1
Introduction

1.1 Motivation of the Thesis

The oil well drilling is still an interesting topic of research. There are still many challenges involving the modeling of the complex dynamics of a drill string. It presents interesting phenomena, such as coupled axial, lateral and torsional vibrations [86], bit-rock interaction, geometric nonlinearities, impacts, fluid-structure interaction. The literature dealing with modeling the drill string dynamics is vast (see [14, 36, 69, 79, 77]).

Besides this complex dynamics, the drill string dynamics involves also numerous sources of uncertainties. In this context of modeling, uncertainties should be taken into account in the computational models in order to improve the robustness of the numerical predictions [39, 92, 38, 67].

Recently this problem of modeling and simulation of nonlinear dynamics of a drill-string including uncertainty modeling has been intensively studied, as [74, 76, 80, 74, 82, 78].

Due to the growth of perforation depth over the years, the drilling process requires a constant improvement in energy efficiency. Reduction of costs and increase in bit life and in rate of penetration are always challenges for oil companies.

During conventional rotary drilling, many different forms of dissipation, as axial vibrations, can generate the waste of the energy applied in the drillstring. To compensate these losses, many new concepts of drilling were proposed over the years. These new approaches consider the efficient use of energy as an important factor, bringing an increase in rate of penetration, and consequently a reduction the cost of hard rock drilling. One example, is the concept of percussive drilling, introduced in the last decades [5]. The percussion proposes to insert energy into the drilling process through impacts to fracture the rock, and then facilitate the penetration of the bit [3, 2, 28, 27, 60, 58, 70, 22]. The objective is to combine rotary and impact action in order to increase the drilling rate.

This concept of use of impacts in drilling motivates this Thesis. We are interested in simple systems that present the phenomenon that somehow mimic the dynamical behavior found in the percussive drilling process: the vibro-

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impact action. Despite the systems analyzed do not consider the rotary action, we do believe that they represent an initial step to study the percussive drilling.

As percussive dynamical systems can be affected by many factors, their analysis requires to take into account uncertainties in the computational models that are used (see for instance [87]). Thus, we are interested also in problems that involve uncertainty quantification and stochastic modeling.

The analysis of vibro-impact systems is not a new subject, and is frequently encountered in technical applications of mechanisms. The interest of analyzing their performance is reflected by the increasing amount of research in this area (see for instance [63, 68, 98, 75, 33, 96], and also the book by Ibrahim [32], which is completely devoted to this problem). Besides the theoretical research in vibro-impact dynamics, numerous applications to vibro-impact systems have also been developed, such as vibration hammer, impact damper, and gears. The vibro-impact dynamics appears also in several other situations, as for example in earthquakes, where the interest is the seismic mitigation [66].

The focus of this Thesis is to analyze numerically the performance of vibro-impact systems with motion driven by an electrical motor. This performance is measured by the impact power (transferred from the system to an external barrier) and by the electric power consumed by the electrical motor that drives the system motion. In the developed model of the system, the influence of the DC motor in the dynamic behavior of the system is taken into account.

The electromechanical systems analyzed in this Thesis were first designed by R.R. Aguiar in his PhD Thesis [1]. He investigated experimentally a vibro-impact system with motion driven by an electrical motor, with a similar coupling mechanism between the mechanical and electrical parts of the system, the *scotch yoke* mechanism. The main objective of R.R. Aguiar was to characterize the impact force magnitude and to make numerical analysis through bifurcation diagrams, Peterka map [72] and basins of attraction. Aguiar published some journal papers about his work, as [3, 2].

Mechanical systems with motion driven by electric motors are usually modeled eliminating the motor and saying that the force between the mechanical and electric systems is imposed, so no electromechanical coupling is present, and it is harmonic with frequency given by the nominal frequency of the motor. In this Thesis, it is shown that this hypothesis is far from true and leads to a completely different dynamics. In the systems we analyze here, the coupling force is not prescribed by a function, it comes from the coupling, varying with the coupling conditions [44, 18]. Therefore, the dynamics of electromechanical systems is characterized by a mutual interaction between the

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mechanical and electric parts, that is, the dynamics of the motor is heavily influenced by the mechanical system and the dynamics of the mechanical part depends on the dynamics of the motor [4].

