4
Experimental study of a real size vibro-impact system for the RHD

In this chapter the application of a vibro-impact system for improving the drilling performance of oil well drilling will be considered. This experimental part of the thesis was conducted in an exchange program with CSIRO Petroleum, Perth Australia, in the Drilling Mechanics Group. A brief description of this research group will be presented. The test rig where the experiment was performed will also be presented, along with applicable results. These experiment results show that impact forces during drilling improve the rate of penetration. Finally, some design considerations will be addressed, to indicate the optimum parameters for the use of a vibro-impact system in oil well drilling.

4.1
CSIRO and the Drilling Mechanics Group

CSIRO is Australia's national science agency and one of the largest in the world. CSIRO research delivers solutions for agri-business, energy and transport, environment and natural resources, health, information technology, telecommunications, manufacturing and mineral resources.

The availability of more sophisticated, cost effective and time efficient drilling technologies provides significant benefit to the oil and gas industry. CSIRO Petroleum conducts advanced research and development to improve drilling performance for the industry, delivering innovative solutions based on a robust theoretic and practical scientific approach. As global exploration efforts move to more challenging locations, the results of the Drilling Mechanics group are enabling industry to substantially mitigate the risk and cost associated with exploring in deep and remote locations.

The Drilling Mechanics group has invested in modeling capacity and the development of innovative laboratory scale equipment designed to reflect various field conditions with a view to better quantifying the influence of various factors on the specific energy required for drilling. These parameters include cutter size and shape, depth of cut, cutting speed and mud pressure. Machines affectionately named *Wombat* (the rock scratcher), *Taz* (the Tasmanian Devil), DIVA, *Frank*, *Ibis* and *Thor* (a modified lathe) together comprise a globally unique suite of facilities that assist researchers gain invaluable insight into drilling processes [21]. A brief description of the group of test rigs is listed below.

- **DIVA** - Drilling Induced Vibration Apparatus for testing of stick-slip oscillations. Rotary drilling systems equipped with PDC (fixed cutter) bits systematically experience torsional vibrations, which can often degenerate into stick-slip oscillations (where the drill bit sticks and slips on the rock during drilling). Laboratory scale experiments (DIVA) reflecting conditions on field rigs are being conducted to verify the predictions of the stick-slip vibration.
- **FRANK JUNIOR** - Drilling tests for Resonance Hammer Drilling (RHD). RHD consists of a new generation of rotary-percussive drilling, which can be a pneumatic knocker or an elastically suspended and periodically excited mass (hammer), which generates impulsive loads when impacting the bit that always remains in contact with the rock under the action of static weight-on-bit.
- **WOMBAT** - Kinematically controlled experiments for cutter-rock interaction. The horizontal velocity between the cutter and the rock is kinematically controlled. The depth of cut is fixed and remains constant along the cut.
- **TAZ** - Kinematically controlled experiments for cutter-rock interaction. Can also provide experiments under constant force and variable cutting speeds.
- **IBIS** - Kinematically controlled apparatus to drill small scale (diameter 50 mm), straight and curved borehole in soft rock material
- **THOR** - Kinematically controlled modified CNC lathe to study impregnated bloc/ rock interaction. Cylindrical rock samples are machined at high speed with cutting element made of artificial small diamonds embedded in a cobalt matrix.

The machines use sufficient precision to isolate and monitor the interaction between drill bit and rock, the consequences of microscopic drill bit wear, the force required to generate precise cuts in rock, the impact on equipment of drilling at different and curved trajectories, the consequences of vibration and so on.

4.2
RHD, Frank Jr. and experimental results

RHD (Resonance Hammer Drilling) is a new rotary-percussive technology, which is being studied at CSIRO as an alternative method to improve drilling performance in deep wells. This drilling method consists of a small hammer mounted in a conventional rotary drilling assembly. RHD is a hybrid form of drilling, different than percussive drilling, where normal operating parameters, namely the weight-on-bit and the angular velocity are still acting as in conventional rotary drilling [31].

