An ultrasonic corer for planetary rock sample retrieval

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Abstract. Several recent and planned space projects have been focussed on surface rovers for planetary missions, such as the U.S. Mars Exploration Rovers and the European ExoMars. The main functions of similar extraterrestrial vehicles in the future will be moving across planetary surfaces and retrieving rock samples. This paper presents a novel ultrasonic rock sampling tool tuned in a longitudinal-torsional mode along with the conceptual design of a full coring apparatus for preload delivery and core removal. Drilling and coring bits have been designed so that a portion of the longitudinal motion supplied by the ultrasonic transducer is converted into torsional motion. Results of drilling/coring trials are also presented.

1. Ultrasonic Drilling and Coring

Ultrasonic drilling for planetary rock sampling has a number of benefits compared to traditional rotary drilling. These include a reduction in required end-load (an unfeasibly high-mass planetary lander such as the six-ton Luna 24 would be required if large forces were to be generated in low gravity environments), the elimination of the heavy motors and clutches associated with rotating machinery, and mass-reduction of the drillstring itself due to the fact that only a very small mechanical effort must be delivered from the planetary lander on the surface to the bit operating downhole.

A mechanism by which an ultrasonic device can be delivered to the bottom of a shaft by a planetary lander has been set out in a previous work [1]. However, that work focused on a drill system which must, by definition, pulverize all the material which lies before it if the unit is to descend. Such an approach is acceptable for coarse chemical analysis but it is more desirable to recover the strata whole, undamaged, and in their proper lithographic sequence via a coring operation. This is particularly the case where the intention is to return the samples to Earth for analysis, as is envisaged for the future Mars Sample Return mission.

A coring approach is also advantageous when compared to drilling in that not all the rock, soil or ice in the path of the exploratory shaft must be pulverized, as creating the central core requires no power. Despite its huge advantages in terms of preload, reacted torque and system mass, ultrasonic drilling and coring is not expected to be particularly competitive in terms of energy expenditure for shallow-drill operations, requiring 10 to 20 GJ/m$^3$ in medium-strength rock [1-3], a value which is as much as 50 times higher than the requirements of a conventional drill. However, ultrasonic devices do not require a rotating drillstring and do not experience the friction loads between drillstring and shaft which can absorb up to 80% of the torque applied to deep rotational systems [4], and thus they become progressively more competitive as deeper drilling (> 1m) is considered.
2. System Architecture

The proposed mechanism for sinking and withdrawing the bit, securing the shaft against collapse and shielding against trundling and saltating sand particles has been described in a previous publication [1]. In summary (see figure 1) a coilable tube similar to the Northrop Grumman STEM [5] is proposed to sink the ultrasonic bit complete with transducer, into the surface and secure the resulting shaft. A growing core will pass through the annulus of the coring bit, through the centre of the ring transducers, and up into the bottom section of the STEM.

![Figure 1. Schematic of system architecture (aligned horizontally)](image)

The core will then be broken and collected by a shuttle with an integral wedge. The load required to break the core will reduce linearly with core length suggesting that the shuttle can be lowered into the hole, touchdown with sufficient force to break off even the strongest rock cores, and be withdrawn to the surface with the core sample secured inside by a core-catcher. Such devices are essentially a ring of triangular doors, arranged so that items can only pass in one direction, rather like a biological valve. It is further proposed that the bottom of the shuttle should be tapered inwards to ensure that fines tend to be moved into the centre of the shuttle rather than building up on top of the ultrasonic bit.

3. Development of the coring bit

In a previous study [1] a longitudinal-torsional motion was developed at the tip of an ultrasonic drilling bit by coupling the first longitudinal (L1) and second torsional (T2) modes of vibration in a cylindrical stepped horn. The step provides the horn with longitudinal amplitude gain whilst some of the longitudinal excitation applied to the base of the horn is transferred to the torsional mode by helical structures, namely diagonal slits, positioned at one of the two torsional nodes. The success of this approach is demonstrated in figure 2.

![Figure 2. (a) Unslitted, L1 drilling horn, (b) slitted, L1T2 mode-coupled drilling horn.](image)

3.1. Applying the geometric principles of drilling horns to coring horns

The aim in the corer design is to maintain the high degree of L1 amplitude gain obtained by the stepped drillers by similarly reducing the cross-sectional area of the horn from base to tip. It has also been previously shown [1] that coupling the L1 and T2 modes improves the rate of drill penetration in sandstone. The aim is also therefore to preserve a longitudinal-torsional motion in the proposed coring horn by incorporating helical structures to transfer energy from longitudinal to torsional motion.
3.1.1. Reducing cross-section to increase gain. Because both transducer and horn must penetrate the ground, the front surface of the horn must have a working surface area at least equal to any other part of the horn and proposed ring transducer. In seeking to integrate area reduction into the design, this presents some difficulties. However, it can be achieved by creating voids in the front end of the horn and closing them off with a thin disc of material at the tip. This can be done either by a single toroidal void or a number of radial voids, leaving behind the same number of circumferential columns. The gains of these horns are similar but the radial-void geometry is considerably easier to manufacture and so was selected for development.

