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

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ABSTRACT

Ability of 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 ones 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 various piezoelectric wafer configurations, we are conducting a series of experiment to measure the elastic wave velocity, scattering, impedance and the shift in resonance frequency. We are testing various rocks to determine their characteristics. Preliminary results are encouraging. We are currently investigating 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) using conventional drilling and coring techniques is limited by the need for high axial force. Jointly with Cybersonics, Inc., under the initiative and lead of the PI, the novel USDC mechanism was developed overcoming this and other limitations of the conventional techniques (Bar-Cohen etc., [2001]). 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 15-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 held from its power cord while drilling a sandstone rock -- this is possible because relatively low axial preload is required.

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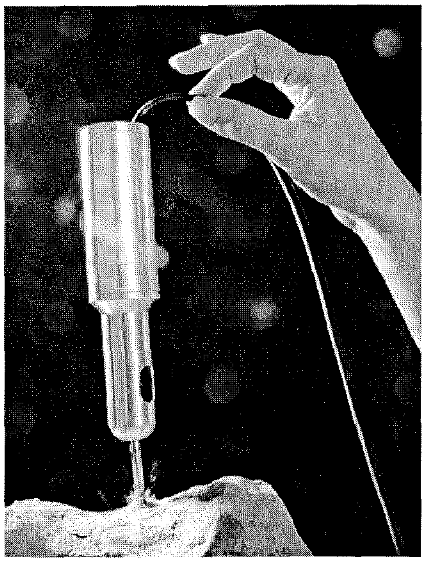


Fig. 1 Ultrasonic/Sonic Driller/Corer (USDC) in action.

Considering the fact that the drill bit does not turn, it is possible to integrate sensors near the tip of the drill/coring bit and allows examination of the freshly produced surfaces and sampled material while penetrating soil/rocks. Besides, 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. It's been under investigation to use USDC as a platform for probing, sampling, sensing, and in-situ analysis. This paper will be focusing on the probing capability of the USDC.

The USDC hammering action will be considered for use as a sounder for geophysical probing mechanisms. Since the technology of geophysical probing is well established only the sounding characteristics of the device will be investigated. Also, the effect of the sampled materials on the mechanical impedance of the piezoelectric driver will be considered for qualitative gauging of the mechanical stiffness.

2 SURFACE WAVE VELOCITY

As mentioned earlier, the hamming action of USDC is a good source of ultrasonic elastic wave. The first study about its probing ability is to utilize this feature of USDC to send surface wave onto a sample and receive it with ultrasonic transducers. Surface wave velocity of a media is determined by its elastic constants and mass density. By measuring the surface wave velocity, we may be able to identify the sample.

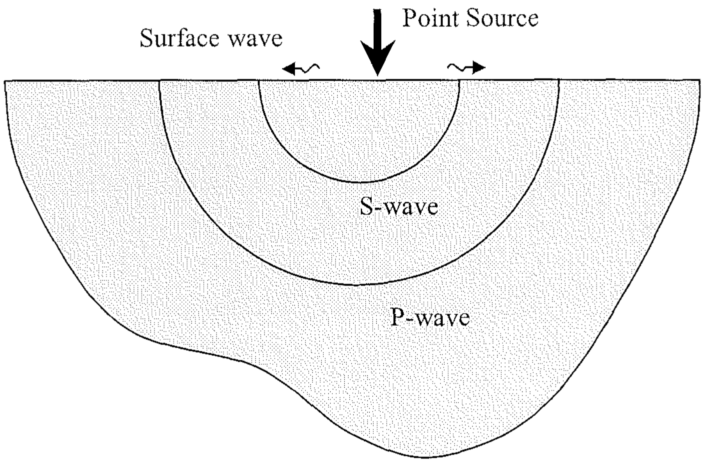


Fig. 2 Waves generated by a point source on a half-space.

Basically, the surface wave velocity test is like applying a point source to a half space, as long as the sample is thick enough to avoid the reflection from bottom to interfere with the signals of interest. Fig. 2 shows the various types of waves generated by a point source loading on a half-space. The waves are 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%. So the signals received by the transducers are dominated by the surface wave (Graff [1973]).

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

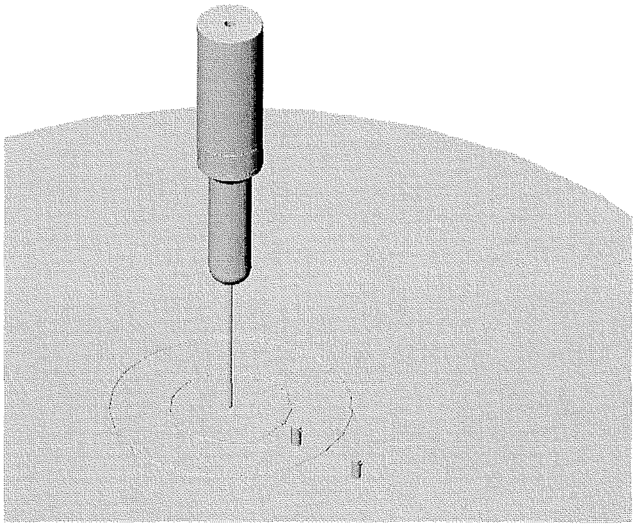
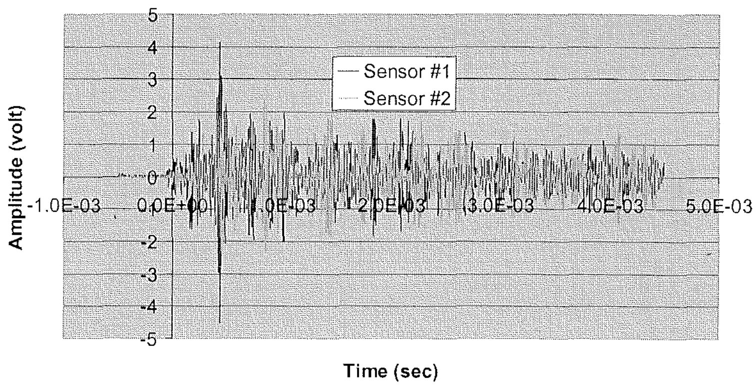


