Proceedings of the SPIE Smart Structures Conference San Diego, CA., SPIE Vol. 5388-34, Mar 14-18. 2004

Design and analysis of ultrasonic horn for USDC (Ultrasonic/Sonic Driller/Corer)

Zensheu Chang, Stewart Sherrit, Xiaoqi Bao, and Yoseph Bar-Cohen

JPL/Caltech (MS 67-119), 4800 Oak Grove Drive, Pasadena, CA 91109-8099[1]

ABSTRACT

In-situ sampling and analysis is one of the major objectives of future NASA exploration missions. Existing drilling techniques are limited by the need for large axial forces, holding torques, and high power consumption. Lightweight robots and rovers have difficulties accommodating these requirements. These requirements are becoming increasingly tougher to meet as the need for drilling techniques is expanding to reach deeper into the subsurface. To address these key challenges to the NASA objective of planetary in-situ rock sampling and analysis, a drilling technology called ultrasonic/sonic driller/corer (USDC) was developed. The USDC uses a novel driving mechanism, transferring ultrasonic vibration to sonic frequency impacts with the aid of a free-flying mass block (free-mass). The free mass then drives the drill bit. The actuator consists of a stack of piezoelectric disks with a horn that amplifies the induced vibration amplitudes. To meet the need for deep driller the USDC was modified to form the Ultrasonic/Sonic Gopher. Drilling to the depth of several meters in ice or hard rocks requires the optimization of the amplification of the vibration displacement and velocity that are generated by the piezoelectric materials. For this purpose, various horn designs were examined analytically. Conventional and new designs of the horn were analyzed using finite element modeling and the results allow for the determination of the control parameters that can enhance the tip displacement and velocity. The results of the modeling are described and discussed in this paper.

Keywords: Ultrasonic/sonic driller/corer (USDC), ultrasonic horn, planetary exploration.

1. INTRODUCTION

In-situ sampling and analysis, and possibly the return of samples to earth are becoming increasingly important in NASA's space exploration missions. Existing drilling techniques are limited by the need for large axial forces and holding torques, high power consumption, large mass and inability to efficiently duty cycle. Jointly with Cybersonics, Inc., a novel USDC mechanism [Bar-Cohen et al, 2001] was developed to address these issues. 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, (refer to Figure 1). The ultrasonic horn is driven at its resonance frequency, ranging from 5 KHz to 25 KHz depending on the specific design. The free mass bounces back and forth between the ultrasonic horn and the drill stem, converting the high frequency vibration of the horn to a hammering action with a frequency range of tens to a thousand Hz. 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 has drilled 25-mm (1-inch) deep holes in granite from a 4-kg platform, 15-cm and 3-mm diameter in sandstone and 10 cm long, 1 cm diameter cores of basalt. 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 over a wide range of temperatures including those expected on Mars as well as Venus. In Figure 2, 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.

Some of NASA's missions require deep penetration into rocks, ground, or ice for sampling and analysis. Based upon the USDC mechanism, the Ultrasonic/Sonic Gopher (USG) was developed for deep drilling. Instead of using a drill bit that

[1] Correspondence: Email zchang@jpl.nasa.gov; web: http://ndea.jpl.nasa.gov

is long enough to reach the required depth, the USG features a coring bit with an outer diameter larger than that of the rest of the USG. So the USG can core into the target material, break the core and discard it or store it for later analysis. The drill is returned to the hole and drills, breaks and retains another core repeating the process until the required depth is reached. Currently, the authors are developing this technology under a NASA's Astrobiology for Science and Technology for Exploring Planets (ASTEP) task. This task has the goal of developing and testing a USG for drilling into ice (–20 degree Celsius) to a depth of 20 meters [Bar-Cohen et al, 2004].

As the target depth gets deeper, the power consumption, the drilling rate, and the efficiency of the USDC becomes more important an issue. The three major parts of the USDC, namely, the ultrasonic actuator, the free mass, and the drill bit, are being optimized to address the efficiency and drilling rate issue. In this paper, we focus on the optimization of the ultrasonic horn. A series of design and analysis of the ultrasonic horn have been carried out to improve the performance of the USDC. The results will be presented and discussed in this paper.

