vibrations, as illustrated in Figure 1.9. These vibration modes may occur simultaneously (coupled) and exhibit significant nonlinearities arising from the complex physical mechanism of drilling. Besides, these vibrations are detrimental to the process as they may lead to premature component failures (see Figure 1.10), dysfunction of measurement devices, decrease rate of penetration and increase of time and cost of the process. A failure analysis may be found in [13, 23–25].

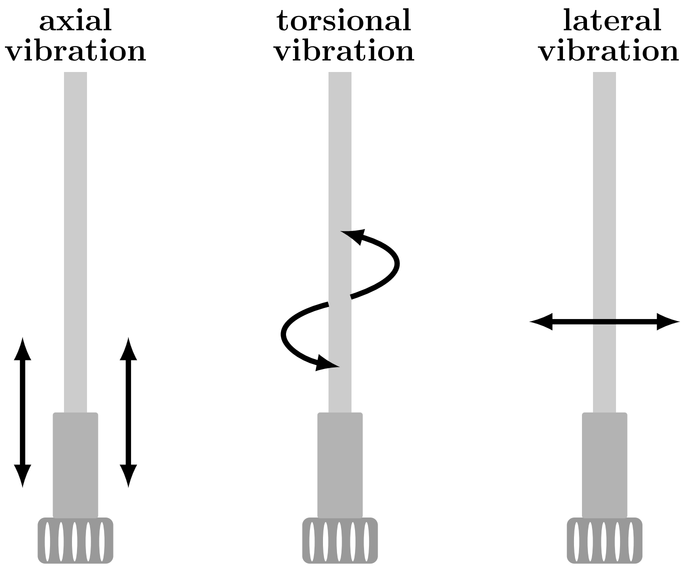

Figure 1.9: Scheme of the types of vibration modes on drill-string. Adapted from [14].

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These modes are briefly described in order to understand the complex dynamic phenomena involved in the drilling process:

- **axial vibration** is a longitudinal motion of the drill-string. In its most severe stage, the drill-bit loses contact with the formation and suddenly hits the rock back. This phenomenon is called *bit-bounce* and it may lead to drill-bit destruction, damage the BHA and increase time/cost drilling process [26, 27];
- **lateral vibration** is the whirling motion of the drill-string, causing irregular borehole and damaging the BHA components. This vibration mode presents no detectable indication at surface and it is considered one of the most destructive phenomenon in drilling systems [27]. However, as part of the BHA, the stabilizers serve to prevent unbalancing [28];
- **torsional vibration** consists of twisting/untwisting motion of the drill-string. The top end rotates constantly (or almost constantly) driven by the top-drive while the bottom end oscillates, mainly, due to nonlinear bit-rock interaction.

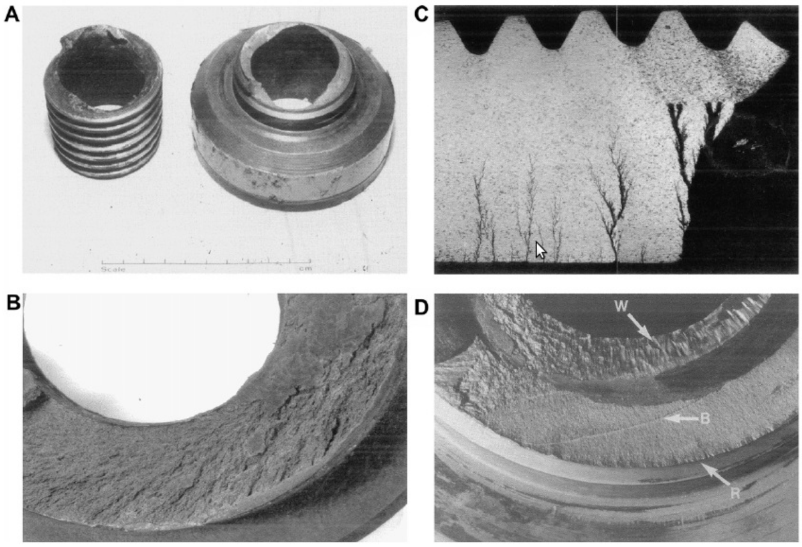

Figure 1.10: Types of failures: (A) ductile; (B) fragile; (C) stress corrosion cracking and (D) fatigue [13].

Axial oscillations may be detected by fluctuations of WOB, whereas torsional vibrations may be observed by the surface velocity variation [27]. Nevertheless, these vibration modes are detectable in their severe stage, *i.e.*, bit-bounce and stick-lip. This latter phenomenon is further discussed in the next section.

