1
Introduction

We live in a petroleum age. One would be hard pressed today to find a product or service that does not rely on oil derivative compounds. A naturally occurring fluid found within rock formations, oil powers billion-dollar industries employing thousands of technicians, engineers, and scientists. Considerable resources have been devoted to research and development of new technologies and tools for drilling wells, extracting, transporting and refining oil.

1.1
Oil well drilling

Oil well drilling [77] is performed by using a drillstring, as shown in Figure (1.2.a).

In rotary drilling [77], a rock formation is drilled by using the rotary action and weight applied to a drill bit installed at the free end of the drillstring. Typical drillstring consists of drill collars (thick wall tubes) and drill pipes (thin wall tubes). Rock fragments are continuously removed through drilling fluid or mud. When a certain depth is reached, the drillstring is removed from the borehole. Then sections of steel tubing known as casing, which are slightly smaller than the borehole, provide an annular for cementing. The casing provides structural integrity for the newly drilled well bore in addition to isolating potentially dangerous high pressure zones from each other and from the surface. After the process of drilling and casing process, the well must be “completed”. Completion enables the well to produce oil and/or gas. More information on this subject can be found in the book of Thomas [77] and at Wikipedia [90].

Figure 1.1: Oilwell drilling - field photos (website geocities.yahoo.com.br).

Percussive drilling fragments rock formations by means of blows, which occur only for a fraction of a second. This method relies entirely on crack propagation and the brittleness of the formation, because bit rotation does not contribute to the cutting process. If the load on the bit is inadequate, the rate of penetration decreases due to small chip formation and therefore energy is wasted. Though percussion drilling is preferable in very hard sedimentary rocks due to low bit wear and fast penetration, this method cannot produce the same rate of penetration when drilling at greater depth. Percussive drilling can produce only small diameter holes.

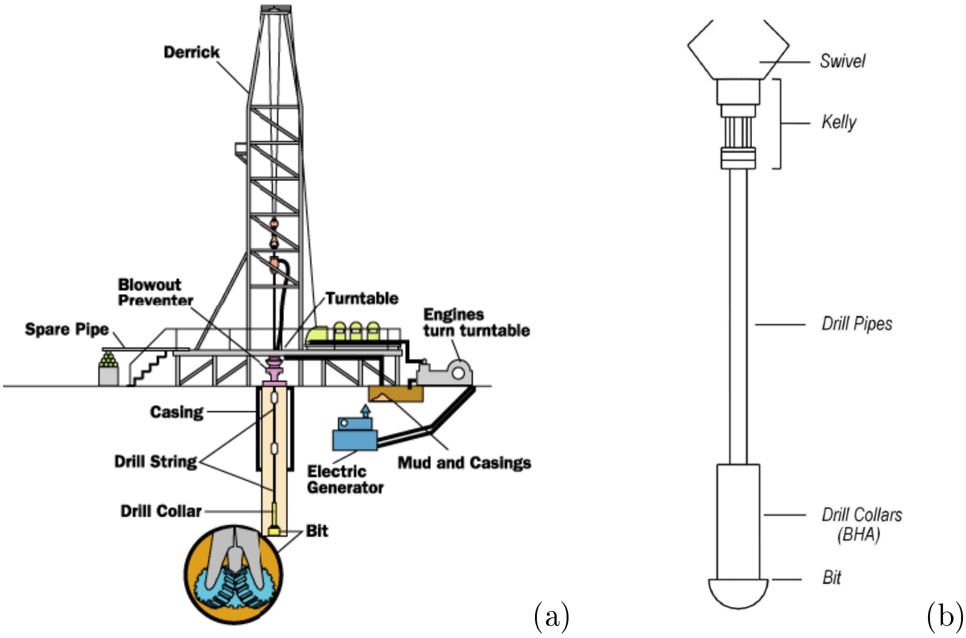


Figure 1.2: Sketches: a) drilling rig (website www.howstuffworks.com); b) oil well drillstring.

1.2
Rotary drilling - oil well drillstring

During oil well drilling it is necessary to have a huge amount of energy concentrated on the drill bit in order to cut the various rock formations. Such energy, in the form of drillstring rotation and weight on the bit, is transferred to the rock to cause it to rupture. The generated rock chips are swept up by the drilling fluid as it circulates back to surface between the drill pipe and the borehole wall.