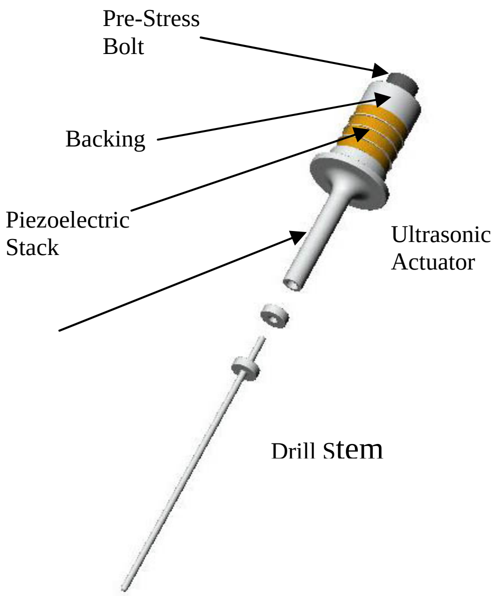


Figure 1. Exploded view of a typical USDC.

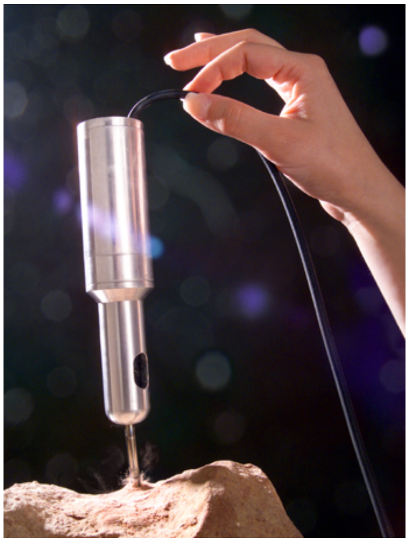


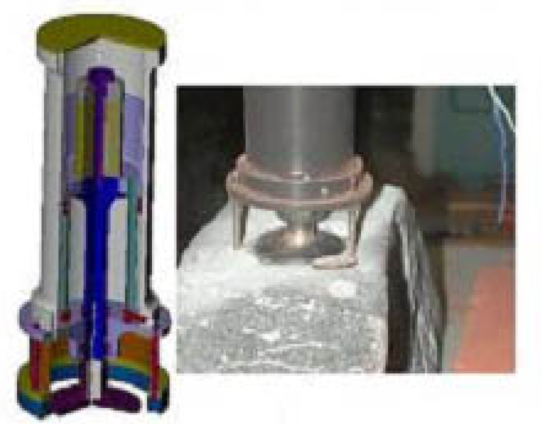
Figure 2. Ultrasonic/Sonic Driller/Corer (USDC) in action.

2 ULTRASONIC/SONIC DRILLER/CORER (USDC)

The USDC consists of three major components, the ultrasonic actuator, the free mass, and the drill stem. The ultrasonic actuator is made of a stack of piezoelectric rings, an ultrasonic horn, a metal backing, and a pre-stress bolt to connect all these parts and provide pre-strain to the piezoelectric stack (Figure 1). The piezoelectric material needs to be pre-strained so it doesn't break during the extension. The stack of piezoelectric material is excited at the resonance frequency of the ultrasonic actuator. Through the amplification of the ultrasonic horn, the displacement of the vibration reaches tens of microns at the tip of the horn. A free mass is contacted to the horn tip of the USDC. During a drilling operation, the free mass bounces and moves back and forth between the ultrasonic horn and the drill stem. Due to the fact that the velocity of the free mass is smaller than the velocity of the horn tip vibration, the free mass usually contacts the horn tip at a favorable phase of horn tip vibration. During which the free mass picks up momentum and is accelerated back to the drill stem. The free-mass transfers impact momentum from the ultrasonic transducer to the drill stem at a frequency ranging from tens of Hz to about 1000 Hz. The shock waves caused by the impacts of the free mass upon the drill stem propagate to the bit/rock interface. The impacted brittle medium (rock, ice, etc.) is fractured when its ultimate strain is exceeded at the medium/bit interface.

In order to determine the critical issues related to the control and optimization of the USDC the interaction at the various interfaces of the drill were investigated [Bao et al, 2003]. This model consists of five elements including the electrical driver, ultrasonic transducer, free-mass, drill bit, and the rock. In the initial modeling effort, the main elements and the interaction between them were analyzed and modeled separately. A one-dimensional model was developed for each interaction (except the bit-rock interaction). Later, the strain that is induced in the rock was calculated by using a two-dimensional axisymmetric model and the drilling rate was estimated based on the specific energy required to fracture the rock. The four interactions that were modeled include: 1) transducer with the driving circuit, 2) horn tip with the free mass, 3) free mass with the drill stem and 4) base of the drill stem (bit) with the rock.

