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Development Of A Switchable System For Longitudinal And Longitudinal-Torsional Vibration Extraction

Patrick Harkness and Margaret Lucas

School of Engineering, University of Glasgow, Glasgow G12 8QQ
United Kingdom

Abstract. High-frequency/low-frequency drilling is an attractive technology for planetary exploration tools, and one which has seen considerable innovation in the techniques used to ensure rotation of the front-end cutting bit. This rotation is essential to prevent tooth imprintation in hard materials, and extracting the rotation from the high-frequency or ultrasonic system has obvious benefits in terms of simplicity and robustness. However, extracting the rotation from an ultrasonic horn raises the possibility of bit-walk if it is used to operate a coring device and the authors therefore propose an ultrasonic horn which uses an excitation applied to a single input surface to yield torsional and longitudinal vibration on two physically separated output surfaces. By engaging with the two output surfaces, longitudinal vibration can be extracted to achieve initial percussive drilling, even where a coring bit is applied, and the torsional output can subsequently be added to prevent tooth imprintation once the coring bit has settled into the site in question. In this manner, the horn provides a mechanism whereby high-frequency/low-frequency drilling technique can be applied to coring operations without the need for an exceptionally robust drill structure capable of resisting bit-walk forces.

Keywords: High-frequency/low-frequency drilling; ultrasonic motors; momentum exchange; longitudinal-torsional vibration
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INTRODUCTION

Extensive networks of features resembling dried-up river beds, streamlined islands and shorelines on Mars suggest that liquid water may have been a feature of the Martian environment over a relatively long period of geological time. Subsequent impact events upon these regions have produced lobate ejecta blankets, suggesting that the debris pictured in Fig. 1 was semi-liquid. Thus, it may be inferred that volatiles remained beneath the surface even after the water ceased to flow around the end of the Noachian period – a period which likely coincided with the emergence of the first life on Earth. This is significant because life may have evolved in the shallow seas and could have found a niche in the water-rich subsurface long after the rivers had disappeared.

Thus, exploration of the subsurface is of great importance for planetary scientists. However, planetary drilling using traditional rotary tools is a major challenge, as the low gravity and uncertain terrain makes reaction of drilling forces difficult. Even under close human supervision, rotary drill tools proved troublesome during the Apollo missions to the moon. [1]

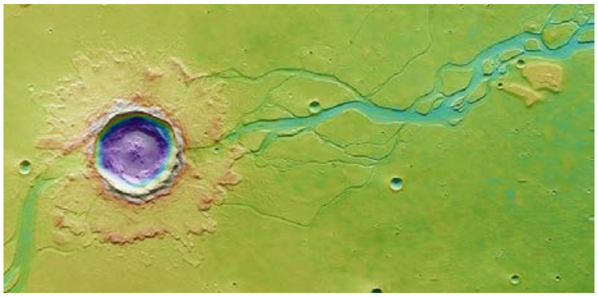

FIGURE 1. Hephaestus Fossae, Mars (False-color image by ESA/DLR/FU Berlin). Water has cut the blue valley, which dried out and was subsequently impacted by a meteorite. However, the lobate form of the ejecta suggests that it behaved as a semi-liquid, indicating that volatiles were still present in the soil.

Given that robotic exploration is likely to take place in order to determine attractive sites for human exploration, mission planners consider a lightweight and low-force drill tool to be an attractive system for future landers. High-frequency-low-frequency drill tools, which use ultrasonic vibration to excite a lower-frequency oscillation in a free-mass and then use the hammering action of the free-mass to pulverize rock, were described during the 1990s [2] and put forward as a potential solution.

A range of improvements were put forward during the 2000s. It was suggested that the ultrasonic horn could be folded to reduce the size of the device, that a bulge on the end could improve momentum transfer to the free-mass, and that a pair of free-masses could be used so that the tool could dig itself out of the ground [3]. Optimization and modeling efforts suggested design rules for the shape of the horn [4] and yielded better understanding of the dynamics of the horn/free-mass/drillbit stack [5], whilst efforts were made to toughen the system by inserting polycrystalline diamond tip-pieces in the horns the better to withstand repeated impacts of the free-mass [6].

In parallel with this effort it was recognized that bit-rotation is essential to prevent tooth imprintation and consequent loss of under-tooth pressure – a parameter which is known to be directly related to rate-of-progress. Some success was been achieved with asymmetric tooth patterns [7] and auxiliary motors, the latter being employed to rotate the ultrasonic drill tool shown in Fig. 2. However, it was suggested [8] that using the ultrasonic horn itself to rotate the bit would simplify the drill tool. This was subsequently achieved by the ingenious use of a longitudinal-torsional horn, whereby the torsional output of the horn is used to impart rotation to the free-mass [9]. This rotation is delivered to the cutting bit with each impact of the free-mass.