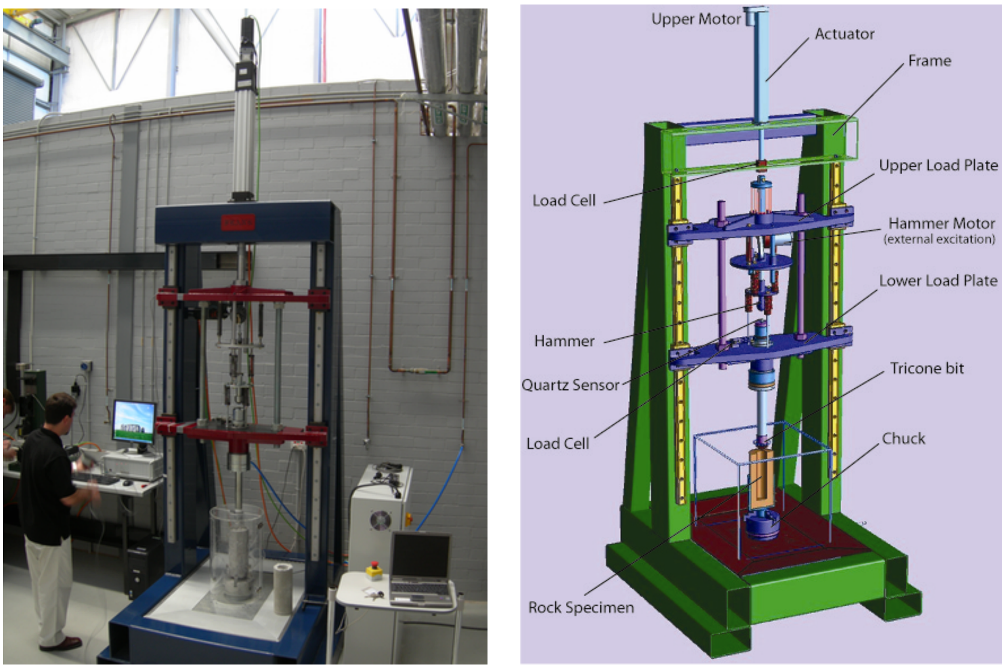


Figure 4.1: Frank photo and schematics (*Courtesy of Dr. Luiz Fernando Franca, CSIRO*).

The Frank Jr. apparatus, shown in Figure 4.1, was designed to represent the bit/rock interaction and its influence over the rate of penetration (ROP). The main components of Frank Jr. are described below:

- **Load frame** - It is composed of steel profiles and is designed to support the various elements while avoiding vibrations. Height of the frame is about 2.8 m, and its weight is 860 kg. The base part of the load frame bears a steel plate supporting the core drive mechanism.
- **Core drive mechanism** - This component drive the rock sample in a controlled condition. Located at the bottom part of the load frame, it consists of a brushless servo-motor combined with a 90-degree gearbox

and a chuck assembly. The maximum rotary speed and torque that can be provided are 400 RPM and 45 N.m, respectively. The chuck assembly is in line with the motor/gearbox and it is used to support the rock specimen. It should be mentioned that the rock sample is rotating, unlike conventional field drilling systems where the rotary speed is imposed on the bit.

– **Upper motor assembly** - It is designed to transmit weight (W) or rate of penetration (ROP) to the bit. This component consists of a geared brushless servo-motor mounted in line with a linear actuator. The linear actuator, which has 500 mm of stroke, is attached on the top of the frame. The maximum rotary speed and thrust are 600 RPM and 23.5 kN, respectively.

– **Upper and lower load plates** - These plates are designed to support the hammer system and the bit assembly. Weighting 89 kg each, both plates are fixed on linear guides and between them by two long threaded bars. As the upper load plate is fixed on the linear actuator, the whole system can move up and down as a rigid body.

– **Hammer system** - It consists of a drive system, slider-crank mechanism, reciprocating plate, springs and a steel mass (hammer) as shown in Figure 4.1. The drive system consists of a brushless servo-motor, bearings, a shaft and an excitation scale. The drive system and the slider-crank mechanism are used to transform the rotary motion of the motor into linear motion. The excitation scale is capable of modifying the amplitude of excitation. The gap, which is the distance between the head of the hammer and the anvil, can be modified using the thread bars, by increasing or decreasing the distance between the two load plates. In another experiment, not shown in this thesis, the hammer system is replaced by a pneumatic knocker, composed of an air supply, an airflow controller and the knocker itself.

– **Bit assembly** - It consists of a roller cone bit (tricone bit), a shaft and a small anvil.

– **Circulation fluid** - An air supply provides the required air pressure (700 kPa) to the beam inlet. The debris produced while drilling moves up in the annulus space. Additionally, an acrylic cover (guard) around the rock specimen is connected to a vacuum machine to facilitate debris evacuation.

