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# Analytical model of the contact interaction between the components of a special percussive mechanism for planetary exploration

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ABSTRACT

Special percussive mechanisms, e.g. Auto Gopher and UltraSonic/Sonic Driller/Corer (USDC) have been developed by NASA Jet Propulsion Laboratory and Honeybee Robotics Spacecraft Mechanisms, Corp. to address some of the limitations of current drilling techniques for planetary exploration. The percussive mechanism consists of an ultrasonic horn, a free mass (hammer) and the drill rod. This paper presents the analysis of the interaction between these three components. The impact between the components (i.e. ultrasonic horn and free mass, and free mass and drill rod) is analyzed using solid body collision analysis applying the principle of conservation of momentum. The drill rod is modeled for both undamped and damped cases with equivalent generalized single degree of freedom system. Various values are used for the coefficient of restitution to account for energy loss during impact. The energy transferred to the drill rod by the free mass is obtained determining the change in kinetic energy due to impact. It is observed that the free mass converts the high frequency of oscillation of the ultrasonic horn into lower frequency impacts on the drill rod. A decrease in the coefficient of restitution results in a decrease in the number of impacts, impulse imparted to the drill rod and energy transferred to the drill rod by the impact of the free mass.



## 1. Introduction

For years, humans have spent great effort and resources in studying and understanding the environment in the moon and other planetary bodies (i.e. Mars, asteroids) with the ultimate goal of facilitating human colonization. A study of lunar regolith and soil/rock samples of other planetary bodies is vital to achieve this goal. However, the task of obtaining a regolith/ soil sample is a great challenge given the radically different conditions on these planetary bodies compared to that of Earth [1–4]. Regolith (soil) samples obtained from previous lunar missions, such as those obtained using self-recording penetrometer (SPR) in Apollo 15 and 16 missions, have provided some useful information on properties of the regolith [5]. However, more information is needed in order to fully understand the mechanical properties of the lunar soil. The challenges of the current drilling techniques are the large axial forces and holding torques needed [6], which means that a relatively large mass equipment is needed. To address these challenges, a percussive ultrasonic/sonic driller/corer (USDC) was developed [7].

The USDC mechanism consists of an ultrasonic horn that is vibrated by a piezoelectric actuator. The ultrasonic horn drives a free-mass, which hits the drill bit (rod), creating a stress wave that propagates through the rod. This stress wave is transferred to the rock/soil, making the rod

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penetrate into the rock/soil. During operation the free mass oscillates between the horn and drill rod creating multiple impacts [8]. While the percussive mechanism is effective for drilling hard-brittle materials, it is not as effective in soft materials, in which rotary drilling provides a better efficiency. A percussive augmenter for a commercial rotary drill was developed to combine the advantages of both, rotary and percussive drilling [9]. Based on this concept the Auto-Gopher [10] was designed to combine rotary and percussive drilling in a single device specifically for space applications [11]. In the Auto-Gopher device that is developed by Honeybee Robotics Spacecraft Mechanisms Corporation and NASA Jet Propulsion Laboratory, the rotation is provided by an electromagnetic motor, while the percussive impacts are provided by the ultrasonic actuator of the USDC.

During impact within the different components of the ultrasonic percussive mechanism energy could dissipated in different forms, such as plastic deformation and propagation of longitudinal waves [12]. Furthermore, it has been shown that in the case of repeated impacts, as in percussive drills, the coefficient of restitution (for identical impacts) increases as the number of impacts increase [13]; then it reaches a maximum value.

This paper focuses in developing a practical analytical model to analyze the interaction between the ultrasonic horn, the hammer (free mass), and the drill rod of the ultrasonic percussive mechanism. The drill rod has been modeled with and without structural damping by an equivalent generalized single degree of freedom (SDOF) system in order to develop an simple and practical solution methodology. Only the underdamped case, which is the most practical case, has been investigated in this study. The impact between the different components is analyzed using solid body collision analysis applying the principle of conservation of momentum. Special attention is given to determine the position of each component of the percussive mechanism as a function of time for different values of the coefficient of restitution to account for energy loss during impact. The impulse imparted to the drill rod by the free mass is calculated using impulse–momentum principle. Additionally, the energy transferred to the drill rod by the free mass (for different values of the coefficient of restitution) is presented as a function of the frequency of oscillation of the free mass. Moreover, an energy balance method (Cox Method), introduced by Cox (1849) [14], is used to determine force generated between the free mass and the drill rod during impact and the duration of such impact. This theory assumes that the kinetic energy of the striker (before impact) is transferred entirely into strain energy of the rod and it has been used to estimate the contact force due to transverse impact on a beam [15] and railway rails subjected to central impact [16].

## 2. Interaction of percussive mechanism components

The ultrasonic percussive mechanism (Fig. 1) is composed of an ultrasonic horn, a free mass, and a drill rod. The operation of the ultrasonic percussive system begins with the excitation of the ultrasonic horn by imparting high frequency voltage to the piezoelectric actuator. The ultrasonic horn vibrates harmonically with a frequency of about 22.5 kHz and amplitude, $B_0$, of around 10 μm [6]. For convenience, the horn position function is selected so that the horn tip is able to move up and down from its initial position. The position and the velocity of the horn tip are given by:

$$u_h = B_0 \sin(\varpi t) \tag{1}$$

$$v_h = B_0 \varpi \cdot \cos(\varpi t) \tag{2}$$

where $B_0$ is the amplitude of vibration, and $\varpi$ is the vibration frequency. The excitation imparted to the horn causes it to impact the free mass. The velocity, $v'_{fm}$, of the free mass after impact is obtained by applying conservation of momentum principle, thus:

$$m_h v_h + m_{fm} v_{fm} = m_h v'_h + m_{fm} v'_{fm} \tag{3}$$

where $m$ is the mass, $v$ is the velocity immediately before impact, $v'$ is the velocity immediately after impact, and the subscripts $h$ and $fm$ correspond to horn and free-mass, respectively. By definition the coefficient of restitution $e$ is given by:

$$e = \frac{v'_{fm} - v'_h}{v_h - v_{fm}} \tag{4}$$

Using Eqs. (3) and (4) the velocity, $v'_{fm}$, of the free mass after impact is given by:

$$v'_{fm} = \frac{m_{fm} v_{fm} + m_h v_h + m_h e (v_h - v_{fm})}{m_h + m_{fm}} \tag{5}$$

Since the ultrasonic horn is controlled by the piezoelectric actuator, and its mass is much greater than that of the free mass, it is assumed that its motion is not affected by the impact of the free mass (i.e. $v'_h = v_h$). Considering particle motion, the position/displacement, $u_{fm}$, of the free mass is given by:

$$u_{fm} = u_0 + v_{fm} \cdot t + \frac{1}{2} a t^2 \tag{6}$$

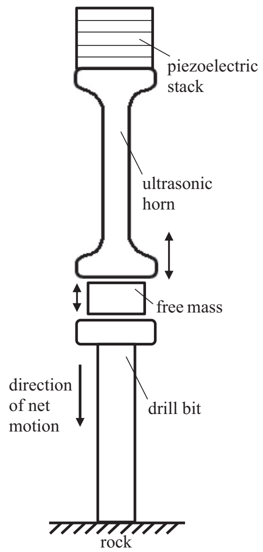


**Fig. 1.** Interaction between vibrating ultrasonic horn, free mass, and drill bit.