Reaction force of percussive corer, rotary-friction corer, and rotary-percussive corer

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ABSTRACT

Future NASA exploration missions will increasingly require sampling, in-situ analysis and possibly the return of material to Earth for laboratory analysis. To address these objective, effective and optimized drilling techniques are needed. This requires developing comprehensive tools to be able to determine analytically what takes place during the operation and what are the control parameters that can be enhanced. In this study, three types of coring techniques were studied and were identified as potential candidates for operation from a possible future Mars Sample Return (MSR) mission rover. These techniques include percussive, rotary-friction, and rotary-percussive coring. Theoretical models were developed to predict the dynamic reaction forces transmitted from these three types of corers to the robotic arms that hold them. The predicted reaction forces will then be used in a dynamic simulation environment to simulate a representative corer tool to obtain a best estimate of a tool that can be operated from a small rover. The predicted dynamic reaction forces will be presented in this paper.

Keywords: Ultrasonic Percussive corer, Rotary-friction corer, Rotary-percussive corer.

1. INTRODUCTION

Core sample acquisition from a planetary rover currently requires that the rover be a stationary platform for a manipulation system on which a coring tool is mounted. Future Mars rover missions, such as a possible Mars Sample Return (MSR) mission, may need to minimize mission cost by reducing the rover mass. With a low-mass rover, the interaction forces between the tool and terrain may cause the rover to slip during a coring operation. A research activity is underway to study the reaction forces. A rover-tool concept has been developed to act as the context for the work. Alternative core sampling tool concepts are being investigated and modeled to determine what type of tool would be preferable for the low-mass rover system.

In this paper, three types of coring techniques were studied and were identified as potential candidates for operation from a future Mars Sample Return (MSR) mission rover. These techniques include percussive, rotary-friction, and rotary-percussive coring. Theoretical models were developed by using the MatLab/Simulink as well as ANSYS to predict the dynamic reaction forces transmitted from these three types of corers to the robotic arms that hold them. Details of the models and the predicted dynamic forces are presented in this paper.

2. Coring Tool Models

The type of coring tool used to acquire the sample is very important. Different types of coring tools require different control relative to their environment and produce different quality cores. There are three basic types of coring tools for a possible Mars sampling missions: rotary friction, ultrasonic, and rotary hammer.

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2.1 Rotary-Friction Coring Tool Model

Rotary friction coring tools impart normal and tangential forces into the material. Large normal forces cause the bit teeth to catch and compress the rock surface and the rotary action causes tension or shear stress buildup that is relieved by the formation of tension or shear fractures along the direction of tooth motion 0. There are two primary drawbacks of rotary friction coring tools, the relatively large normal force, or preload, required between the bit and rock and the need for a centering bit to start a coring hole. For coring from a low-mass rover, the large normal force required affects the rover mass by requiring the tool deployment device to apply this force against the environment. An example of this type of coring tool is the Mini-corer from Honeybee Robotics 0.

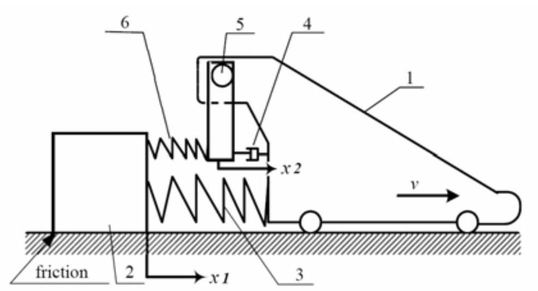

Figure 1. The planar model of the rotary-friction drill system. 1: Drive with constant velocity v; 2: tip of the bit with mass m_1; 3: main spring with stiffness k_1; 4: dashpot with viscous coefficient c_2; 5: pin, attached with a lever with mass m_2; 6: secondary spring with stiffness k_2.