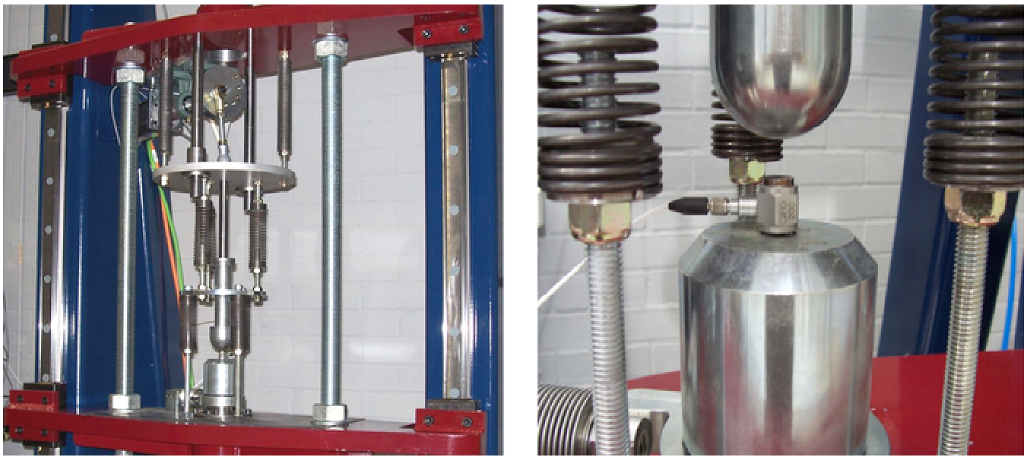
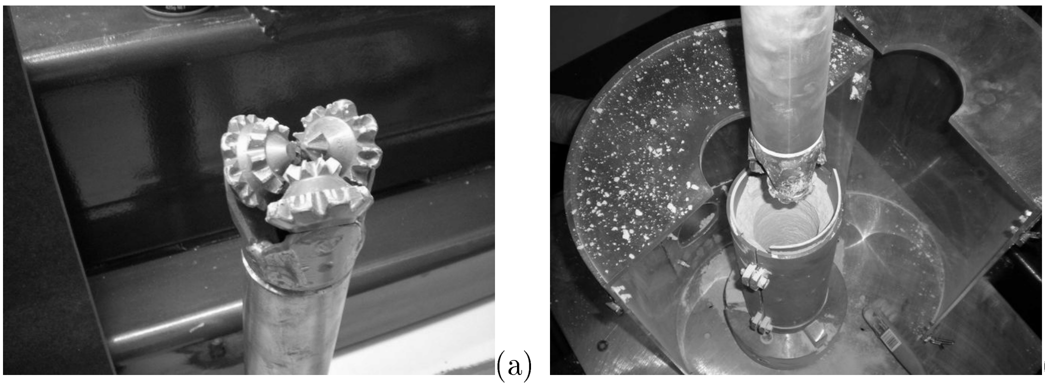


Figure 4.2: Frank's hammer device.

There are three control systems: the system controlling the upper motor assembly, the hammer system, and the core drive mechanism. Any velocity profile can be imposed on all motors, mainly constant RPMs or ramp profiles. Tests can be conducted either under given axial velocity (ROP) or imposed axial force W. In the latter case, the linear actuator is disconnected and only the dead weight of the plates, hammer system and the bit assembly are acting on the bit, $W = 2.83$ kN.



(a) (b)

Figure 4.3: Frank Jr. photos: a) Roller-cone bit; b) Set up before drilling test.

The main components of the control system are described as follows:

- **Driver** - Each motor is connected to its designated digital servo drive. The function of the drive or power amplifier is to provide the motor with the current necessary to produce a desired torque.
- **Controller** - The controller model utilized in this device has four independent axes of motion, one per motor. The controller is directly connected to the computer.

– **Computer** - The PC dedicated to the machine is utilized as a host computer for the controller. The connection between the PC and the controller and drives is made through a serial-type communication.

The instrumentation and data acquisition are designed to measure, process and save data from each test. The axial displacement (or penetration of the bit), the weigth-on-bit (W) and the torque-on-bit (T) are the parameters normally measured during the drilling process. Basically, the sensors measure the parameters and the data acquisition system processes and digitizes the data. The computer is used to monitor and to save data.