A variety of devices based on the USDC mechanism have been designed, built and tested. The Ultrasonic/sonic Rock Abrasion Tool (URAT) removes the top weathered surface of rocks to reveal the un-weathered layers underneath. It is achieved by replacing the drill bit of the USDC with a tool with an array of pyramidal teeth similar to a meat tenderizer. The ultrasonic crusher crushes rock samples into powders with sizes suitable for analysis. It utilizes the impact loading provided by the free mass to directly smash the rock samples into powders. The Ultrasonic/Sonic Gopher (USG) aims at deep drilling. It features a coring bit larger than the rest of the USG body, allowing the whole USG to go deep into the target material as long as it keeps on coring, breaking, removing the core, and then reacquiring the borehole. Figure 3 shows the prototypes of a URAT and a USG.



URAT

USG

Figure 3. Ultrasonic Rock Abrasion Tool (URAT) and Ultrasonic/Sonic Gopher (USG).

Parallel to the development of the various devices, efforts have been made in exploiting the versatility of USDC in order to make it capable of a variety of tasks. The USDC drills by impacting the target material with a stress wave. In doing so, it also sends out elastic waves into the materials. Combined with a pair of signal receivers, the USDC can be used to probe the material it is drilling [Chang et al, 2003]. This ability allows pre-screening of sampling area to increase the probability of success in acquiring a sample containing useful information. The drill stem of USDC does not rotate as it drills, which makes it possible for the idea of lab-on-a-drill. By utilizing the drill stem as a platform for sensors, various types of sensors have been mounted on the bit, including thermocouple and fiberoptic. Real time analysis and measurements down the hole reduce concerns of cross contamination that may result from sample handling.

3. ANALYTIC MODELING OF USDC

To optimize the performance of the USDC, all the three major components must be carefully examined and adequately modeled. By establishing a successful theoretical model of the USDC, we are able to predict the performance of various designs of the gopher, and thus make the optimal design possible. A complete model had been developed [Bao et al, 2003] to describe the behaviors of and the interactions between the three major components, and to predict the performance of the USDC. The interactions between the free mass, the transducer, and the coring stem are very complicated. Finite Element Analysis (FEA) is done to investigate these interactions. With information derived from the FEA, a computer program is developed to simulate the operation of the USDC system including the ultrasonic actuator, the free mass, and the drill stem. This model is modified for the analysis of a series of different designs of ultrasonic horns. We studied 5 different ultrasonic horn designs including; the conventional horn with a cross-section area reduction, a horn without cross-section area reduction, a horn with a neck section located at middle span, a horn with a neck located closer to the horn tip, and a horn with a neck located closer to the piezoelectric stack. The 5 designs of the ultrasonic horn are shown in Figure 4 below. Note that the 5 horns are not of the same scale due to the requirement that the overall length be adjusted to keep the neutral plane at the piezoelectric/horn boundary. The actual size of the piezoelectric stack is the same for each horn.

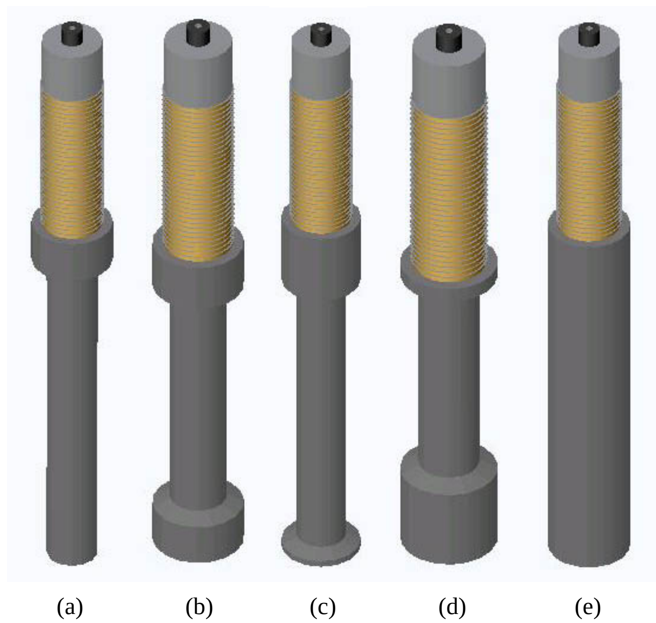


Figure 4. The 5 designs of ultrasonic horn studied:
(a) Conventional
(b) Neck at middle span of horn
(c) Neck moved down 20 mm
(d) Neck moved up 20 mm
(e) No neck