After an extensive literature review, no references dealing with this mutual interaction between electric and percussive systems were found. Hence we believe that this Thesis is a first work on this topic.

1.2 Percussive systems

Percussive systems are usually composed by a cart with motion driven by an external system (in our case it is an electrical DC motor) and, by an embarked hammer in the cart. The cart acts like a hammer case and induces the hammer motion. An external barrier (representing the soil, in the case of percussive drilling systems) constrains the hammer movements. Due to the relative movement between the hammer and the barrier, impacts can occur between these two elements. The interaction between those components (DC motor, cart, hammer, and barrier) gives to the system dynamical special features, and turns the dynamical behavior very nonlinear. These interactions are described as following:

- Between the mechanical and electrical parts of the system appears an electromechanical coupling in which the coupling force varies with the coupling conditions. The result is a mutual interaction between the mechanical and electric parts.
- The motion of the hammer is induced by the motion of the cart, in a way that there is no direct control on the hammer motion. Therefore, the hammer introduces a new feature since its motion acts as a reservoir of energy, i.e. energy from the electrical system is pumped to the hammer and stored in the hammer motion, changing the characteristics of the mechanical system (see [13, 59]).
- Part of the energy stored in the hammer motion is transferred to the external barrier through the impacts. The impact power achieved is one the variables used for measuring the system performance. In the case of drilling, this power would be used to fracture the soil and enhance the penetration.

To understand the role played by each one of these phenomena in the dynamics of the electromechanical percussive systems, we decided to split the problem into four simpler problems, in hierarchical complexity: from simpler to more complexity. With this division, to every concluded step, we gained some

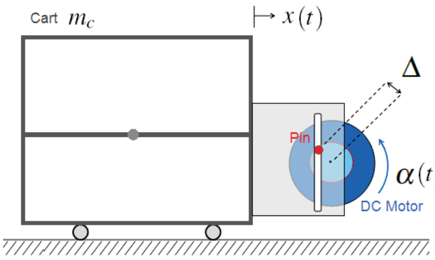

Figure 1.1: First system: cart-motor system.

insight into the behavior of the electromechanical percussive systems and, we published some works. The systems studied are described in the next Section.

1.3 Hierarchical electromechanical systems analyzed

We started the study analyzing the dynamics of a very simple system, composed of a cart whose motion is driven by an electrical DC motor, as shown in Fig. 1.1. The coupling between the motor and the cart is made by a mechanism called *scotch yoke* so that the motor rotational motion is transformed into a cart horizontal motion. This system is a bare minimum to analyze the effect of the electromechanical coupling, i.e., the mutual interaction between the mechanical and electric systems, in which the coupling torque appears as a parametric excitation, i.e., a time variation of the system parameters (see for instance [10, 97]). In this simple motor-cart system the coupling is a sort of master-slave condition: the motor drives, the cart is driven, and that is all.

The second system analyzed has the same two elements of the first and also a pendulum with suspension point fixed in cart, as shown in Fig. 1.2. The pendulum is the embarked system and its motion is driven by the motion of the cart. So there is no direct control of the motion of the pendulum. The pendulum introduces a new feature since its motion acts as a reservoir of energy, i.e. energy from the electrical system is pumped to the pendulum and stored in the pendulum motion, changing the characteristics of the mechanical system. The objective of the study of this motor-cart-pendulum system is to analyze the influence of an embarked element in the dynamics of the electromechanical system. One of the main results is that the master-slave condition, that appeared in the cart-motor system, is not anymore a characteristic of the system.