The drillstring is the central element responsible for this process, and the drill collars, heavy-weight drill pipes and drill pipes are its main components. Each drillstring section is made up of several components, joined together using especially threaded connections known as tool joints. Some of these components are:

- The Bottom Hole Assembly (or simply BHA), composed of a drill bit, drill collars and stabilizers which keep the drilling assembly centered in the hole. The BHA may also contain other components such as a downhole motor, a Rotary Steerable System, and Measurement While Drilling system (MWD) and Logging While Drilling (LWD) tools.
- Heavyweight drill pipes (HWDP), used to make the connection between the drill collars and the drill pipe. The function of the HWDP is to provide a flexible transition between both components. This helps to reduce the number of fatigue failures that may occur directly above the BHA. A secondary use of HWDP is to add additional weight to the drill bit.
- Drill pipe, which makes up the majority of a drill string. A drill string is typically about 5 kilometers in length for an oil or gas well vertically drilled onshore in the United States, and may extend to over 10 kilometers for an offshore deviated well [90].
- Drill stem subs, used to connect drill string elements.
- Accessories [77] [2], such as: kelly, swivel, stabilizers and dampers.

1.2.1 Drill bits

The bits are subdivided depending on soil condition. There are three main categories: soft, medium and hard formation bits. A roller-cone bit is a drill bit used for drilling rock. These bits may have one to four cones. Tricone bits are used most often, due to their efficiency and lower cost. Roller cone bits are composed of two main elements: the cutting structure and the bearings [90].

The cutting structure of the bits varies according to the rock formation. Soft bits will have longer protruding teeth, or chisel-shaped buttons with fewer more widely spaced teeth. Medium formation bits will have closer teeth and shorter protrusion. The teeth are very short and closely-spaced on hard formation bits.

Figure 1.3: Roller cone bits (website geocities.yahoo.com.br).

1.3 Drillstring vibration and bit/rock interaction

The dynamical behavior of an active drilling assembly as used in the oil or gas industry is complex. Drillstring vibrations result in premature failure of drillstring components and drilling inefficiency, and lead to intensive bit wear and an increase of overall cost. The drillstring undergoes various types of vibration during drilling [27] [23] [24] [25] [50]:

1. Axial (longitudinal) vibrations, mostly due to the interaction between drilling bit and the hole bottom. In its extreme form, called *bit bounce* effect, the bit loses contact with the hole bottom.

2. Bending (lateral) deformations, often caused by pipe irregularity, leading to centripetal reaction forces during rotation, which are called drillstring whirl:

    - forward whirl: the rotation of a deflected drill collar section around the borehole axis occurs in the same direction as the drillstring rotation.
    - backward whirl: a rolling motion of the drill collar or the stabilizer over the borehole wall, opposite to the direction of drillstring rotation.

3. Torsional (rotational) vibrations, caused by nonlinear interaction either between the bit and the rock, or between the drillstring with the borehole wall. These are called stick-slip vibrations: the torsional vibration of the drillstring characterized by alternating stops (during which the BHA sticks to the borehole) and large angular velocities of the BHA.

4. Hydraulic vibrations in the circulation system, stemming from pump pulsations.

These vibrations are to some degree coupled: for instance, the interaction between torque on the bit (TOB) and weight on the bit (WOB) will link the axial vibrations to the torsional vibrations. Drillstring vibrations were intensively studied in the works of Chen [18], Dareing [23] [25] and Dykstra [27]; and investigated in the works of Alamo [33], Franca [29], Plácido [43] and Ritto [65].

Axial vibration, especially in the region close to the drill bit, affects the directional control of the hole. It may cause damage to the drill bit and is the main cause of profile formation on the rock (on the bit/rock interaction). Such profiles produce harmonic excitations in axial and torsional directions [25].

The main cause of drillstring axial vibration is the excitation generated during bit/rock interaction. These excitations vary according to the rock formation and the drill bit used. For tricone bits, harmonic excitation generated by the cones results in a smooth BHA axial movement with a beat frequency three times the rotation velocity of the drillstring [18] [25]. During the drilling process, a typical lobed surface is generated. The number of lobes corresponds to the number of cones of the bit, as shown in Figure (1.5). The lobe formation on the bottom of the hole is more evident in