In order to compare the horn designs we first performed modal analysis on the various actuators to derive the resonance and anti-resonance frequencies. Next, we conducted a harmonic analysis to derive the maximum horn tip displacements. The resonance frequency and maximum horn tip displacement were then used to do a contact analysis to determine the rebounding velocity of the free mass after interacting with the horn. Contact analysis was also performed to study the interaction between the free mass and the drill stem. Finally, all the information derived from FEA was input into the model and the performance of each horn design was predicted. The power at different level of the impact momentum is used as a criterion to determine the performance of a horn design.

3.1 Finite Element Analysis

The finite element analysis was performed by using the commercially available code ANSYS. In this high power ultrasonic application, the actuator is designed and fabricated to have high mechanical Q, and is operated at or near its first longitudinal resonance frequency. Using modal analysis allowed us to isolate this resonance mode. The anti-resonance frequency of the same mode was derived too, and together with the resonance frequency the electro-mechanical coupling factor was theoretically calculated. The modal analysis is also very useful in determining the neutral plane of the vibration of the actuator. It is desirable to have the neutral plane coincident with the location where the USDC is mounted to the structure of, say, a rover or a robotic arm. Otherwise, the whole structure will interact with the actuator and the interaction may significantly change the design resonance mode of the isolated USDC. Consequently, some energy will be lost dissipating into the whole structure and the efficiency of USDC will go down. Experiments show that if the mounting point is not designed to be located at the neutral plane, the mounting does not last and screws or bolts holding the structure to the USDC may thread out or break. Therefore for each design of the ultrasonic horn, the length of the horn is adjusted to align the neutral plane and the mounting point.

After performing the modal analysis a harmonic analysis was performed by exciting the piezoelectric stack with 200-volt peak-to-peak electric field at the resonance frequency. The harmonic analysis provides the maximum horn tip displacement data. The results from the modal and the harmonic analysis are shown in Table 1 below.

Table 1. Results of modal and harmonic analysis

Horn Type	Horn length (mm)	Resonance (Hz)	Anti-Resonance (Hz)	Coupling Factor	Max. Displacement (mm)
Conventional	250	5314	5726	0.372	0.209
Neck at middle	200	5473	5947	0.391	0.185
Neck up 20 mm	175	5421	5916	0.400	0.185
Neck down 20 mm	255	5266	5666	0.369	0.209
No Neck	240	5304	6016	0.472	0.133

The interaction between the free mass and the ultrasonic horn is too complicated to be properly described by a simple collision model. The interaction lasts for a very short period of time, on the order of 10s of microseconds. During the short time duration that the impact lasts, the impact wave propagates to a limited range within the horn. The remaining part of the actuator is actually not involved in the impact. So, the assumption in the simple collision model of a horn mass much greater than the free mass may not be correct. To explore the details of the real impact/driving process, a finite element contact analysis was constructed. For the same reason, the interaction between the free mass and the drill stem was also analyzed by FEA. This FEA approach provides a more accurate description of the free-mass speed after the collision and the time duration of the collision, (refer to Figure 5). The maximum speed derived through FEA is typically lower when compared to the speed calculated using simple collision model. This implies a limited effective mass of the horn. A finite element model similar to that used for horn tip and free mass interaction, was utilized to investigate the interaction between the free mass and the drill stem. A typical result is shown in Figure 6.

3.2 Integrated Computer Simulation Model

A computer program was developed to simulate the operation of the drill system including the ultrasonic horn, the free mass, and the drill stem. All the results derived from FEA were used to initialize some of the parameters in the integrated model. These parameters include coefficients used to calculate the free mass rebound speed from the horn tip and from the drill stem, the duration of impact between the free mass and the horn, and between the free mass and the drill stem. The program was able to predict the performance of the USDC with different types of horn designs. This program traces the translation movements of the actuator and the free mass as well as the vibration of the ultrasonic horn as functions of time. It predicts the time and location of the free mass/horn or free mass/bit collision. It also calculates the changes of the variables as time evolves. The movements and vibration due to the impact are recorded along with the impact momentum and time. The program then proceeds to predict the next impact. The energy supplied by the electric source and delivered to the transducer is integrated and recorded concurrently. The statistics reported by the program include electric input power, mechanical output power delivered to the coring stem, average and distribution of the free mass speeds, etc. The first 20% of the events are excluded in order to eliminate the possible influence of the initial settings. Figures 7, 8, and 9 show typical results derived from the integrated model.