A model for rotary friction coring tools was proposed by Batako, Babitsky, and Halliwell 0 to simulate the motion of a rotary corer with and without percussive actions. The model focuses on the tip of the corer bit. The movement of the tip of the corer bit is modeled as a stick-slip motion. The tip of the bit is connected to the shaft of the motor through the corer stem which is represented by a spring-damper system, as shown in the planar model in

Figure 1. Note that the velocity v is the linear speed of the bit rotation; the lever connected to the drive at pin 5 is free to rotate, but with length accommodated so x2 is horizontal; and there is dry friction between the bit and the surface of rock. The shaft of the motor is assumed to be rotating at a constant velocity. A preload is applied to the corer system, and the corer bit is pressed against the rock. When the motor just starts working, the tip of the bit sticks to the rock due to friction; and then when the maximum static friction is reached, the tip of the bit slips until it sticks again. The stick-slip cycle repeats itself and such motion is known as "stick-slip motion".

The governing equations of the motion of the tip of the corer bit are:

$$
\begin{aligned}
m_1 \ddot{x}_1 &= -k_1 x_1 - k_2 (x_1 - x_2) - F_r\left(\dot{x}\right) \\
m_2 \ddot{x}_2 &= -c_2 \dot{x}_2 - k_2 (x_2 - x_1)
\end{aligned} \qquad (1)
$$

where $F_r\left(\dot{x}\right)$ is the friction force,

$$F_r\left(\dot{x}\right)=\begin{cases} f_{st}\left(1-\dfrac{\left|\dot{x}\right|}{v_{cr}}+\dfrac{\left|\dot{x}^3\right|}{3v_{cr}^3}\right)\operatorname{sgn}\left(\dot{x}\right) & \text{for } \dot{x}\neq 0 \\ \min\left[\left|k_1x_1+k_2\left(x_1-x_2\right)\right|,\ f_{st}\right]\operatorname{sgn}\left(k_1x_1+k_2\left(x_1-x_2\right)\right) & \text{for } \dot{x}=0 \end{cases} \tag{2}$$

where f_{st} is the maximum static friction, and $x = x_1 + vt$; x_1 and x_2 are the coordinates of the bit and the lever, respectively, relative to drive 1.

A computer program was developed in Matlab/Simulink to solve the governing equations. To verify the validity of the computer program, the example problem shown in the paper 0 was solved by the program. It is found that the computer program we developed successfully repeated the results shown in the paper. We then modified the variables, m_1, m_2, k_1, k_2, c_2, and v, in the program to simulate the rotary-friction corer under investigation, the Mini-Corer developed by Honeybee. Some of the parameters in the model are not available, for example, the spring constants, equivalent mass of the bit-head (not the whole bit), etc. So we chose some values for these parameters so the results are compatible with the data we received from Honeybee including the rotational speed (about 200 RPM), the preload (155 N), and the average torque (2 N-m), etc. The preload (155 N) is also felt by the robotic arm, and it is taken as a constant in the model.

The model depicted in
Figure 1 gives us the friction force between the drill bit and the surface of the rock, as well as the torque that exists in the drill stem. However, what we need is the torque felt by the robotic arm that holds the drill. So we modified the model to predict also the rotational speed of the rotor of the motor which drives the drill stem, and through the torque-rotational speed relationship we are able to derive the torque that was delivered from the stator to the rotor. The torque delivered across the stator-rotor interface is actually the torque that the robotic arm needs to provide to hold the drill.

Figure 2 shows the dynamic torque that transmitted from the corer to the robotic arm. It is predicted by the model that the torque reaches the steady state after a short period of transient state. It should be noted that the solution is not unique, since there are more than one combination of variables in the model which would satisfy the specifications of the corer. To be able to predict the reaction forces more precisely, we need to know the spring constants, k_1 and k_2, the mass, m_1 and m_2, and the damping coefficient c_2, that characterize the corer bit.

