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In-situ Rock Probing Using The Ultrasonic/Sonic Driller/Corer (USDC)

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ABSTRACT

In-situ sampling and analysis are important capabilities to allow meeting the major objectives of future NASA's planetary exploration missions. The development of an ultrasonic device that can serve as a probe, sampler and sensors platform for in-situ analysis is currently underway at JPL. The device is based on the novel Ultrasonic/Sonic Driller/Corer (USDC) technology, which was co-developed by the Non-Destructive Evaluation and Advanced Actuator laboratory (NDEAA, http://ndeaa.jpl.nasa.gov/), JPL, and Cybersonics. This sampling technology requires low axial force, thereby overcoming one of the major limitations of planetary sampling in low gravity using conventional drills. This device allows the design of an effective tool that is compact, low mass and uses low power. To assure effective use of power for drilling/coring rocks in-situ probing is needed to allow selecting rocks with the highest probability of containing information (biological markers, water, etc.). While the major function of the USDC is sampling, drilling and coring, it also has great potential to serve as a probing device. The USDC imparts elastic waves into the sampled medium offering a sounding method for geophysical analysis similar to the techniques used by the oil industry. Also, the characteristic of the piezoelectric actuator, which drives the USDC, is affected by the medium to which it is coupled. Using a variety of device configurations, a series of experiments were conducted to measure the elastic wave velocity, scattering, impedance and the shift in resonance frequency. Various rocks are being tested to determine their characteristics. Preliminary results are encouraging. Currently, investigation is conducted to find methods of minimizing the effect of surface roughness, geometry and sample dimensions on the data.

Keywords: Ultrasonic/sonic driller/corer (USDC), in-situ analysis, probing, planetary exploration.

1. INTRODUCTION

The search for present or past life in the universe is one of the most important objectives of NASA's mission. Sampling in low gravity environment (as on Mars, comets, and asteroids) using conventional drilling and coring techniques is limited by the need for high axial force. Jointly with Cybersonics, Inc., a novel USDC mechanism was developed overcoming this and other limitations of conventional drilling and sampling techniques [Bar-Cohen et al, 2001a and b]. The USDC mechanism is based on an ultrasonic horn actuated by a piezoelectric stack, which impacts a free-mass resonating between the horn and a drill stem. The USDC involves mechanical frequency transformation via the free-mass allowing the drill bit to operate in a combination of the 20 kHz ultrasonic drive frequency and a 60-1000 Hz sonic hammering action. This novel drill is capable of high-speed drilling using low axial preload and low power, and it is highly tolerant to misalignment. The USDC was demonstrated to operate from such robotic platforms as the Sojourner rover and the FIDO robotic arm and it has been shown to drill rocks as hard as granite and basalt and soft as sandstone and tuff. It drilled 25-mm (1-inch) deep holes in granite from a 4-kg platform, 15-cm and 3-mm diameter in sandstone. This new USDC device is highly tolerant to changes in its operating environment, since it is driven by piezoelectric ceramics, which can be designed to operate at a wide range of temperatures including those expected on Mars as well as Venus. In Figure 1, the USDC is shown being held from its power cord while drilling a sandstone rock -- this is possible because relatively low axial preload is required.

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Figure 1. Ultrasonic/Sonic Driller/Corer (USDC) in action.

Considering the fact that the drill bit does not turn, it is possible to integrate sensors near the tip of the drill/coring bit allowing examination of the freshly produced surfaces and sampled material while penetrating soil/rocks. In addition, the hammering action that is involved with the drilling offers a sounding mechanism for noninvasive geophysical probing of the drilled location and the surrounding area. Also, the effect of the sampled materials on the mechanical impedance of the piezoelectric driver offers potential for qualitative gauging of the mechanical stiffness. The capabilities of the USDC to serve as a platform for probing, sampling, sensing, and in-situ analysis are being investigated towards establishing a Lab-on-a-Drill system. This paper will focus on the probing capability of the USDC.

2 SURFACE WAVE VELOCITY

As mentioned earlier, the hamming action of USDC is a good source of ultrasonic elastic wave energy. The first test of the probing capability was to utilize this acoustic energy generation feature of USDC to induce surface wave onto a sample and measure the received signal with ultrasonic transducers. The surface wave velocity of a media is determined by its elastic constants and mass density. By measuring the surface wave velocity, it may be possible to identify the type and characteristics of the sample or aid in the identification on whether it is a hard or soft material.