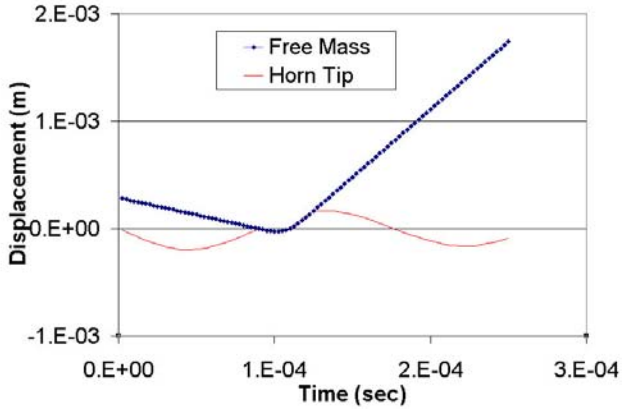


Figure 5. The free mass and horn tip displacement as a function of time.

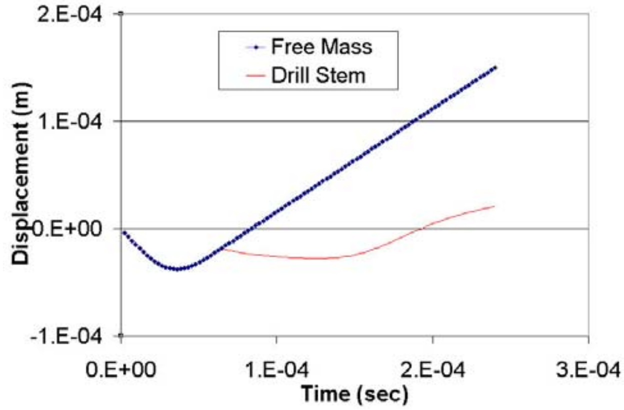


Figure 6. The free mass and drill stem displacement as a function of time.

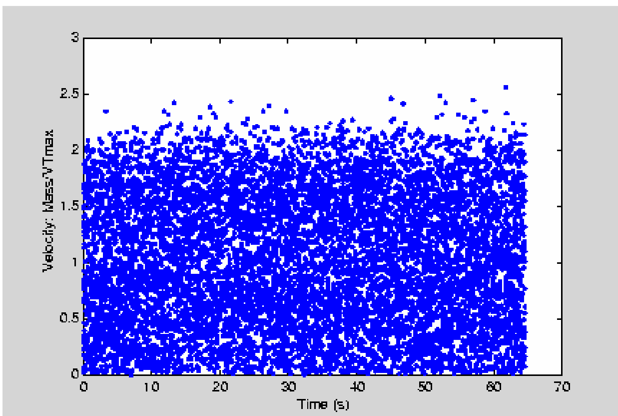


Figure 7. Free-mass velocity normalized by the horn tip vibration velocity.

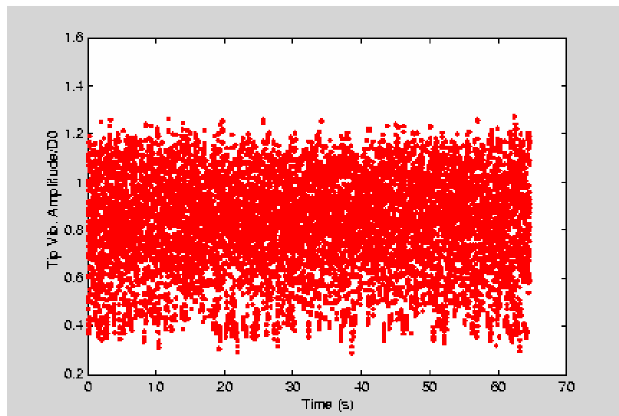
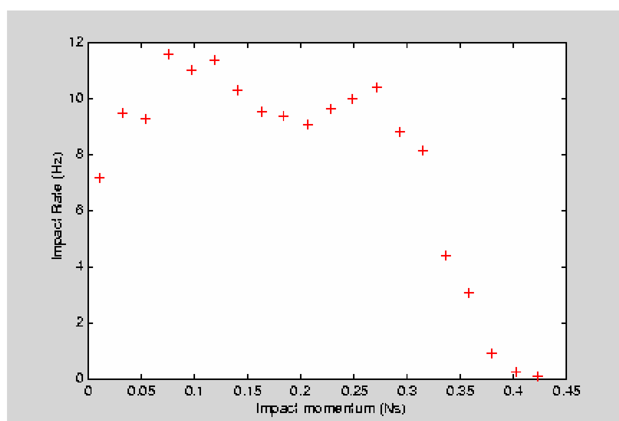