3.1.2. Inclusion of helical structures. Diagonal slits in the body of the driller allowed torsional motion to be developed in the longitudinally excited horn and so this geometry was again evaluated for the corer. As before, a global T2 mode is developed over the entire horn with base and tip oscillating in phase. However, torsional gain is found to be low and torsion is back-transmitted into the Langevin transducer, with possible negative effects such as heating and fatigue. A better strategy is to develop torsion by controlling the vibration of the columns such that torsional motion is developed towards the tip of the horn and not at the base. This can be achieved by applying a slope to the columns.

3.2. Dealing with flexural column modes.
In corer geometries incorporating radial voids, the interstitial columns tend to exhibit half-wavelength oscillation in the first bending mode which does not assist excitation of the desired torsional vibration. A solution is to create tiers of columns joined by equally-spaced rings. The tiers of columns then oscillate as three discrete units, each exhibiting quarter-wavelength bending. The overall effect is that the corer successfully develops a net change in torsion from the base to the tip of the tiered column structure.

Furthermore, to prevent the constant slope of each column tier transferring energy to the global T2 mode, the direction of slant is reversed in one of the three tiers and thus the desired mode shape can be achieved. The mode shape at eight sequential intervals of one half-cycle is shown in figure 3.

![Figure 3](image)

**Figure 3.** The desired operating mode of the corer over one half-cycle.

4. Validation of the finite-element models and testing of the horn
In order to validate the finite element model, the generic geometry shown in figure 3 was manufactured. The corer has a diameter of 33 mm and a length of 80 mm, which allows it to match the diameter of COTS STEM systems and tune to the 20 kHz frequency of the Langevin transducer.

The modal parameters of the coring horn were ascertained by an experimental modal analysis (EMA), with the vibration response at a grid of points on the corer being measured with a 3D laser Doppler vibrometer. The horn was driven over a frequency range of 0 - 40 kHz and a frequency response function (FRF) measured from the working face of the corer is shown in figure 4 (a). As well as the tuned mode, the modal parameters of several other nearby modes were extracted from the measurement data and these mode shapes, along with the associated FEA predictions, are shown in figure 4 (b). The measured modal frequencies and mode shapes were in close agreement with the finite element model predictions.
4.1. Longitudinal and torsional response validation.
The longitudinal and torsional response at 19.5 kHz was measured. The longitudinal excursion at the base and the torsional excursion at the tip are set to 1 and the results compared to FEA in figure 5. Generally agreement was good although there is some discrepancy in the torsional response of the first ring. The results in figure 5(b) also demonstrate that the horn is back-transmitting almost no torsion to the Langevin transducer driving it, a significant advantage over L1T2 mode-coupled designs.

4.2. Rock-cutting performance.
The performance of the corer as compared to the ultrasonic drillers was tested and the results are presented in table 1 in terms of the removal rate of sandstone. Not all horns were excited at the same longitudinal amplitude and therefore the removal rate is expressed with respect to the longitudinal amplitude at the tip. Due to a larger tip radius, the scaled tangential velocity of the corer surface is actually higher than that of the driller by a factor of ~1.4.

Table 1. A performance comparison of the drillers and derived coring system in Sherwood sandstone.

|                  | Applied preload (N) | Torsional output (radians T2 output /10 µm L1 input) | Sandstone removal rate (mm³/µm L1 output/sec) |
|------------------|---------------------|-----------------------------------------------------|-----------------------------------------------|
| L1 driller       | 20                  | 0                                                   | 0.64                                          |
| L1T2 driller     | 20                  | 0.00497                                             | 2.57                                          |
| Corer            | 20                  | 0.0014                                              | 3.00                                          |
5. Optimisation of the coring bit geometry

The performance of the ultrasonic corer compared well with the previously described drilling systems. Given a constant inner core diameter (18 mm) and ring thicknesses, the generic geometry has six main variables: (i) the overall length of the horn, in mm; (ii) the height of each tier, in mm; (iii) the slope of the columns, in horn diameters per complete helical revolution; (iv) the degree of cross-sectional area reduction, as a ratio of tip-end area to base-end area; (v) the number of columns in each tier; and (vi) the outer diameter of the horn, in mm. The effects of these parameters on tuned mode frequency, longitudinal gain and torsional response were investigated by FE analysis.

As a starting point, four of the variables were held constant; (iii), (iv), (v) and (vi) at values of 2.5 diameters per revolution, 30% tip-end area with respect to base-end area, 9 circumferential columns and 17 mm outer diameter respectively. The overall length of the horn was varied from 50 mm to 200 mm and the height of each tier from 5 mm to 12 mm, producing a grid of FE data. This process was then repeated with each of the four held variables incremented and decremented in turn, producing nine data grids in total.

Each data grid yielded three results grids, relating to frequency, longitudinal gain and torsional response. To obtain the torsional response data, which is presented in terms of tip torsional amplitude, the FEA models included a longitudinal excitation of amplitude 10 µm at the base of the horn.