The surface wave velocity test is modeled by applying a point source to a half space, as long as the sample is sufficiently thick to avoid the reflection from bottom no interference with the signals of interest will occur. Figure 2 schematically illustrates the various types of waves that are generated by a point source loading onto a half-space and the waves include P-wave, S-wave, and surface wave. The P-wave consumes about 7% of the total energy, the S-wave consumes about 26%, and the surface wave consumes the rest, about 67%, which means that the majority of energy of the signals is dominated by the surface wave [Graff, 1973].

A schematic diagram of the experimental setup is shown in Figure 3 above, which depicts the use of USDC as the source of surface waves. When USDC is operated at its normal working condition, the drill bit impacts the sample at a random frequency which ranges from 60 to 1000 Hz. If we use this normal operating mode as the wave source, the signals generated will be too random to do a consistent analysis. Instead, a function generator is used to provide a controlled signal to the USDC. A sinusoidal tone burst is sent to the USDC at its resonance frequency. The number of cycles that were induced onto the actuator should be small enough so as not to induce any ultrasonic/sonic transformation in the USDC to cause a drilling action. The key is to keep the drill bit, the free mass, and the horn in contact and vibrating at the nominal 20 kHz ultrasonic frequency. The receiving transducers used for the experiments are broadband transducers B1080 made by Digital Wave Corporation.

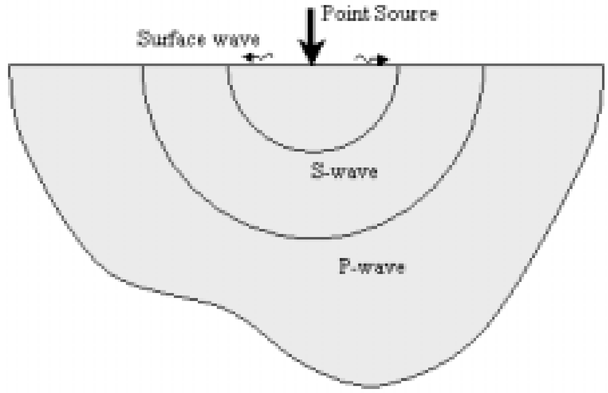

Figure 2. Waves generated by a point source on a half-space.

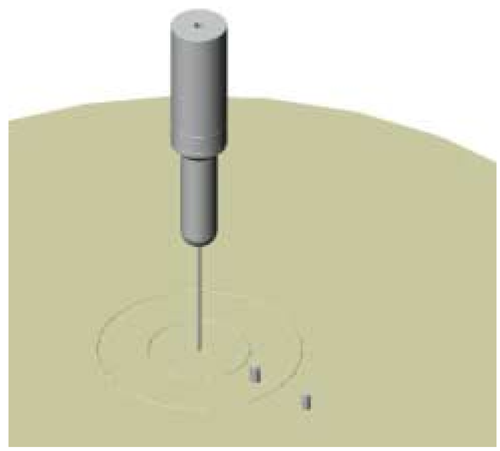

Figure 3. Using USDC as the source of surface waves.

Typical signals generated by USDC on a limestone block using controlled signals from a function generator are shown in Figure 4. The two transducers are placed in line with the USDC and separated by a distance of 2 inches. To calculate the velocity of surface wave, we need to know the time-of-flight for the signal to travel from the first transducer to the second. For complicated signals such as those shown in Figure 4, the best way to determine the time-of-flight is to do cross-correlation analysis of the signals.

$$c_{12}(\tau) = \frac{1}{t}\int_0^t S_1(t)S_2(t+\tau)dt \qquad (1)$$

where S_1 and S_2 are the first and the second signal, τ is the shift of time.