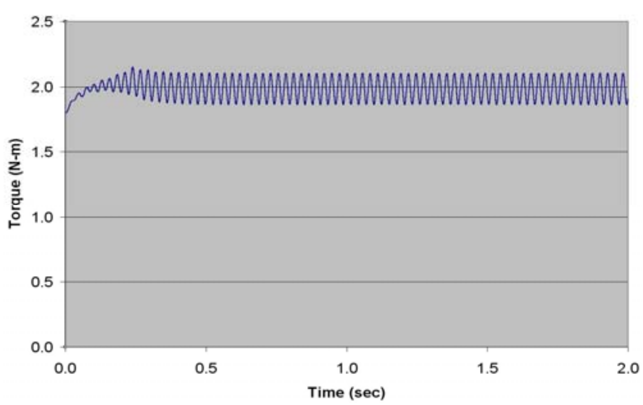

Figure 2. Torque produced by a rotary friction coring tool.

2.2 Rotary-Percussive Coring Tool Model

The model of a self-excited rotary-percussive corer proposed by Batako, Babitsky, and Halliwell 0 is shown in Figure 3. The impact loading is provided by the striker with mass m_2. At impact the friction force increases sharply, and it confines the bit to decelerate and to come to rest. The parameters of the system strongly affect each other, therefore a proper correlation of masses and stiffness in the system is needed for the process to converge to a stable solution.

The governing equations, from Batako, of the motion are:

$$\begin{aligned} m_1 \ddot{x}_1 &= -k_1 x_1 - k_2(x_1 - x_2) - F_r\left(\dot{x}\right) + \Phi\left(x_2, \dot{x}_2\right) \\ m_2 \ddot{x}_2 &= -c_2 \dot{x}_2 - k_2(x_2 - x_1) - \Gamma\left(x_2, \dot{x}_2\right) \end{aligned} \tag{3}$$

where $F_r\left(\dot{x}\right)$ is the friction force,

$$F_r\left(\dot{x}\right) = \begin{cases} f_{st}\left(1 - \dfrac{\left|\dot{x}\right|}{v_{cr}} + \dfrac{\left|\dot{x}^3\right|}{3v_{cr}^3}\right)\operatorname{sgn}\left(\dot{x}\right) & \text{for } \dot{x} \neq 0 \\ \min\left[\left|k_1 x_1 + k_2(x_1 - x_2)\right|, f_{st}\right]\operatorname{sgn}\left(k_1 x_1 + k_2(x_1 - x_2)\right) & \text{for } \dot{x} = 0 \end{cases} \tag{4}$$

and $f_{st} = \mu m_1 g$ is the static friction force, and μ is the coefficient of static friction.

$\Gamma\left(x_2, \dot{x}_2\right)$ is the impact force which is defined as follows:

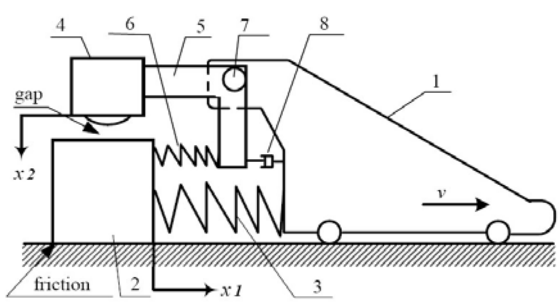

Figure 3. The planar model of the rotary-percussive drill system. 1: Drive with constant velocity v; 2: tip of the bit with mass m_1; 3: main spring with stiffness k_1; 4: striker with mass m_2; 5: lever; 6: secondary spring with stiffness k_2; 7: pin; 8: dashpot with viscous coefficient c_2.

$$\Gamma\left(x_2, \dot{x}_2\right) = \begin{cases} k_0\left(x_2 - \Delta\right) + c_0 \dot{x}_2 & \text{for } x_2 \geq \Delta \quad \text{and} \quad \Gamma\left(x_2, \dot{x}_2\right) > 0 \\ 0 & \text{for } x_2 \geq \Delta \quad \text{and} \quad \Gamma\left(x_2, \dot{x}_2\right) < 0 \\ 0 & \text{for } x_2 < \Delta \end{cases} \tag{5}$$

where k_0 is constant stiffness of the bit and c_0 is constant damping, and Δ is the initial gap between bit and striker.