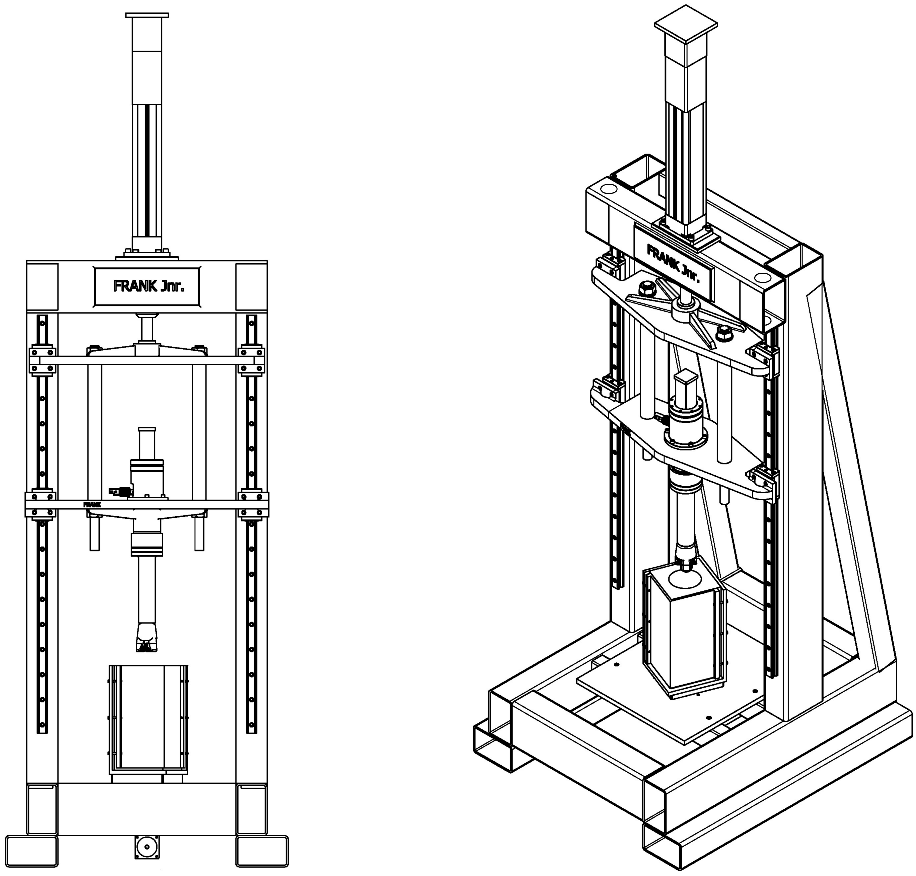


Figure 4.4: Frank Jr. Schematics (*Courtesy of Greg Lupton, CSIRO*).

The instrumentation intended for data acquisition consists of the following:

– **S-type load cell** - This sensor is used to measure the hook load. Although voltage is the output of this sensor, the data is converted to force (Newtons) after digitalization. Thus, the W, which represents the difference between the hook load and the weight of the moving parts, can be obtained.

- **Beam load cell** - This sensor is used to measure the torque-on-bit T. It is located at the junction of the anvil/shaft and the lower load plate. The anvil/shaft and the bit were designed to spin but are obstructed by the load cell. Consequently, T, which is the force used to fix the bit, is measured with the sensor.
- **Linear Variable Displacement Transducer (LVDT)** - This sensor is a displacement measuring sensor used to monitor the axial displacement of the bit and, consequently, the rate of penetration. It is located between the upper beam of the frame and the upper load plate. This transducer provides a regulated 0-10V feedback signal that is linearly proportional to the position of a traveling stainless steel extension cable.

Initially, experiments conducted with the conventional rotary drilling technique at atmospheric pressure are carried out. Afterward, tests performed with the RHD method are performed and the results compared with those of the conventional rotary drilling technique. Two sets of tests are performed: one with the weight-on-bit imposed (weight-control mode or dynamical-control mode) and a second with the rate of penetration imposed (kinematical-control mode). The aim is to determine if there is an improvement in the rate of penetration or reduction in weight-on-bit and/or torque-on-bit by superimposing impulsive loading.

In the dynamical-control mode, the linear actuator is disassembled from the upper plate, and therefore only the plate assembly weight is applied on the bit. In this mode, the weight W is the input parameter, and the rate of penetration is the output.

On the kinematical-control mode the opposite occurs. The linear actuator is attached to the plate assembly and a linear displacement is imposed by the actuator, becoming the input parameter.

Due to CSIRO proprietary information regulations, most of the experimental results can not be presented in this work. However, the results available confirm the application of an impulse force to the actual rotary drilling as an effective method to increase the ROP in oilwell drilling.

4.2.1 Weight-control Mode

Figure 4.7 shows the results of drilling tests performed with cement. Here, a linear response is obtained and the slope represents the ROP.


(a)

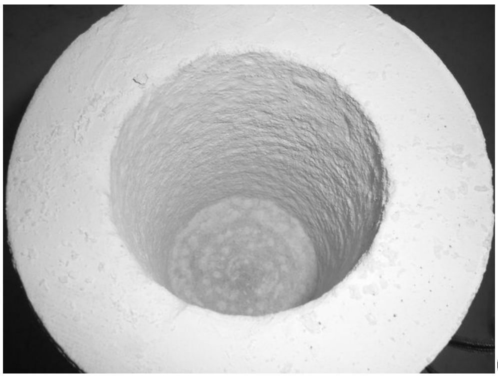

(b)

Figure 4.5: Frank Jr. photos: a) Rock sample after drilling; b) Rock sample borehole.