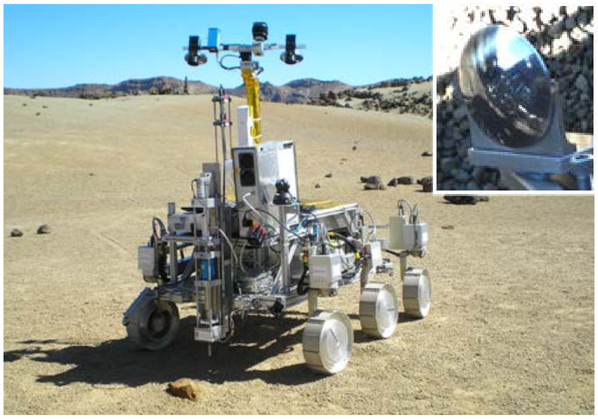

FIGURE 2. A University of Glasgow ultrasonic drill tool undergoing field trials on Mt. Teide, where bit rotation is provided independently of the ultrasonic action through a commutated gearmotor on a splined shaft. Note that drilling is observed (inset) from the twin cameras on the mast via an inspection mirror near the front right wheel.

The rotary-hammering technique is extremely effective, and as the horn has a single working surface percussion and rotation are very closely linked. This is ideal for drilling purposes, but for more challenging sample-retrieval missions coring is preferred. Coring with a rotating bit is initially very difficult due to bit-walk, and so this paper considers an extension of the rotary-hammering technique whereby a specialist smart horn with separate torsional and longitudinal output surfaces, operating at different frequencies, can be used to deliver either rotation, via an ultrasonic motor technique, or percussion, as desired.

THE SMART HORN

The geometry used as the basis of the smart horn was initially designed for direct longitudinal-torsional coring operations [10]. After some modifications, however, a shape can be realized with a torsional ring and longitudinal stem, the taper being selected to maximize the momentum imparted to an excited free-mass [4]. One half-cycle of simulated behavior, extracted using Simulia ABAQUS, is presented in Fig. 3 to illustrate the deformed shapes. This data corresponds to the longitudinal eigenmode of the structure.

FIGURE 3. A half-cycle of simulated behavior in the smart horn at 20 kHz.

The smart horn is manufactured from titanium alloy, attached to a Sonic Systems L500 transducer, and subjected to experimental modal analysis using laser Doppler vibrometry. The most significant transfer functions are those between the base and the longitudinal response at the tip of the stem, the longitudinal response at the ring, and the tangential response at the ring. These functions are presented in Figs. 4, 5, and 6.

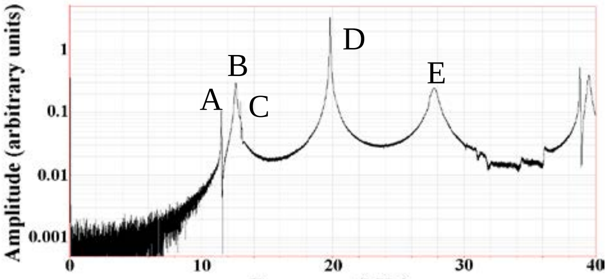

FIGURE 4. Experimental transfer function to the stem longitudinal output.

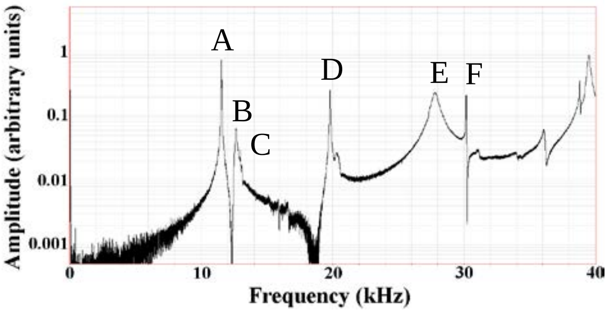

FIGURE 5. Experimental transfer function to the ring longitudinal output.

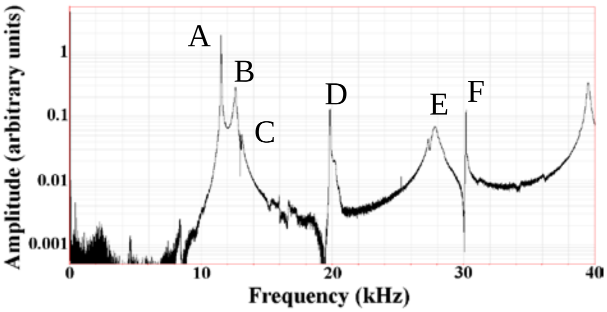

FIGURE 6. Experimental transfer function to the ring tangential output.