Fig. 3 above depicts the use of USDC as the source of surface waves. When USDC is operated at its normal working condition, the drill bit impacts the sample at a frequency ranged from 60 to 1000 Hz, changing vigorously. If we use this normal operating mode as the wave source, the signals generated will be too messy to do any 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 sent should be small enough so as not to induce any ultrasonic/sonic transformation in the USDC. The key is to keep the drill bit, the free mass, and the horn together and vibrate at ultrasonic frequency range. The transducers used for the experiments are broadband transducers B1080 made by Digital Wave Corporation.

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



Typical signals generated by USDC on a limestone block using controlled signals from a function generator are shown in Fig. 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 shown in Fig. 4, the best way to figure out the time-of-flight is to do cross-corelation analysis to 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-corelation. Since the close form for the signal is not available, a discrete form of equation (1) will be used for numerical analysis:

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

Fig. 5 Results of cross-corelation analysis using signals shown in Fig. 4 (limestone).

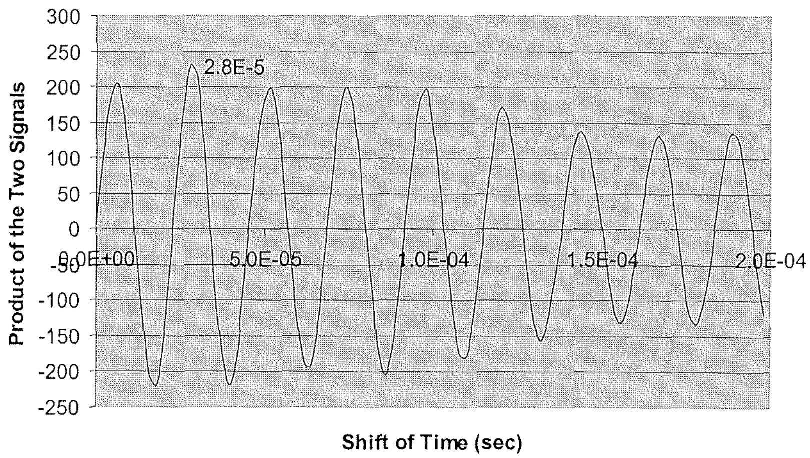


Fig. 5 shows the results of cross-corelation analysis. The highest peak in Fig. 5 gives the time-of-flight between the two transducers. The velocity of surface wave calculated is 1814 m/s, which is in excellent agreement with the results from the pencil-break experiments we performed earlier as a baseline 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.

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. Surface wave velocities for some media.

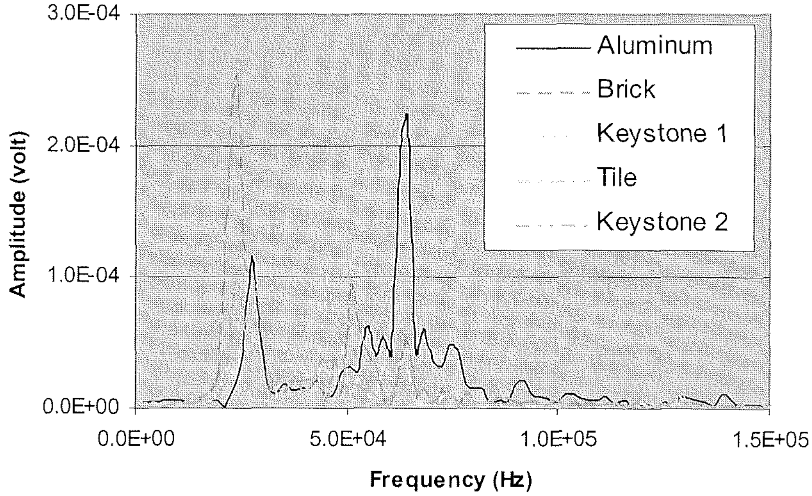
Rock type	Surface wave velocity
Limestone	1.81 km/sec
Sandstone	2.23 km/sec
Concrete	2.54 km/sec
Brick	1.49 km/sec
Talc	2.07 km/sec
Basalt	2.06 km/sec

Table 2 shows surface wave velocities for several media. The experiment 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 we need at least one other effective probing algorithm, and combine its 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 may also be analyzed for rock type recognition. For the purpose of proof of concept, some materials other than rocks were used for preliminary experiments. Fig. 6 below shows the typical frequency spectra for 5 different materials, an aluminum plate, a brick, a tile, and two keystones for construction. It is easily seen that the 5 spectra are very distinct. However, construct a robust algorithm for rock recognition remains a challenge.

Fig. 6 Frequency spectra of surface waves.



The idea is 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-corelation analysis. Theoretically, the best match gives us the answer of what type of rock the sample is made of. During our preliminary experiments, two events of surface wave were sent to the 5 samples shown in Fig. 6. 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-corelation analysis on surface wave spectrua.

	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-corelation 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. They are supposed to be the largest number on each column. However, there is one exception. On the last column, the largest one appears at the second cell, where the number is from the comparison between the brick and the keystone #2. The reason why there is a exception is probably because we did not perform the experiments under the optimized conditions. To avoid exceptions, we will try different type of transducers, various ranges of frequency, different sizes of rocks… in order to find the best results.

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