Notice that there is 100% improvement in ROP when percussive action is introduced to the drilling process. Actually, the overall energy provided to the bit increases by hammering and the ROP has to increase proportionally.

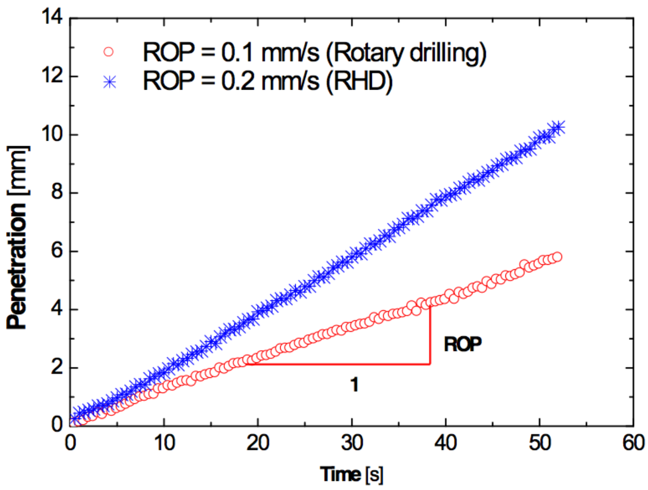


Figure 4.6: Frank Jr. drilling tests on cement. Bit penetration with and without percussive action for weight on bit = 2.83 kN, Ω_d = 20 RPM, excitation amplitude = 40 mm, excitation frequency = 4.8 Hz, hammer mass = 5.03 kg.

It is important to emphasize that such results from Frank were obtained before the work developed in chapter 3, where it was found the hammer parameters that optimizes the impact force. This means that Frank's hammer is not operating in its optimum condition, generating impact forces lower than it could develop.

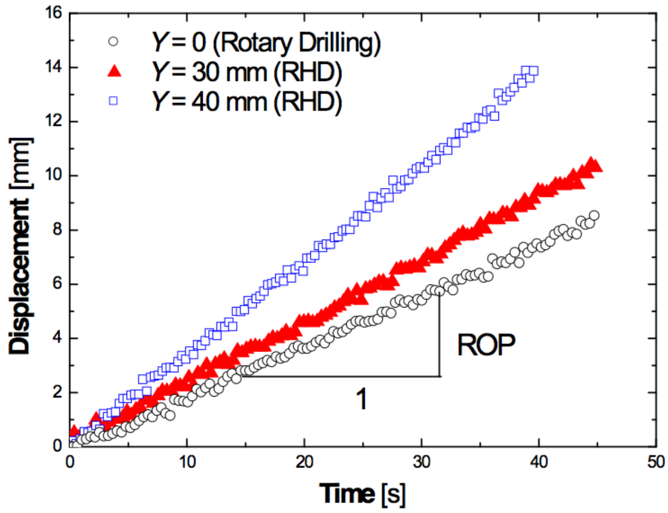


Figure 4.7: Frank Jr. drilling tests on cement. Bit penetration with and without percussive action for weight on bit = 2.83 kN, Ω_d = 60 RPM, excitation amplitude = 30 mm and 40 mm, excitation frequency = 4.8 Hz, hammer mass = 5.03 kg.

4.2.2
Kinematical-Control Mode

The efficiency of the impulsive load in the reduction of the drilling parameters (weight-on-bit and torque-on-bit) can be investigated by performing kinematically controlled tests. In this case, torque-on-bit and weight-on-bit are measured when a constant rate of penetration is imposed. Figure 4.8 illustrates the variation of the output parameters in the time domain, with and without the hammering action. These drilling tests were also performed in cement rock samples.