Six major features are found in the range 0 – 30 kHz. These features, labeled A-F, are respectively A, the torsional mode of the ring; B, the first bending mode of the stem; C, a whirling mode of the stem; D, the first longitudinal mode of the horn; E, a more complex longitudinal mode of the horn; and F, a folding mode of the ring. Modes A and D, at 11.5 kHz and 19.7 kHz, are the two operating modes. Their shapes are presented in Fig. 7 and the results of harmonic analyses at 100 V are presented in Figs. 8 and 9, illustrating that the ring torsionality is H3.1.

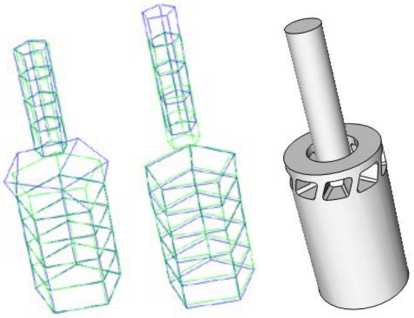

FIGURE 7. Mode shape A, 11.5 kHz (left) and mode shape D, 19.7 kHz (centre) extracted using the 3D laser Doppler vibrometry technique with excitation applied by a Sonic Systems L500 transducer. The undeformed shape is shown by green wireframe and the scaled deformed shape by blue wireframe.

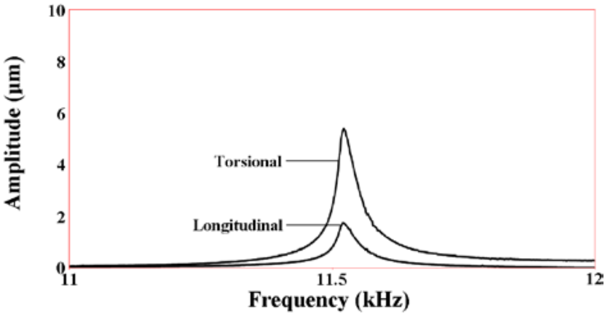

FIGURE 8. Harmonic analysis of mode A at the edge of the ring (100 V).

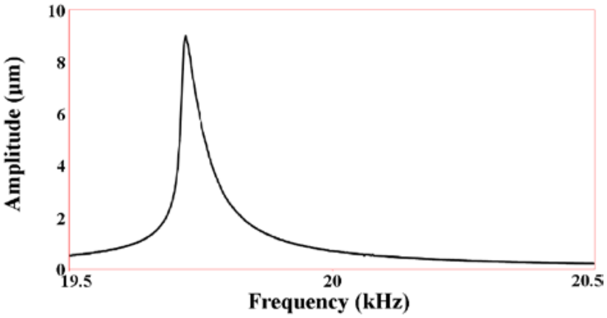

FIGURE 9. Harmonic analysis of mode D at the tip of the stem (100 V).

There is a noticeable softening effect in both analyses, and this non-linearity will be discussed below. However, in general, the usefulness of modes A and D hinges upon whether they can be tracked by a drive system. An impedance analysis of the transducer/horn stack yields the result presented in Fig. 10, which shows that there are significant features associated with both operating modes and therefore suggests that an effective system could be created.

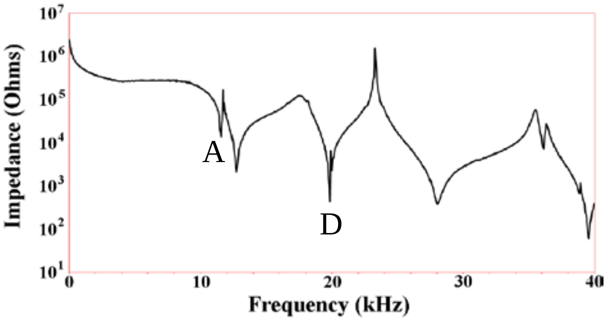

FIGURE 10. Impedance trace of the smart horn on a Sonic Systems L500.

The performance of the horn as both an ultrasonic motor and as a percussive drill is now considered. The device is, of course, intended to be switchable between the two applications by altering the drive frequency to track the appropriate mode.

PERFORMANCE AS AN ULTRASONIC MOTOR

To examine performance as an ultrasonic motor, a smooth titanium cap which rests on the ring but which has a hexagonal port to allow access to the tip is manufactured, such that a bit can be rotated or driven in the percussive mode. The stem of the horn forms a sliding fit with the inside of the cap, ensuring that the two parts remain concentric but creating some frictional losses. The weight of the cap, 2.1 N, creates a contact force upon the smooth ring, which has outer and inner diameters of 34 mm and 18 mm. The contact force can be increased to over 6 N by adding 1 N weights to the cap.