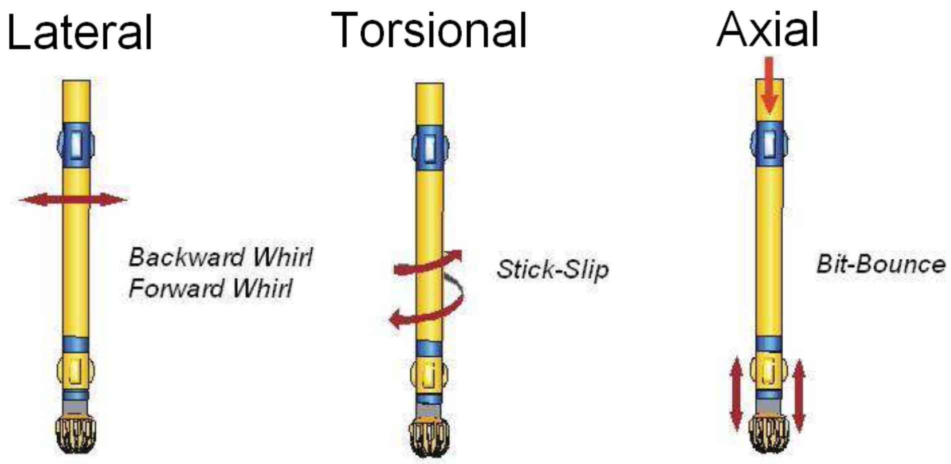
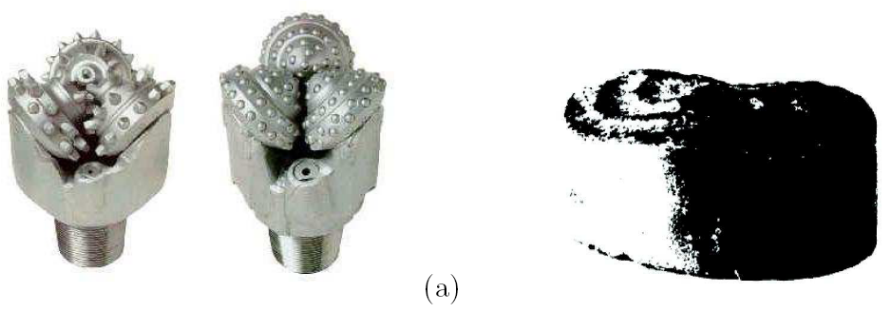


Figure 1.4: Drillstring vibration [29].

hard rock drilling but does not occur in all drilling conditions [24]. This phenomena has been observed in the field for over 35 years [24].

During the drilling process, these lobes are destroyed and regenerated with each bit rotation. Drill bit axial displacement varies from 6 to 13 mm [25]. One of the first works to measure and describe such phenomenon is the article presented by Cunningham [22], where the dynamic fraction of the weight on bit has values from 9 kN to 620 kN. This work also observes the bit bounce effect through field measurements. The author attributes the variation of the weight on the bit to two causes: bit/rock interaction (use of roller cone bits in hard rocks) and drilling mud pressure variation. In this way, the drill bit becomes the source of harmonic excitation. Such downhole measurements are also confirmed in the work of Dareing [24].



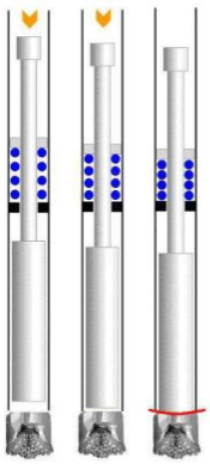
(a) (b)

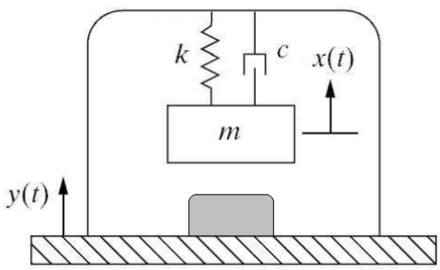
Figure 1.5: a) Roller cone bit (website geocities.yahoo.com.br/perfuracao); b) trilobe formation on hard rocks caused by roller cone bits drilling [25].

1.4
Hard rock drilling and Resonance Hammer Drilling (RHD)

Hard rock drilling is still a great challenge for oil companies. With rates of penetration (ROPs) less than 1 meter per hour, the drilling costs become expensive, even on relatively small onshore operations [29].

To eliminate the negative effects of the vibration, improvements are constantly implemented by introducing new concepts in drilling and new equipment designs. These new approaches have to consider the efficient use of energy as an important factor, bringing an increase in bit life and rate of penetration, which reduces the cost of hard rock drilling. In this context, optimum productivity is possible by combining the advantages of rotary and percussive drilling. Percussive-rotary drilling is not new. It was developed first by the Salzgitter Company and improved by Hausherr and Nusse & Grafer in 1956 [29]. It has mainly been used in underground work. The concept of vibro-impact drilling introduced in the last few decades has proven highly promising. Besides the rotative penetration, where the teeth of the bit penetrate in the rock when the drillstring rotates, the percussion action creates indentation in the formation, so this method requires less thrust and power. PUC-Rio University and CSIRO Petroleum[1] have developed a new drilling technique called **Resonance Hammer Drilling**, **RHD**. This drilling technique was first proposed in the works of Franca [29] and Detournay [20].


(a)



(b)

Figure 1.6: a) Resonance Hammer Drilling (RHD) technique [29].; b) Vibro-impact system.