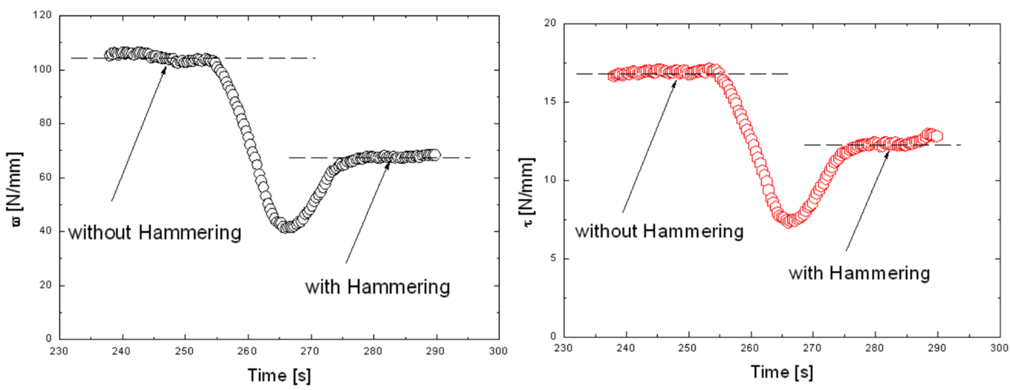


Figure 4.8: Drilling tests performed in cement. Reduction of weight on bit and torque on bit as the hammering system is turned on.

When the hammer is switched on, new values for torque-on-bit and weight-on-bit are obtained (neglecting the transient behavior). Notice that there is a reduction of 34% in the weight-on-bit and of 29% in the torque-on-bit. In reality, the energy supplied to the bit is constant in kinematically controlled tests. So less weight and torque are needed during rotary action when the hammer is switched on, since part of the energy is now provided by percussion. This fact represents another advantage of this new technique, where the magnitude of the drilling parameters can be minimized when impulsive loading or percussive action is added to the drilling process. Based on this result, RHD can be considered to have potential application as an alternative technique for highly deviated drilling or horizontal wells, where the torque-on-bit and weight-on-bit are limited.

4.2.3
Axial behavior of the bit/ rock interaction

The energy source that supplies the percussive action (hammer) for the RHD technique (implemented on Frank Jr.) comes from an external source (AC motor). In fact, the primary aim of the research at CSIRO was to effectively investigate the effect of impulsive load on the conventional rotary drilling with roller-cone bit. Hence, a hammer system driven by a servo-motor (external energy source) was used to generate the controlled percussive action.This is a different method as compared to the basic idea of this thesis, which is to use the existent axial vibration of the drillstring generated by the bit/ rock interaction to excite the hammer. It is not the aim of the thesis to discuss what is the best energy source to excite the hammer. However, this section shows that it is possible to use the axial vibration generated by the bit/rock interaction to excite the hammer.

The Frank Jr. test rig is set to work on weight-control mode (the displacement actuator is disassembled from the plate assembly). An accelerometer is placed on the lower plate, see Figure 4.4, along the vertical axis. The rock sampled is drilled under different rotation velocities and the vertical acceleration of the bit assembly is measured during drilling. The Fourier Transform is applied on the acceleration signal and the results are shown in Figures 4.9, 4.10 and 4.11.

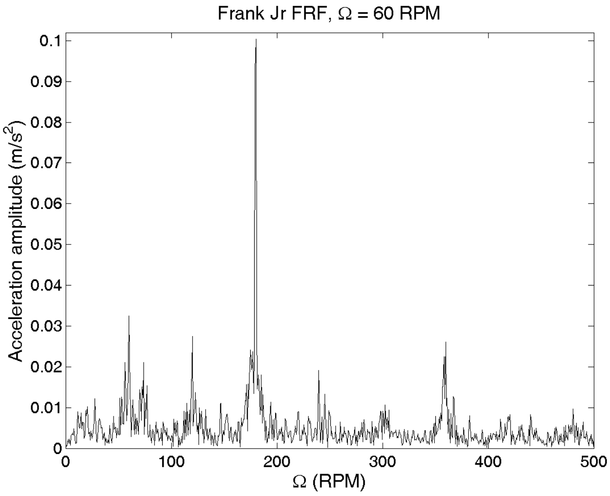


Figure 4.9: FRF of acceleration signal, drilling test under dynamic control: a) $\Omega_d = 60RPM$.

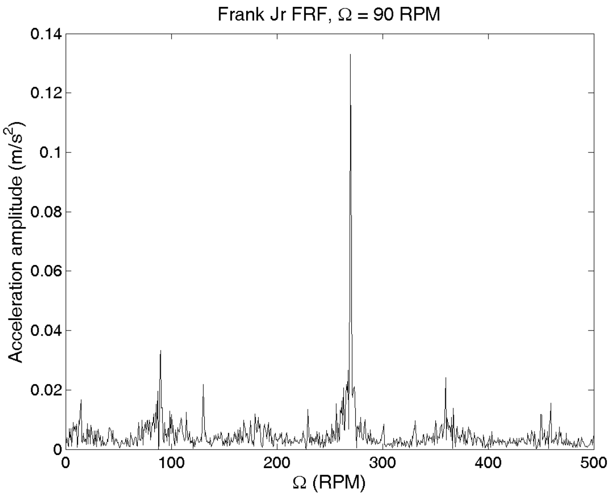


Figure 4.10: FRF of acceleration signal, drilling test under dynamic control: a) $\Omega_d = 90RPM$.