With these arrangements in place, a sinusoidal excitation signal of 300 V, 400 V and 500 V peak-to-peak is applied at 11.5 kHz to correspond to the natural frequency of mode A and the induced rotation of the cap is observed. The relationship between applied voltage, contact force and no-load rotation speed is as presented in Table 1. It is apparent that performance increases with applied voltage and contact force, at least within the parameter space investigated.

TABLE 1. Performance of the Ultrasonic Motor

	Cap RPM 2.1 N	**Cap RPM 3.1 N**	**Cap RPM 4.1 N**	**Cap RPM 5.1 N**	**Cap RPM 6.1 N**
300V	erratic	erratic	erratic	erratic	12.8
400V	9.2	11.7	14.6	16.7	18.2
500V	12.2	15.0	23.0	28.6	31.6

PERFORMANCE AS A PERCUSSIVE DRILL

To examine performance as a percussive drill, mode D is tracked and excited by a Sonic Systems L500 signal generator providing 5 µm of base excitation. The horn is used to excite an 10 mm free-mass against a cutting bit and force transducer, in the manner described in an earlier work [4], and the measured force is time-integrated above a 100 N baseline to provide a measurement of effective impulse.

Typical force histories provided by a control horn (tip thickness t_{tip} = 12.5 mm; base thickness t_{base} = 34 mm) and the smart horn of identical t_{tip} and t_{base} are presented in Fig. 11 and Fig. 12. The peak forces applied are marginally lower in the case of the smart horn, although the dynamics appear similar. The effective impulses calculated above the threshold, per second of operation, are 0.0080 Ns and 0.0048 Ns respectively.

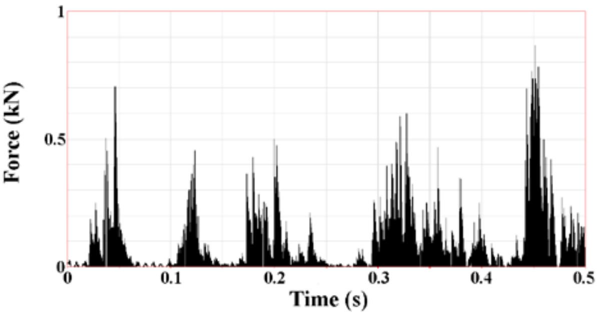

FIGURE 11. Percussive drilling force extracted from the control horn.

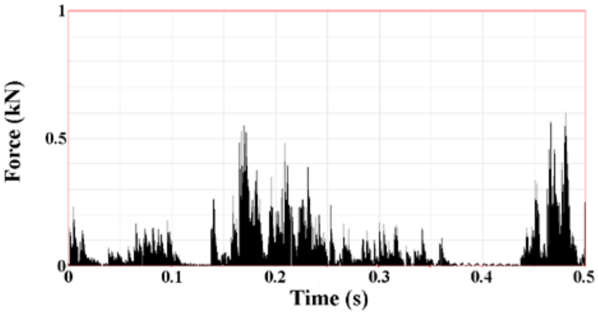

FIGURE 12. Percussive drilling force extracted from the smart horn.

DISCUSSION

The smart horn has been shown to behave as an ultrasonic motor and also as an effective high-frequency/low-frequency percussive driver, and to be switchable between the two modes through adjustment of its operating frequency.

The torque produced by the ultrasonic motor is low, but this is likely to be due to i) the excitation signal not tracking mode A, ii) poor optimization of the interface surfaces and rotational bearing, iii) poor optimization of the contact force, and iv) a non-optimized vibration behavior for effective ultrasonic motoring. However, the concept is demonstrated and is suitable for both ultrasonic and systems-level optimization. In particular, it may be suggested that the tangential vibration and contact force will need careful modulation.

The effective impulse produced by the smart horn is marginally lower than that produced by the control. This could be due to the presence of the torsional ring, but more likely has common cause with the non-linearities in Fig. 8 and Fig. 9. These effects may be associated with the processes employed in manufacturing the horn, because it was necessary to make the hollow torsional section and the central longitudinal section as two separate elements. The central element was cooled with LN_2 before assembly, producing a tight but not perfect fit. Internal friction in the horn at this interface may well be responsible for the nonlinear behavior and the slight reduction in high-frequency/low-frequency percussive drilling performance observed.

CONCLUSION

The smart horn is a promising starting point for the development of a high-frequency/low-frequency drill tool with switchable modes of operation, having demonstrated both rotation and percussive drilling at different excitation frequencies. However, the geometry of the horn must be optimized and broader systems engineering undertaken to achieve and effective ultrasonic motor effect. Furthermore non-linearities and losses in the horn itself must be overcome, perhaps by the use of advanced manufacturing techniques.

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