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Energy behavior of an electromechanical system with internal impacts and uncertainties

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A B S T R A C T

This paper analyzes the maximal energy stored in an elastic barrier due to the impacts of a pendulum fitted within a vibro-impact electromechanical system considering the existence of epistemic uncertainties in the system parameters. The vibro-impact electromechanical system is composed of two subsystems. The first subsystem is the electromechanical system composed by a motor, cart and pendulum, and the second is an elastic barrier. The first will be called striker system. The pendulum is fitted within the cart. Its suspension point is fixed in the cart, so that it may exist a relative motion between cart and pendulum. The influence of the DC motor in the dynamic behavior of the pendulum is considered. The coupling between the motor and the cart is made by a *scotch yoke* mechanism, so that the motor rotational motion is transformed in horizontal cart motion over a rail. The pendulum is modeled as a mathematical pendulum (bar without mass and particle of mass m_p at the end). A flexible barrier, placed inside the cart, constrains the pendulum motion. Due to the relative motion between the cart and the pendulum, impacts may occur between these two elements. The objective of the paper is to analyze the energy stored in the barrier due to impacts as a function of some parameters of the electromechanical system from a deterministic and from a stochastic viewpoint. The system is designed as an aid in drilling. The impacts damage or fracture the rock and facilitate the conventional drilling.

1. Introduction

1.1. Motivation

The oil-well drilling is an interesting topic of research. Due to the growth of perforation depth over the years and the increasing costs, 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 a waste of the energy applied in the drillstring. To compensate for 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 in the cost of hard rock drilling. One example is the concept of percussive drilling, introduced in the last decades [1]. With the

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percussion the intention is to insert energy into the drilling process through impacts to damage or fracture the rock, and then facilitate the penetration of the bit [2–6]. The objective is to combine the impact action with the classical drilling mechanism in order to increase the drilling rate. The effect of impacts in the rate of penetration is the motivation of this paper, but first we analyze how the impacts affect the distribution of energy in a simpler system. The system analyzed presents the phenomenon that somehow mimic the dynamical behavior found in the percussive drilling process: the vibro-impact action. Despite the system analyzed does not consider the rotatory action, we do believe that it represents an essential initial step to study the percussive drilling.

Percussive systems are usually composed of two parts: a mechanical part (designed to impact a barrier, composed, for example, of a cart with a hammer), and an external part which drives the system (an external power supply, that may be, for example, a motor). The expression *hammer fitted within the cart* means that there is no external control of the hammer. The motion of the hammer is induced by the motion of the cart. Unfortunately, vibro-impact systems are usually modeled eliminating the coupling, that is the mutual influence between driver and driven, and saying that the force between the cart and motor is imposed, often harmonic. Different from what is found in the literature, this paper considers the coupling between the striker and driver parts, i.e., it takes into account the mutual interaction between them. Thus, the coupling force is not prescribed by a function, it depends on the process. The force comes from the coupling and varies with the coupling conditions (depends on the initial conditions, for example).

The study of coupled systems is not a new subject. Many works have been done on this topic, as [7–11]. The presence of nonlinearities arising from the mutual interaction between the parts of the system leads to very interesting dynamical behavior [12–14].

The system analyzed in this paper has an electromechanical coupling [15,16]. It is composed of a cart, a DC motor coupled with the cart, and a pendulum fitted within the cart. The suspension point of the pendulum is fixed in the cart, so that there exists a relative motion between pendulum and cart. The pendulum motion is driven by the cart in a non-controllable way. A flexible barrier placed inside the cart constrains the pendulum motion. Due to the relative motion between the cart and the pendulum, shocks may occur between these two elements, and part of the energy stored in the pendulum motion is transferred to the barrier. The maximum transferred energy is one the variables that can be used to measure the system performance.

This work studied a coupled system with a pendulum fitted within the system, i.e., a moveable mass inside the cart that is not controlled from the outside and, therefore, gives a rich dynamics. So the system can have internal shocks that change the cart dynamics in a way surprising to a external observer. This, we believe, is one of the novelties of this paper.

In the system that we analyze in the paper, the barrier is placed inside the cart, in a way that the system analyzed has internal impacts. Consequently, the energy stored in the pendulum is not transferred outside the system, the energy is only redistributed (in the non-dissipative case) within the system. As this paper is a preliminary work to study percussive drilling, we placed the barrier inside the cart instead of outside because we would like to start our study analyzing only the effects of impacts, and not the effect of impacts plus transfer of energy outside the system. Thus, this paper highlights the effects of internal impacts in the dynamical behavior of the system.

It should be noted that, in [17,18], the equations and the numerical integration were presented for a similar electromechanical system for which there was no impact. These works have allowed the coupling torque in the electromechanical coupling to be analyzed as a parametric excitation [19], i.e., the pumping of energy into the system due to the time variation of the system parameters [20,21]. The objective was to observe, by numerical simulations, that the dynamics of electromechanical systems is characterized by a mutual interaction between the mechanical and electric systems, that is, the dynamics of the motor is heavily influenced by the mechanical system and the dynamics of the mechanical system depends on the dynamics of the motor. Additionally, in [17,18] the influence of the pendulum fitted within the cart in the dynamic behavior of the system was investigated. It is shown that 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 solutions of the dynamic equations (see [22–25]).

The mutual interaction between the mechanical and driving parts affects an important variable used to evaluate the performance of the vibro-impact system, which is the energy stored in the barrier [26,27].

1.2. Objectives

The interest in analyzing the dynamics of vibro-impact is reflected by the increasing amount of research in this area (see for instance [28–31]). The books [32,33] are completely devoted to the problem. However, they do not consider in their mathematical models the coupling between the mechanical and driving parts. In this paper, we do consider the coupling. We consider the mutual interaction and, by numerical simulations, we observe how it affects the impact energy.

The objective of the paper is to analyze, in an ideal situation, the impact energy as a function of some chosen parameters of the electromechanical system, as the properties of the barrier and a parameter of the coupling mechanism, called d, which controls the nonlinearity of the problem. Increasing d, the nonlinearity also increases and, also, the computation of the dynamics is more time consuming. Two different configurations of the vibro-impact system were analyzed separately. In the first one, it is considered no coupling between the motor and the mechanical system, i.e., $d = 0$ m. In this case, the motor is uncoupled and, consequently, the cart does not move. In the second configuration, it is considered a coupling, i.e., $d > 0$ m. The focus was in finding the influence of the coupling in the impact energy, and the results show that they are closely