Equation (1) shows the formula for calculation of the cross-correlation. Since the functional form for the signal is not available, a discrete form of equation (1) was used for numerical analysis:

$$c_{12}(n\Delta\tau) = \frac{1}{t}\sum_t S_1(t)S_2(t+n\Delta\tau)\Delta t \qquad (2)$$

The graph shown in Figure 5 is the result of a cross-correlation analysis. The highest peak in Figure 5 provides a measure of the time-of-flight between the two transducers. A surface wave velocity of 1814 m/s was calculated using this time of flight, which is in excellent agreement with the results obtained from the pencil-break experiments that were performed earlier as a baseline for verifying the results of USDC experiments. Table 1 below shows the comparison of results from pencil-break and USDC tests for both limestone and sandstone indicating significant degree of agreement. This result is encouraging with regards to the use of the USDC as a sounding source for the measurement of the surface wave velocity.

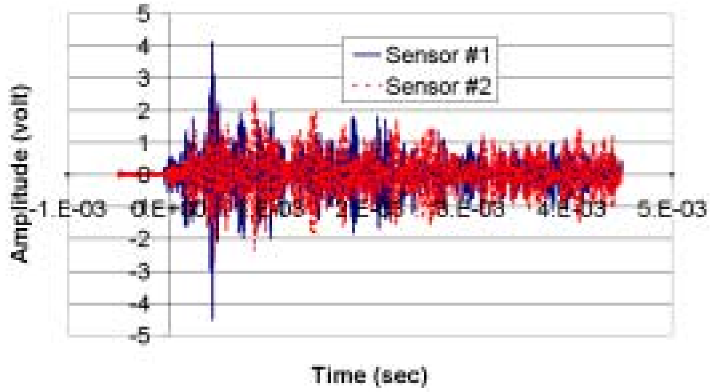

Figure 4. Typical signals generated by USDC on a limestone block.

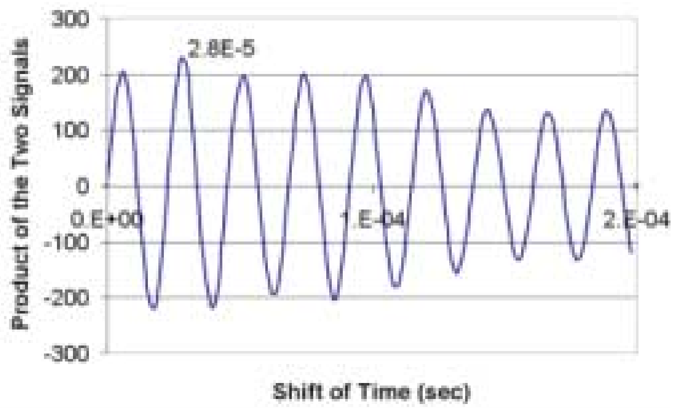

Figure 5. Results of cross-correlation analysis using signals shown in Figure 4 (limestone).

Table 1. Comparison of results from pencil-break and USDC experiments.

	Pencil-break	USDC	Difference
Limestone	1814 m/s	1814 m/s	0%
Sandstone	2230 m/s	2120 m/s	4.9%

Table 2. Measured surface wave velocities for various media.

Rock type	Surface wave velocity
Limestone	1.81 km/sec
Sandstone	2.23 km/sec
Concrete	2.54 km/sec
Brick	1.49 km/sec
Talc	2.07 km/sec
Basalt	2.06 km/sec

Using this approach a series of rock materials were tested and the surface wave velocities are listed in Table 2. It is interesting to point out that the experimental results are repeatable and robust. The velocities for most of the materials tested are distinct. However, the velocities for basalt and talc are very close, although their material properties are very different. This phenomenon indicates the fact that there is a need for at least an additional effective probing algorithm, and combine the results with the surface wave velocity test results, in order to be able to distinguish between different types of rocks.

3. FREQUENCY ANALYSIS OF SURFACE WAVE

In addition to the surface wave velocity measurement mentioned above, the frequency spectrum of the surface wave was also analyzed for rock type recognition. For the purpose of proof of concept, materials other than rocks were used for preliminary experiments. Figure 6 below shows the typical frequency spectra for 5 different materials, including an aluminum plate, brick, tile, and two keystones used in construction. It is easily seen that the 5 spectra are very distinct. However, the task of constructing a robust algorithm for rock recognition remains a challenge.