The third system analyzed has the same three elements of the first and also a flexible barrier placed inside the cart that constrains the pendulum

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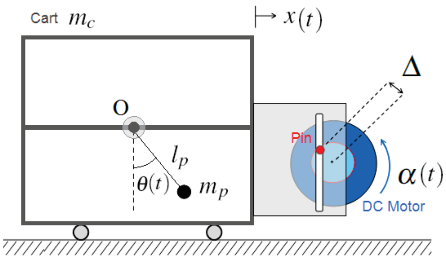

Figure 1.2: Second system: cart-motor-pendulum system.

motion, as shown in Fig. 1.3. Due to the relative movement between the cart and the pendulum, it is possible that occur impact between these two elements. Thus, the third electromechanical system analyzed has internal impacts. The impacts are caused by the motion of the cart that induces the motion of the pendulum. As the impacts are internal, the energy stored in the pendulum motion it is not transferred outside the system, it stays within, with a possible dissipation. This system configuration helps to understand the difference between an internal and an external barrier. The objective in this part of the Thesis is to analyze the maximal energy stored in the barrier in impacts as function of some parameters of the electromechanical system. Due to the presence of uncertainties in the computational nonlinear dynamics model of the electromechanical system with internal impacts, the energy analysis is performed from a stochastic view point for different levels of uncertainties, and also for the deterministic case.

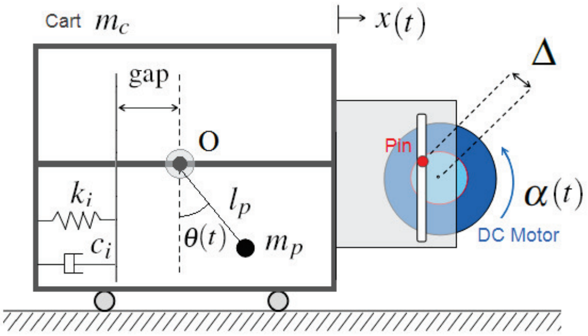

Figure 1.3: Third system: motor-cart-pendulum-barrier system.

The fourth system analyzed is the percussive electromechanical system. It is composed of a cart coupled to a DC motor by the *scotch yoke* mechanism, and of an embarked hammer in the cart. In this percussive system, we opted to change the geometry of the embarked element. We do not consider anymore a pendulum. We took a particle with concentrate mass able to move in only one direction. This hammer is connected to the cart by a nonlinear spring component and by a linear damper, so that a relative motion exists between

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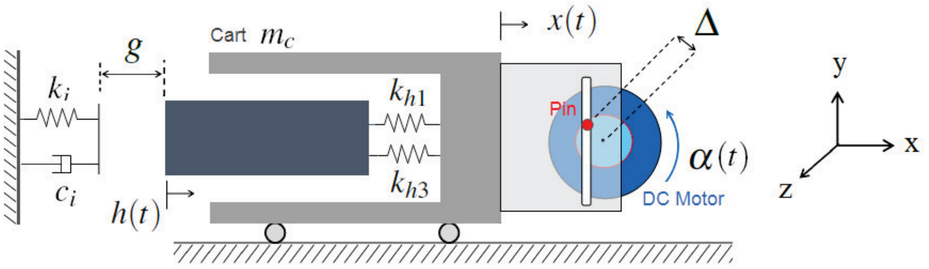

Figure 1.4: Fourth system: motor-cart-hammer coupled system.

them. A linear flexible barrier, placed outside of the cart, constrains the hammer movements, as shown in Fig. 1.4. Due to the relative movement between the hammer and the barrier, impacts can occur between these two elements. As the impacts are in an external barrier, the energy stored in the hammer motion it is transferred outside the system. The objective in this part of the Thesis is to analyze the performance of this percussive system with motion driven by a DC motor. We performed an optimization of the system with respect to design parameters in order to maximize the impact power under the constraint that the electric power consumed by the DC motor is lower than a maximum value. This optimization problem is formulated in the framework of robust design (see [81, 9]) and it is solved for different levels of uncertainties and also for the deterministic case.

1.4 Organization of the Thesis

The Thesis is organized as follows. In Chapter 2, we analyze the simplest eletromechanical system: the motor-cart system. Then, in Chapter 3, we analyze the system that has the same elements of the first system and has a pendulum that is embarked in the cart: the motor-cart-pendulum system. In Chapter 4, we include inside the cart a flexible barrier constraining the pendulum motion. Thus we deal with an electromechanical system with internal impacts. In Chapter 5, we analyze the performance of a percussive electromechanical system. The objective is to optimize of this system with respect to some chosen design parameters in order to maximize the impact power under the constraint that the electric power consumed by the DC motor is bounded. Finally, in Chapter 6, the results are summarized and future works are discussed.

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