$\Phi\left(x_2, \dot{x}_2\right)$ is the added friction force due to impact:

$$\Phi\left(x_2, \dot{x}_2\right) = \mu\, \Gamma\left(x_2, \dot{x}_2\right) \tag{6}$$

Since the rotary-percussive corer we want to model is actually a "forced" impact system instead of a self-excited one, we have modified the model shown in Figure 3 accordingly. The impact is created mechanically by a cam-spring system. The cam is fixed onto the drill stem, and while the stem rotates, the cam strains the spring and releases it periodically to create the impact. It is assumed that the cam-spring system creates three impacts with each rotation of the drill stem, and since the rotation speed of the stem is about 800 RPM, the impact rate is about 40 impacts per second. Equation (5), the impact force is rewritten as,

$$\Gamma(t) = \begin{cases} a_0 \sin(2\pi f t) & \text{for } 0 < t < 0.0001,\ 0.025 < t < 0.0251, \\ & \quad 0.05 < t < 0.0501, \cdots \\ 0 & otherwise \end{cases} \tag{7}$$

where the impact force is assumed to be sinusoidal with a frequency *f*, and *f* is assumed to be 5000 Hz. So the duration of the impact is 1000 micro-seconds. The a_0 is the amplitude of the impact, and it is assumed to be 200 N. And Equation (6), the added friction force, is rewritten as,

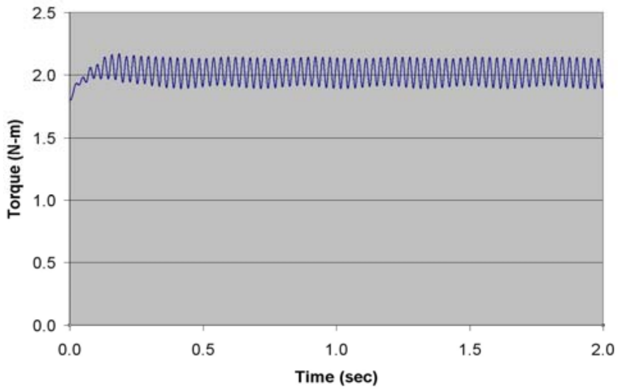

Figure 4. Torque generated by a rotary-percussive coring tool with 155N preload.

$$\Phi(t) = \mu \, \Gamma(t) \tag{8}$$

Upon careful inspection of the Equation (3), it is found inadequate to add the "added friction force" directly to the governing equation. Instead, it should be treated as an increase of normal force between the drill bit and the surface of the rock, and be added to the static friction force, f_{st}, as shown in Equation (4). So both Equations (3) and (4) are rewritten as,

$$\begin{aligned} m_1 \ddot{x}_1 &= -k_1 x_1 - k_2 (x_1 - x_2) - F_r\left(\dot{x}\right) \\ m_2 \ddot{x}_2 &= -c_2 \dot{x}_2 - k_2 (x_2 - x_1) - \Gamma\left(x_2, \dot{x}_2\right) \end{aligned} \tag{9}$$

and

$$F_r\left(\dot{x}\right) = \begin{cases} \left(f_{st} + \Phi(t)\right)\left(1 - \dfrac{\left|\dot{x}\right|}{v_{cr}} + \dfrac{\left|\dot{x}\right|^3}{3v_{cr}^3}\right)\operatorname{sgn}\left(\dot{x}\right) & \text{for } \dot{x} \neq 0 \\ \min\left[\left|k_1 x_1 + k_2 (x_1 - x_2)\right|, \left(f_{st} + \Phi(t)\right)\right]\operatorname{sgn}\left(k_1 x_1 + k_2 (x_1 - x_2)\right) & \text{for } \dot{x} = 0 \end{cases} \tag{10}$$

Figure 4 shows the time history of the torque generated by a rotary-percussive corer with 155 N preload, and transmitted to the robotic arm which holds the corer. All the conditions and parameters used in this model are the same as the ones used for the rotary-friction model, except that periodic impact is imposed upon the drill bit here. Compared with the torque created by a rotary-friction corer, shown in **Figure** 2, the average torque shown in Figure 4 is slightly higher. Also, the peaks of the torque in Figure 4 oscillate due to the periodic impact.