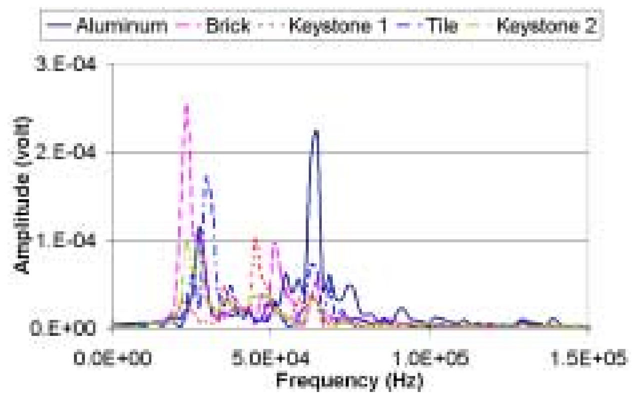

Figure 6. Frequency spectra of surface waves.

The idea was to establish a spectrum database for various types of rocks. The spectrum derived from surface wave tests on an unknown sample is then compared to all the spectra in the database through cross-correlation analysis. Theoretically, the best match provides the answer of what type of rock the sample is made of. During the preliminary experiments, two events of surface wave were sent to the 5 samples mentioned earlier. The first event from each sample was compared to the second event from the same sample and the first events from other samples.

Table 3. Results of cross-correlation analysis on surface wave spectra.

	Aluminum	Brick	Keystone 1	Tile	Keystone 2
Aluminum	**0.881**	0.438	0.458	0.599	0.571
Brick	0.438	**0.903**	0.451	0.473	0.862
Keystone 1	0.458	0.451	**0.903**	0.391	0.663
Tile	0.599	0.473	0.391	**0.900**	0.585
Keystone 2	0.571	0.862	0.663	0.585	**0.830**

The results of the cross-correlation analysis are shown in table 3. The numbers on the diagonal axis, shown in bold font, are the comparison between two events from the same sample. In general the results conform to what we would expect except for the brick/keystone#2 element in the second row of the last column. The largest value should always be the diagonal element. The reason why there is an exception is likely due to un-optimized experimental conditions. In order to reduce these exceptions and increase the confidence in the results, other transducers are being tested and the experiment is being redesigned (various ranges of frequency, different sizes of rocks).

4. RESONANCE AND IMPEDANCE ANALYSIS

The source of acoustic energy of the USDC actuator is the stack of piezoelectric ceramics (PZT) that are pre-stressed between the horn and the backing. In addition to the converse piezoelectric effect, piezoelectric materials also have a direct piezoelectric effect which allows the material to function as sensors. When a USDC actuator touches different types of rocks, the resonance frequency and the electric impedance of the actuator changes due to the change of the mechanical boundary condition on the horn tip. As shown in Figure 7 below, the horn/PZT assembly was used as a resonator with the tip of the horn attached to a rock sample. The resonance frequency and the impedance of the assembly were monitored by an impedance analyzer.

Figure 7. Resonance and impedance test using USDC actuator.

The impedance analysis was carried out using the HP 4194A Impedance Analyzer, where the real and imaginary parts of the admittance of the USDC were recorded (see Figure 8). The reference value of the resonance frequency is 22.77 kHz with a Q of 4484 and it is measured when the USDC is not loaded. Once the USDC was attached to a limestone block the resonance frequency was shifted to 23.15 KHz and Q value was shifted to 368. Both the resonance frequency and the impedance of the USDC actuator changed due to the loading by the limestone. Using this approach the resonance and impedance tests were also conducted for sandstone and brick and the results are shown in Figure 9. It is observed that the resonance frequencies are 23.15, 22.92, and 23.09 KHz while attached to limestone, brick, and sandstone respectively. The Q values are 368, 2103, and 589 respectively.