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1.1.2 Torsional vibration and stick-slip phenomenon

Because of diameter-to-length ratio of the drilling system, torsional vibration mode is present in most drilling processes and may reach an undesired severe stage: stick-slip. This stage consists in a complete arrest of the drill-bit (stick phase), while the top continues rotating and storing elastic torsional energy in the drill-string. Suddenly, the energy stored overcomes the bit torque and the drill-bit is released to rotate (slip phase) - converting potential energy into kinetic energy. Experimental and field observations found out that during slip phase, the angular velocity of the drill-bit may increase three times (or more) the nominal angular velocity imposed [14, 20, 29]. Figure 1.11 illustrates the stick-slip phenomenon occurring [30].

The stick-slip phenomenon occurs approximately 50% of the total drilling time [31] (*apud* [32]) and is the main source of component failures during drilling process. Patil *et al.* [32] states that torsional vibrations while drilling is one of the severe types of drill-string vibration which deteriorates the overall drilling performance, causing damaged of the bit, failure of bottom-hole assembly (BHA), torsional fatigue of drill-string, and excites other vibration

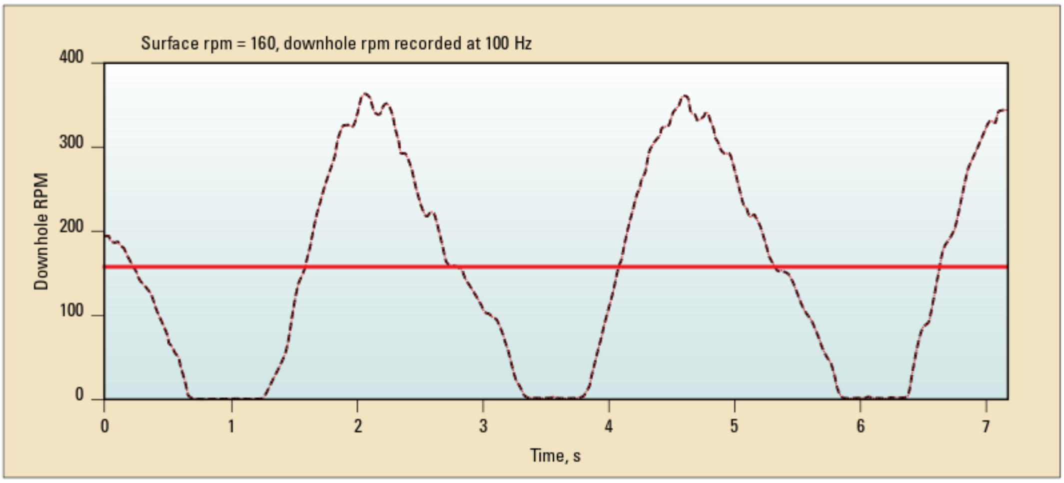

Figure 1.11: Stick-slip oscillation with completely standstill of the bit [30]. The red and dashed lines represent the surface and downhole angular velocities, respectively.

modes.

This phenomenon is a self-excited drilling dysfunction that is characterized by large oscillations of the angular velocity of the drill-bit [33]. It arises mainly from the resistive bit-rock interaction which basically depends on the lithology, but always keeping the strongly nonlinear character [34] between the resistive torque and angular velocity of the drill-bit. In general, the self-excited system performs periodic motions which are sustained by non-harmonic sources [35].

According to [30], it is possible to address stick-slip using mud motor if it is caused by bit-rock interaction. However, it does not prevent torsional oscillations above the motor, *i.e.*, the components above the motor may enter into stick-slip even when the bit possesses a steady velocity. This behavior illustrates the complexity of this phenomenon.

In field operations, some standard procedures are performed aiming to suppress the stick-slip phenomenon such as: increase the Surface RPM, and decrease the weight-on-bit. This procedure is empirically performed, *i.e.*, each company holds its own percentage of increasing and decreasing of Surface RPM and WOB. Remaining in this state, the drilling process must be stopped and the drill-string must be lifted in order to untwist the system, rising the maintenance time and cost.

1.1.3
Other drilling system applications

Drilling systems also create well holes for other applications. Groundwater, for example, is the "*water present beneath Earth's surface in*

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soil pore spaces and in the fractures of rock formations" [36]. It is commonly used as supply.