The results grids were arrayed such that each horizontal, vertical and diagonal line in the array represents a progression in one variable to the exclusion of all others, with the variables themselves being as laid out in table 2.

| Result plot | Variable (iii) (Column slope, dia/rev) | Variable (iv) (Area ratio) | Variable (v) (Column count) | Variable (vi) (Outer diameter, mm) |
|-------------|--------------------------------------|---------------------------|---------------------------|----------------------------------|
| 1           | 2.5                                  | 30 %                      | 7                         | 17                               |
| 2           | 1.5                                  | 30 %                      | 9                         | 17                               |
| 3           | 2.5                                  | 22.5 %                    | 9                         | 17                               |
| 4           | 2.5                                  | 30 %                      | 9                         | 14                               |
| 5           | 2.5                                  | 30 %                      | 9                         | 17                               |
| 6           | 2.5                                  | 30 %                      | 9                         | 20                               |
| 7           | 2.5                                  | 37.5 %                    | 9                         | 17                               |
| 8           | 3.5                                  | 30 %                      | 9                         | 17                               |
| 9           | 2.5                                  | 30 %                      | 11                        | 17                               |

Surface-fitting software was used so that beyond the data points a surface is extrapolated to fill the entire grid space and therefore those regions of the surfaces which are not well-supported by data points should be treated with caution. A data point that is lifted from the surface indicates the degree of discrepancy between the FEA result at that point and the overall fitted surface.

The frequency results are presented in figure 6, longitudinal gain in figure 7 and torsional response in figure 8.
Figure 6. The frequencies predicted for the corer by FEA.

Figure 7. The longitudinal gain predicted for the corer by FEA.
5.1. Evaluation of the FEA results

5.1.1. Geometric influences on frequency. In each subfigure, frequency is increased by reducing the overall length of the horn and the height of each tier. Other factors which tend to increase the frequency of the horn include an increase of area ratio, a decrease of column slope and, to a lesser extent, a reduction in the number of columns. As each of these geometric drivers will result in respectively wider, straighter and deeper columns, we can conclude that the increased longitudinal stiffness in each case serves to increase the frequency of longitudinal vibration in the horn as a whole.

5.1.2. Geometric influences on longitudinal gain. In each subfigure, gain is maximised along the ridge joining small horns with low tiers to long horns with high tiers. We can therefore conclude that there is an optimal ratio of tier height to horn length, which appears to be approximately 7%. A closer inspection of the FEA results than can be presented in this paper indicates that, at this ratio, the longitudinal response plotted along the horn bears a strong similarity to figure 5 (a) in that the L1 node lies very close to the base of the first tier of columns. This arrangement appears to maximise longitudinal gain in the coring horns in much the same manner as it would maximise the performance of a step horn. Further details of this finding are presented in another publication [6].

Gain is also increased in horns with low area ratios and highly sloped columns. It can be concluded that the greater slope of the columns results in a greater proportion of the bending mode of each column being translated into longitudinal amplitude at the front face of the horn.

The maximum longitudinal gain definitively predicted (as opposed to estimated by the interpolated and projected surface) by a corer of figure 7(3) is 6.75. An FEA model of a simple longitudinal stepped horn of the same area ratio (22.5%) was created and the longitudinal gain was calculated to be 4.5, a value which does not vary significantly with changing frequency. The corer therefore significantly outperforms a comparable half-wavelength stepped horn in terms of longitudinal gain.

Figure 8. The torsional response predicted for the corer by FEA.
5.1.3. Geometric influences on torsional response. The torsional response is found to be proportional to the longitudinal response in most cases, but one exceptional result is the torsional response of the smaller-diameter horns in figure 8(4), which are significantly influenced by the reduction in rotary inertia. Generally, corers have achieved torsional responses in the region of 0.001 to 0.002 rad/10μm excitation, with a maximum value of 0.0042 rad/10μm excitation in the aforementioned figure 8(4).

The best mode-coupled drilling horns previously described [1] achieved a value of 0.005 rad/10μm excitation, although this falls to a net torsional differential, from base to tip, of 0.0018 rad/10μm excitation when the torsion at the base due to the global T2 mode is subtracted. Therefore, depending on the metric used, corers can approach the levels of torsion generated by mode-coupled drilling horns.

6. Conclusions
The design of mode-coupled drilling horns has been successfully extended to develop a coring horn which delivers a longitudinal performance well in excess of that which can be developed by comparable stepped horns and has a torsional performance to match mode-coupled drillers. The coring horn is also considerably shorter than stepped horns or mode-coupled drillers operating at the same frequency and has the crucial advantage that the external cross-sectional area does not change, despite quite large effective area reductions. This ensures that the large front surface of the corer can operate on the substrate with its full longitudinal and torsional amplitude.

We have further established the effects of design parameters in terms of operating frequency, longitudinal gain and torsional response and shown that, in general, gain can be maximised by increasing the effective area ratio and increasing the slope of the columns. Meanwhile, the torsional response can be increased by reducing the diameter of the horn.

The finite element model of the corer has been validated by experimental modal analysis and the performance of the manufactured ultrasonic corer has been tested on Sherwood sandstone and found to be comparable to mode-coupled ultrasonic drillers.

7. References
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