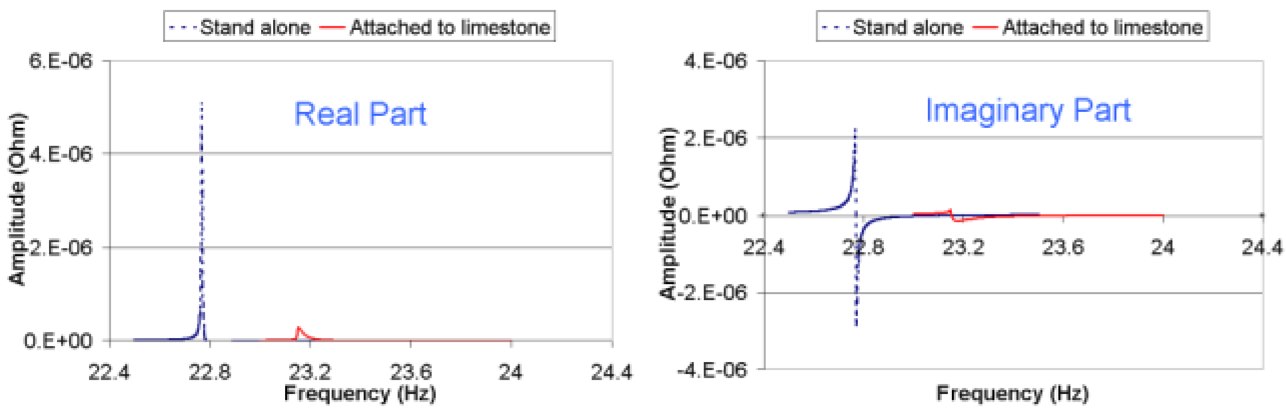

Figure 8. Resonance and impedance analysis for USDC actuator when standing alone and attached to a limestone.

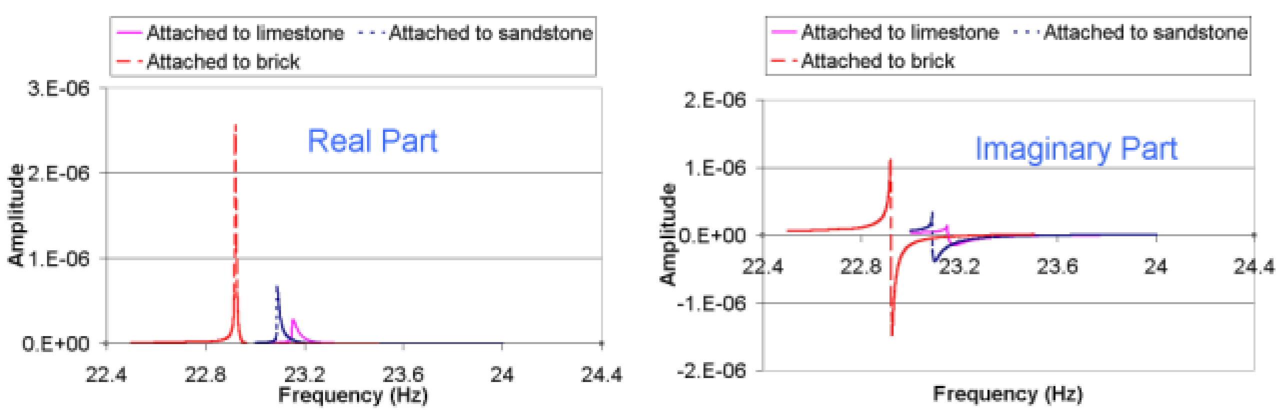

Figure 9. Comparison of resonance and impedance analysis between limestone, sandstone, and brick.

This data indicates the values of the resonance frequency and the impedance of the USDC actuator are sensitive to the material of the object attached to it. However, the measured data was found to be highly sensitive to the coupling condition between the USDC actuator and the sample. The characteristics of rocks that include irregular shapes, surface roughness, etc. make it extremely difficult to keep the coupling conditions the same for each and every test. In order to produce a predictable and controllable load the interface between the rock and the horn tip needs to be standardized. In the initial tests we found a large fluctuations of the results depending upon the quality of the rock/horn coupling.

5. SUMMARY

Preliminary experiments and analysis were conducted using the ultrasonic/sonic driller/corer (USDC) as a source of elastic waves and as a resonator. The measurement of surface wave velocity was found to be very promising. Good agreement between experiments done with USDC and with pencil-break technique suggests that this result will allow us to determine surface velocities with USDC. This experimental technique was found to be robust and the data quite repeatable. Another algorithm that may be useful is the spectral analysis of the surface wave. The initial experiments gave results that in general were as expected, however one sample set produced an incorrect correlation suggesting refinements to the experiment. This technique will need to be fine-tuned by trying different type of transducers, various ranges of frequency, different sizes of rocks before it can be used as a robust algorithm for rock recognition.

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