Other energy source achieved by drilling process is the geothermal energy. It is the energy created in Earth. Geothermal electricity energy is already used in 24 countries, while geothermal heating is established over 70 countries [37]. To do so, it is necessary to achieve the thermal source beneath Earth's crust. Table 1.1 presents the top five countries with their installed electric capacity provided by geothermal power.

Table 1.1: Installed electric capacity of geothermal power stations in 2015 [37].

Installed capacity		
	Country	**Capacity [MW]**
1st	United States	3 450
2nd	Philippines	1 870
3rd	Indonesia	1 340
4th	Mexico	1 017
5th	New Zealand	1 005

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According to [38], research efforts related to geothermal prospection and exploration have followed the way of groundwater and oil reservoir had followed once. Also, it is considered renewable and sustainable [39].

1.2 Objectives of the thesis

In view of the above and bearing in mind the scenario taking shape in the coming years, this work aims to model and analyze the torsional behavior of a drill-string experimental set-up with dry friction-induced vibration in order to prevent torsional vibrations in its drastic form: stick-slip phenomenon. The system is approached by isolating the torsional vibration and including a second torque source on an intermediate rotor (R_2) - placed between R_1 (drill-bit) and DC-motor (R_3 or top-drive). Subsequently a mathematical model is proposed and validated with comparisons to experimental test results. Therewith, periodic solution and equilibria zones are identified, and large torsional vibration amplitudes are predicted. Finally, it was verified a mitigation possibility of the oscillation via an active torque device placed in R_2. The result analysis may provide knowledge to avoid large torsional oscillation amplitudes and future developments of new drilling equipment.

This thesis does not claim to represent a full-scale drill-string system. Instead, the main goal is to investigate and understand phenomena involved in the drill-string system.

1.3 Main contributions

The main contributions provided by this doctoral study may be described as follow:

1. *the modification of the experimental set-up including a second dry friction source*: in previous works (such as [40–42]) the experimental set-up did not have a second torque source placed on a intermediate disc. This simulates a possible contact of the drill-string or an active torque possibility. Also, the friction device was modified in order to provide directly the normal force acquisition. This device is described in Section 3.2;

2. *the characterization and validation of the mathematical modeling of the drill-string experimental set-up*: a mathematical model is proposed in order to describe the experimental set-up. All the mechanical parameters of the test bench were identified. The experimental and numerical data were compared for the purpose to verify whether the mathematical model is representing the experimental apparatus;

3. *the analysis of the nonlinear torsional behavior*: subsequently to the model validation and observation of the test bench, the nonlinear analysis was performed in order to identify stable solutions of the system [43, 44]. A bifurcation diagram was performed using the imposed angular velocity as a bifurcation parameter. Therewith, equilibrium points (non torsional vibrations) and limit cycles (torsional vibrations) were found. Basins of attraction illustrated the coexistence of periodic and equilibrium solutions;

4. *the verification of the influence of the torque source*: a bi-stability range of the bifurcation parameter is found, *i.e.*, the system may present or not torsional vibration depending on the imposed conditions. Thereafter, perturbations are deliberately imposed in order to change from one solution (limit cycle) to another solution (equilibrium); and

5. *the strategy to mitigate torsional oscillations*: using a second torque source placed intermediately in the test bench, a mitigation strategy is proposed in order to provide perturbations. Such perturbations must be sufficient to change from periodic solution to equilibrium point (desired situation), and acceptable when the energies involved are compared.

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1.4 Outline of the thesis

This thesis is organized into six chapters. Firstly, Chapter 1 comprises this introduction. Chapter 2 contains the literature review about drill-string vibrations. Most part of the listed papers include drilling system modeling, dry friction-induced vibration and proposed solutions for this undesired behavior. In Chapter 3, the test rig description, parameter estimations and friction devices are described. The dynamic model for the drill-string experimental set-up and the dry friction model for the resistive torque is discussed in Chapter 4. Also, this chapter includes stability analysis of the addressed system. The Chapter 5 comprises the analysis of results comparing numerical and experimental approaches, and a mitigation proposition of the test rig torsional vibrations. Finally, general conclusions, discussions and future works are described in Chapter 6. In addition, the publications originated from this thesis are highlighted in this chapter.

1.5 Recommendation to cite this work

Due to some doubts about the author citation name, this brief section provides a recommendation as follows:

– Cayres, B.C. **Nonlinear dynamic analysis of dry friction-induced torsional vibration in a drill-string experimental set-up**. D.Sc. Thesis, Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro, Brazil, 2018.

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