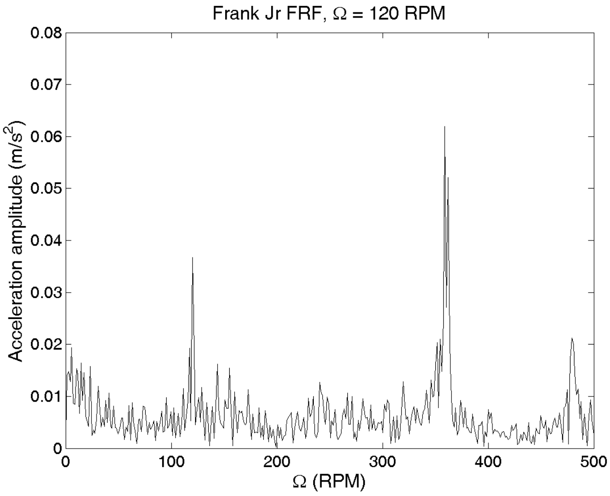


Figure 4.11: FRF of acceleration signal, drilling test under dynamic control: a) $\Omega_d = 120RPM$.

It is observed in all three charts that there is a strong peak in the acceleration signal. This peak happens always for a frequency that is three times the rock sample rotation. This is explained by the fact that rock is being drilled using a tricone bit (3 cones). These experimental results on Frank Jr. confirms the phenomenon firstly observed by Cunningham [22], and assures the axial behavior of the drillstring as an excitation source for the hammer.

4.3 Hammer design considerations

In this section it is discussed the hammer parameters which maximize the impact force magnitude. As observed during the previous chapters of this thesis, if the maximum value of the impact force is desired the hammer has to operate with 0.0 mm gap and at its impact resonance, which is twice the value of the hammer natural frequency (in the case of 0.0 mm gap). The input excitation frequency is determined by the drillstring rotation velocity. With the excitation frequency defined, the relation between the hammer stiffness and mass is according to the following:

$$\frac{\Omega}{\omega} = 2 \Rightarrow \frac{k}{m} = \frac{\Omega^2}{4} \tag{4-1}$$

A brief study is carried out in order to understand how the variation of these parameters (k and m) affects the impact force magnitude. With the data collected from Frank Jr., for a drillstring rotation of 60 RPM

(Ω_d), see Figure 4.9, the hammer excitation frequency becomes three times the drillstring rotation ($\Omega = 180RPM = 3Hz$). Using the mathematical modeling of the hammer supported by beam springs developed in Chapter 3, see Equations (3-30) and (3-32), the impact force magnitude will be observed as the hammer mass is varied. The mass ratio m/M is considered, where m is the hammer mass and M is the cart mass. The impact force is evaluated in both absolute and non-dimensional values (F_i and F_i/mg). The results of this simulation are shown in Figure 4.12.

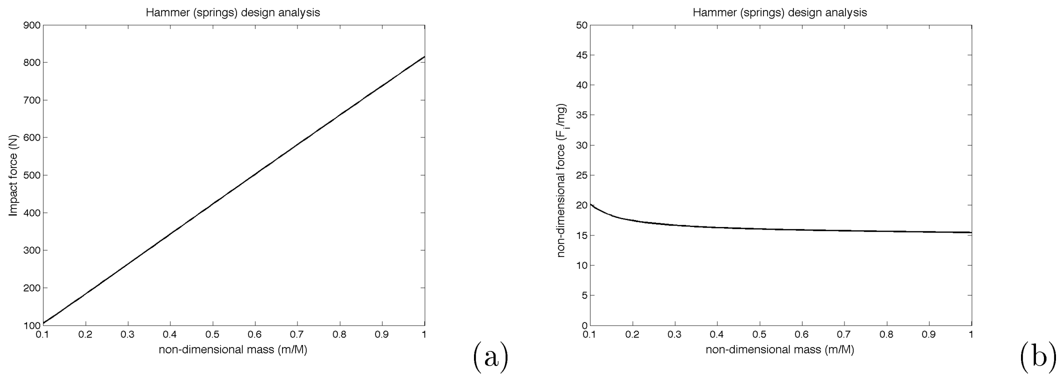


Figure 4.12: Hammer springs design, excitation frequency $\Omega = 3Hz$: a) Impact force *versus* mass ratio; b) Non-dimensional force (F_i/mg) *versus* mass ratio.