Figure 8. Horn vibration amplitude normalized by the amplitude without loading.

Figure 9. The impact frequency versus momentum.



4. RESULTS AND DISCUSSION

When USDC drills a rock, or other brittle materials, the strain at the bit/rock interface must exceed a critical level related to the rock's strength in order to cause a fracture. The strain at the bit/rock interface is proportional to the level of momentum transfer from the free mass to the drill stem. The total power delivered to the rock while the strain exceeds the critical level determines the drilling rate. Figure 10 shows the power delivered to the target while the impact momentum is greater than a certain level. The input power is 345 watts, and the preload is 4 kg. Among the 5 ultrasonic horns that were investigated, the horn with a neck at its middle span is clearly superior to the rest. The difference is especially distinct at higher level of impact momentum.

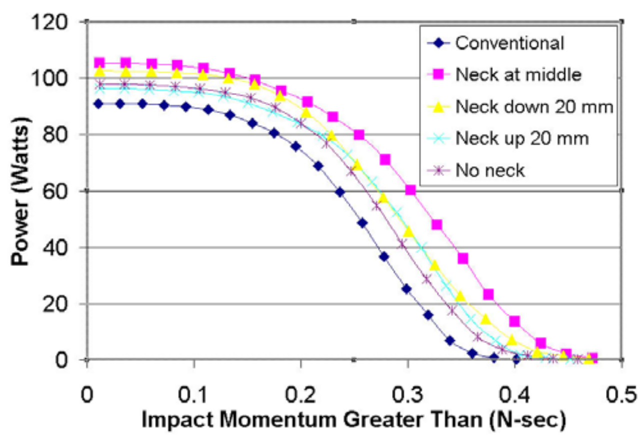


Figure 10. Power delivered while the impact momentum is greater than a certain level.

5. SUMMARY

Theoretical and numerical analysis was conducted to study the performance of 5 USDCs designs with different ultrasonic horns. Results show that increase of horn tip cross-section area and the introduction of a neck improves the performance of the USDC. More analysis will be done for horns with different neck-thickness. Experiments are currently being set up to verify the validity of the analytical results.

ACKNOWLEDGMENT

Research reported in this manuscript was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with National Aeronautics Space Agency (NASA).

REFERENCES

Bao X., Y. Bar-Cohen, Z. Chang, B. P. Dolgin, S. Sherrit, D. S. Pal, S. Du, and T. Peterson, "Modeling and Computer Simulation of Ultrasonic/Sonic Driller.Corer (USDC)", *IEEE Transaction on Ultrasonics, Ferroelectrics and Frequency Control (UFFC),* Vol. 50, No. 9, (Sept. 2003), pp. 1147-1160.

Bar-Cohen, Y., Sherrit, S., Dolgin, B., Bao, X., Chang, Z., Krahe, R., Kroh, J., Pal, D., Du, S., and Peterson, T., "Ultrasonic/Sonic Driller/Corer(USDC) for planetary application," *Proc. SPIE Smart Structure and Materials 2001*, pp. 529-551, 2001.

Bar-Cohen, Y., Sherrit, S., Chang, Z., Wessel, L., Bao, X., Doran, P.T., Fritsen, C.H., Kenig, F., McKay, C.P., Murray, A., and Peterson, T., "Subsurface Ice and Brine Sampling Using an Ultrasonic/Sonic Gopher for Life Detection and Characterization in the McMurdo Dry Valleys", *Proc. SPIE Smart Structure and Materials*, 2004.

Chang, Z., Sherrit, S., Bao, X., and Bar-Cohen, Y., "In-situ Rock Probing Using The Ultrasonic/Sonic Driller/Corer (USDC)", *Proc. SPIE Smart Structure and Materials*, 2003.