[1]CSIRO, the Commonwealth Scientific and Industrial Research Organization, is Australia's national science agency

RHD has as its premise using the vibrations in the drillstring, particularly the axial vibration created during the cutting process. The axial vibration generated by the bit/ rock interaction excites a hammer. When the excitation frequency approaches the mass resonance, impacts on the bit occur, since the hammer displacement is limited by the gap. Therefore, in addition to the rotative penetration, a percussive action happens due to the impact of the hammer on the bit. That increases the rate of penetration (ROP). The impulsive force generated by the hammer should never be larger than the preload (WOB), due to the possibility of the bit bounce effect.

A first investigation of the RHD was presented by Franca & Weber in 2004 [29]. In this work, a model for the longitudinal behavior of the bit-rock with a vibro-impact system was investigated. Their work drew the conclusion that the behavior of period-1 (one impact per cycle) always created the best condition for penetration, increasing the ROP. A second investigation was later presented by Aguiar & Weber [1] [2] [3]. These works presented a new mechanism to enhance the ROP. A mathematical model validated through experimental data was developed in order to predict the impact forces of the hammer. This hammer consists of a mass-spring system with very low damping, which can impact a surface with a variable gap. The hammer increases the rate of penetration, not only with the increase of the dynamic force, but also by providing additional control on the weight on bit.

1.5 Literature survey

Due to number of subjects discussed in this thesis, the literature survey for each will be introduced sequentially. For instance, the review of drillstring basis and drill bit types were studied from the work of Thomas [77] and from several topics of Wikipedia [90]. As mentioned, drillstring vibration, drillstring axial vibration and bit/rock interaction were reviewed from the works of Chen [18], Cunningham [22], Dareing [23] [24] [25], Dykstra [27], Franca [29] and Alamo [33]. The current research on this new drilling technique, Resonant Hammer Drilling, was initiated in the works of Detourney [20] and Franca [29], and continued in the works of Franca and Weber [30] and Aguiar and Weber [1] [2] [3] [4] [5] [7]. Other subjects that will be discussed in this thesis include discontinuous and nonsmooth systems, impact mechanics and numerical simulation of nonsmooth systems.

1.6
Objective and scope of the thesis

The main objective of this thesis is fully understand the hammer behavior inside a vibrating structure. The hammer should have very low damping in order to generate large displacements. Such displacements can be limited by a gap, reducing hammer movement and generating impacts. During previous experiment [3], isolating the simultaneous actions and evaluating the influence of each proved difficult. Two test rigs were built in order to better understand these phenomena. They make use of laser displacement sensors and mini accelerometers. This hardware allows a better understanding of each phenomenon. The methodology of previous investigation [3] was used to collect data for several impact conditions. The use of new equipment improved the capability of investigating the system in a shorter time scale, enhancing knowledge of contact mechanics. In a previous experiment at the Dynamics and Vibration Laboratory at PUC-Rio, the hammer always impacted against a rigid support. The experiment was important to characterize the impact force generated by the hammer under different stiffness/gap combinations and different excitation frequencies. However, the hammer concept is proposed to be assembled in a vibrating structure (BHA). In other words, it is necessary to take into account that the impact support will also vibrate inside the structure.

The study of this test rig includes defining its characteristics, like the range of possible excitation frequencies and the measurement of the impulsive forces. The experimental part of the thesis presents data regarding the vibro-impact system under different hammer characteristics. A mathematical model will be proposed based on experimental data. This mathematical model will allow further investigations and suggest different possibilities for hammer construction.

This thesis contains an introductory chapter which surveys oilwell drilling, showing the two existing drilling techniques in the field and proposes a new hybrid drilling. The first chapter also discusses the different types of drillstring vibration, and the bit/rock interaction. This will lay the groundwork necessary to build an experimental test rig to better reproduce the relevant field characteristics for the new drilling technique.

Chapter 2 presents the experimental part of the work, presenting the two test rigs, describing the measurement hardware, experimental methodology and results, and discussing the results.

The main subject of Chapter 3 is the mathematical model of the hammer. The chapter starts with the literature survey on impact models and the numerical integration of non-smooth differential equations. The next section is dedicated to parameter identifications, including the impact force. Afterwards, a comparison will be performed between experimental results and numerical simulations, and observations regarding the mathematical model will be made.

Chapter 4 deals with the experimental analysis of a real size vibro-impact system that is being developed by CSIRO Petroleum in Perth, Australia, for the purpose of testing the Resonance Hammer Drilling design in the field. The test rig is called “Frank Jr.”, and its experimental analysis was the result of a 4-month exchange program with CSIRO. It is an important step in verifying the field application of this vibro-impact system. The test rig is fully described and relevant experimental results are presented.

Finally, in Chapter 5 a short overview of the thesis is given and its contributions are summarized. Unresolved problems are listed for further research and recommendations are given regarding the experimental analysis and the impact force behavior.