From the chart above it is shown that the impact force magnitude increases linearly as the non-dimensional mass increases. However, when considering the non-dimensional term F_i/mg there is no substantial difference as the non-dimensional mass increases. Similar results are observed when the drillstring rotation Ω_d is varied. These results are show in Figures 4.13 and 4.14. As the excitation frequency is increased, higher values of the impact force are observed, both in absolute and non-dimensional terms. However, it is important to emphasize that drillstring rotation is a service condition, and should be varied according to field conditions (rock formation, for instance). Also, with higher values of the excitation frequency more energy is applied to the hammer, as noticed in Equation (2-1).

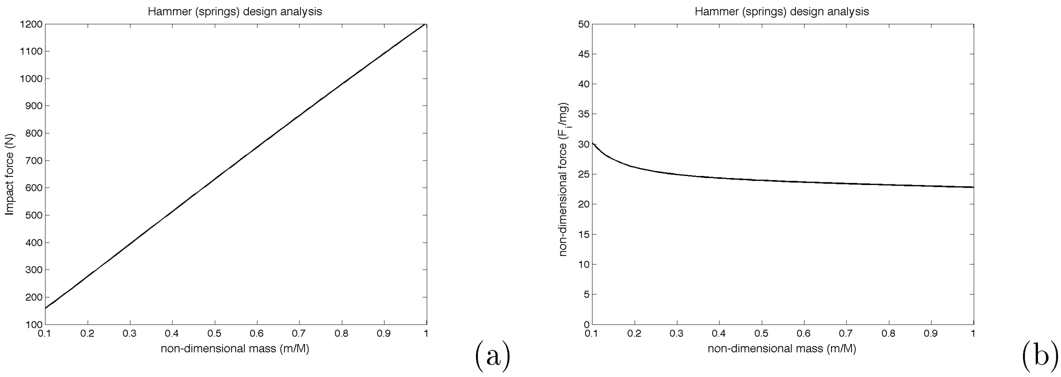


Figure 4.13: Hammer springs design, excitation frequency $\Omega = 4.5Hz$: a) Impact force *versus* mass ratio; b) Non-dimensional force (F_i/mg) *versus* mass ratio.

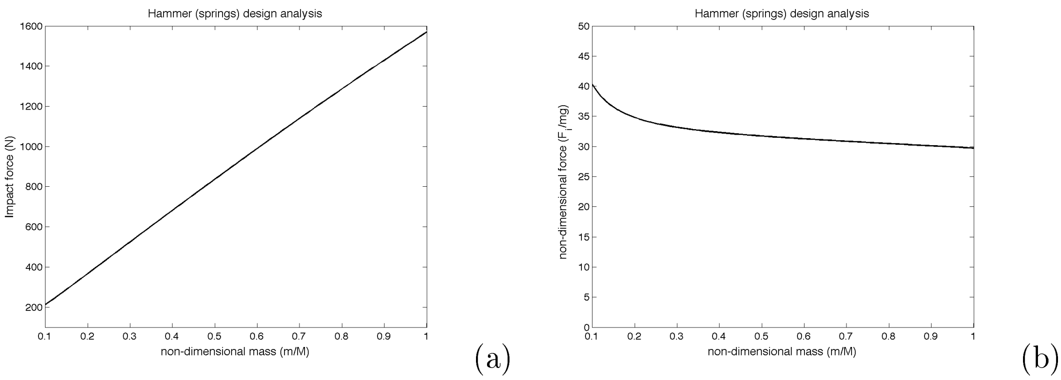


Figure 4.14: Hammer springs design, excitation frequency $\Omega = 6Hz$: a) Impact force *versus* mass ratio; b) Non-dimensional force (F_i/mg) *versus* mass ratio.

Obviously, the maximum impact force of the hammer should not be the only design criteria observed. The maximum value of the impact force should be chosen so that the structural integrity of the bottom hole assembly, including the drill bit, is not compromised.

4.4 Final remarks

In the case of the RHD method, the application of an impulsive load to the drilling process brings an increase of the rate of penetration (ROP) in tests under weight-control mode as well as a reduction of the drilling parameters (weight-on-bit and torque-on-bit) in tests under kinematical-control mode. Indeed, the percussive action provides extra energy to the bit, during tests under weight-control mode, consequently causing an improvement in the ROP. For tests conducted under kinematical-control mode, the energy supplied to the bit is constant, and thus less weight-on-bit and torque-on-bit are observed, because part of the energy is now provided by percussion. These results support this new drilling method as a alternative technique to improve drilling performance.