Figure 5 shows the time history of the torque generated by a rotary-percussive corer with 50 N preload. Compare to Figure 4 where the preload is 155 N, the average torque here is lower. The phenomenon is expected since lower preload creates lower friction which results in lower torque. Additionally, when the preload is higher, the dynamic torque reaches its steady state faster.

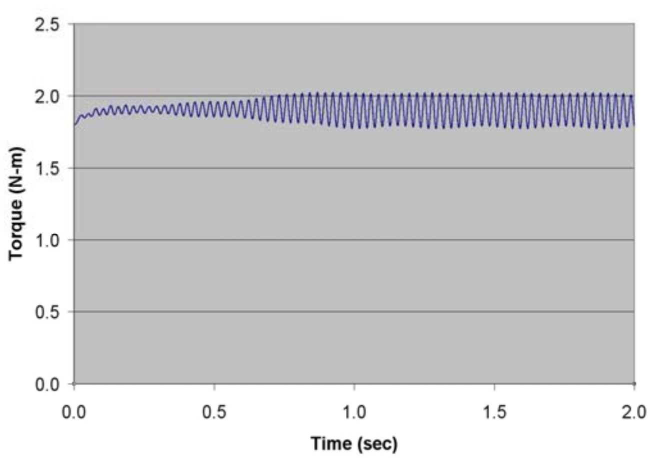

Figure 5. Torque generated by a rotary-percussive coring tool with 50N preload.

2.3 Ultrasonic Coring Tool Model

An ultrasonic drill/coring tool (USDC) consists of three main parts: an ultrasonic transducer (piezoelectric stack, a backing element, and a horn), free-mass and a drill stem. The ultrasonic transducer vibrates at a frequency of about 20 kHz. These vibrations of the horn tip excite the free-mass, causing it to hop between the horn tip and the top of the drill stem at frequencies around 1000 Hz. The free-mass transfers energy from the ultrasonic transducer to the drill stem. In order to determine the reaction force transmitted from the USDC to the robotic arm, a computer program was developed to simulate the interaction between the ultrasonic horn and the free mass, and between the free mass and the drill bit **Error! Reference source not found.**. Time history of the location of the ultrasonic horn was predicted by the program, and it is assumed that the ultrasonic horn is connected to the robotic arm through a spring. Thus the reaction force can be calculated with the location of the ultrasonic horn and the spring constant available. Specifications for a USDC prototype are shown in Table 1. Figure 6 shows the time history of the reaction force.

Table 1. Specifications of Prototype USDC

Mass	0.3 kg
Envelope	4 cm dia. × 25 cm
Power	40 watt
Resonance Frequency	22500 Hz
Free mass	2 g

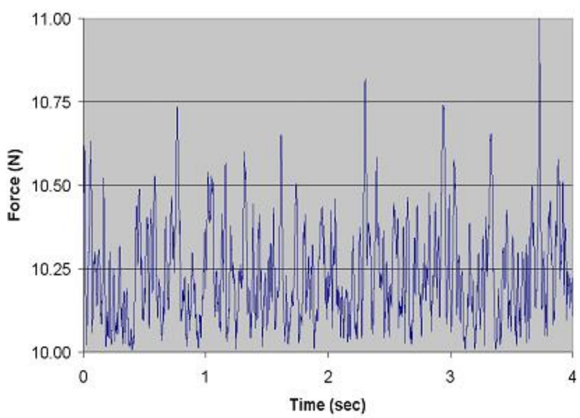

Figure 6. USDC Reaction Force

3. SUMMARY

Coring from a low-mass rover provides new technical challenges where the rover cannot be assumed to be a stationary platform during the coring operation. Coring tool models have been developed to help in the selection of the best type of coring tool to use when coring from a low-mass rover. A MatLab routine and a Finite Element Analysis model (using ANSYS) has been created to study the reaction forces induced by an ultrasonic coring tool. Two MatLab/Simulink programs have been developed to simulate the behavior of a rotary-friction coring tool and a rotary-percussive coring tool, respectively. The predicted reaction forces will be used in a dynamic simulation environment to simulate a representative corer tool to obtain a best estimate of a tool that can be operated from a small rover.

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