"ROCK DRILLER"

CONTRACT # NAS3-99122

FINAL REPORT

Submitted By:
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PROJECT SUMMARY

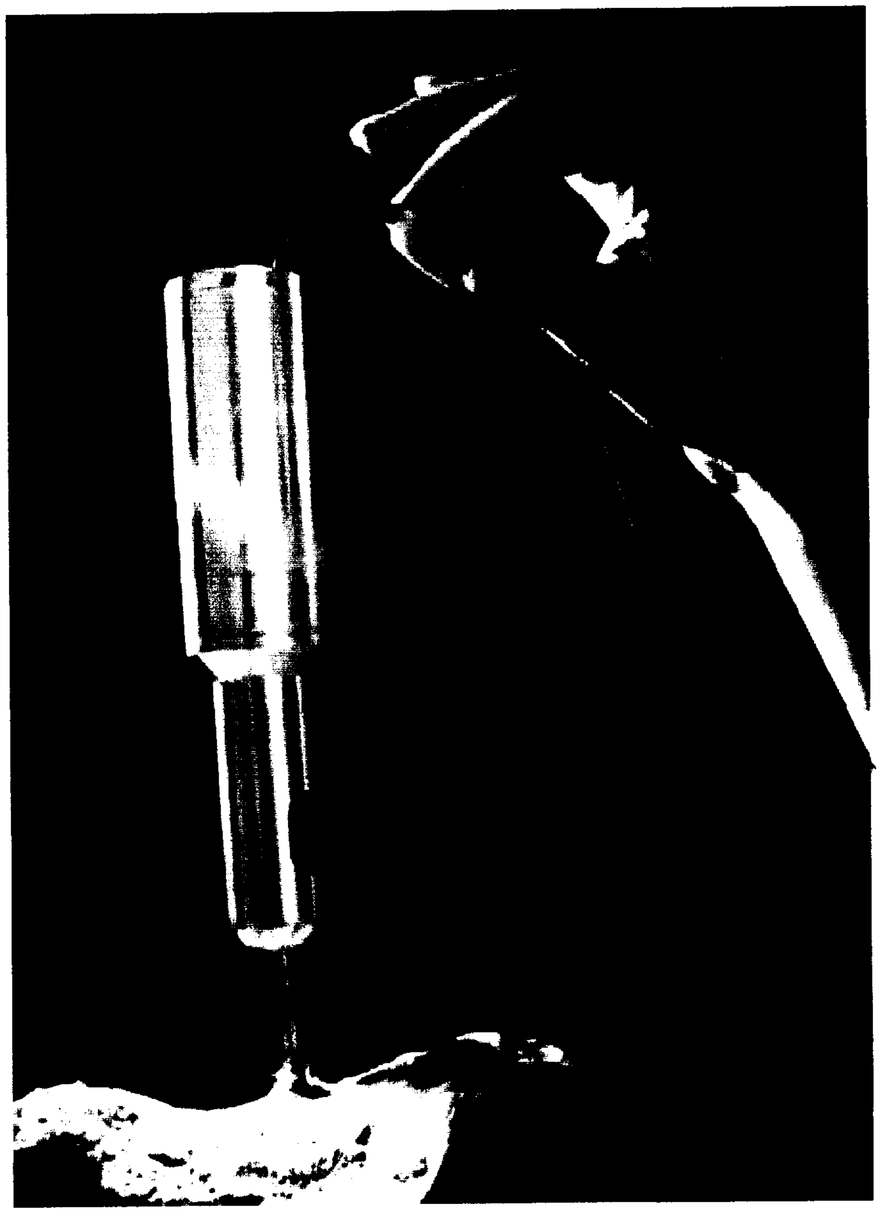
As future NASA exploration missions to Mars, Europa, Titan, comets and asteroids are undertaken, sampling for in-situ analysis and possibly material return to Earth are objectives for advancing knowledge of the planetary environments. This research project was undertaken to develop a device that could perform the sampling function of drilling and coring in a low gravity environment. Conventional drilling requires high axial forces that result in heavy robotic mechanisms that constrain mission objectives. An Ultrasonic/sonic driller/corer (USDC) that is driven by a piezoelectric stack was developed to help achieve mission objectives.

Computer modeling (ANSYS) was used to design a piezo transducer stack with a floating probe coupled to a free mass. It can be integrated with various end effectors that would be used to acquire samples from the desired terrain. The stack, with its titanium horn drives a free mass and end effector that drills through various types of rock including granite, diorite, basalt and limestone. Although the USDC is driven at 20 kHz, a sub-harmonic component as a result of the free mass greatly increases the drilling and coring performance.

The USDC is lightweight at 450 g. and can be driven at low power with 5 watts. The electronics to power the USDC were first modeled on Circuit Maker Pro to save development time and minimize the generator footprint. A microprocessor was used to control signal generator and achieve drilling performance at 5 watts. The signal generator was reduced to 3x5 inches and weighs less than 75 grams.

The USDC system that was developed can operate at high or low temperature and does not require sharpening of the bit. It has been operated from a Sojourner class rover and the FIDO robotic arm and has proven its capability to integrate with the rovers for planetary exploration.

Commercial applications of this technology are being examined daily. Medical instruments using elements of the USDC are being used in animal studies and some instruments will undergo human trials this year. The signal generator with its microprocessor control has been applied to commercial quality control instruments and is currently being evaluated for hand tools. Figure 1 demonstrates the lightweight and zero torque of the USDC.



PROJECT OBJECTIVES

1. Develop a finite element model that will provide analysis of the response of the piezoelectric actuator and corer and its interaction with a rock.

Work Performed

Multiple FEA (Finite Element Analysis) models have been developed to help in evaluating and optimizing the transducer. A parametric model was developed in ANSYS that was used to provide a number of hardware configurations that in turn were converted into actual transducers for evaluation and testing. The parametric model provided a baseline so all of the key elements such as dimensions, material construction, power inputs etc could be varied to determine the corresponding effect on the transducer components and performance. By varying the frequency of the model, the horn tip displacement, or excursion, could be measured and compared to displacement of other frequencies in a range from 15 to 60kHz. By varying the frequencies to find the maximum displacement in the model, significant time was saved compared to conventional methods where a base line horn would be machined and the tip would be shortened in small increments until the desired performance was attained. Our method allowed a large matrix of configurations to be evaluated in software. It then provided data for the final selected model for conversion to hardware and testing in the lab.

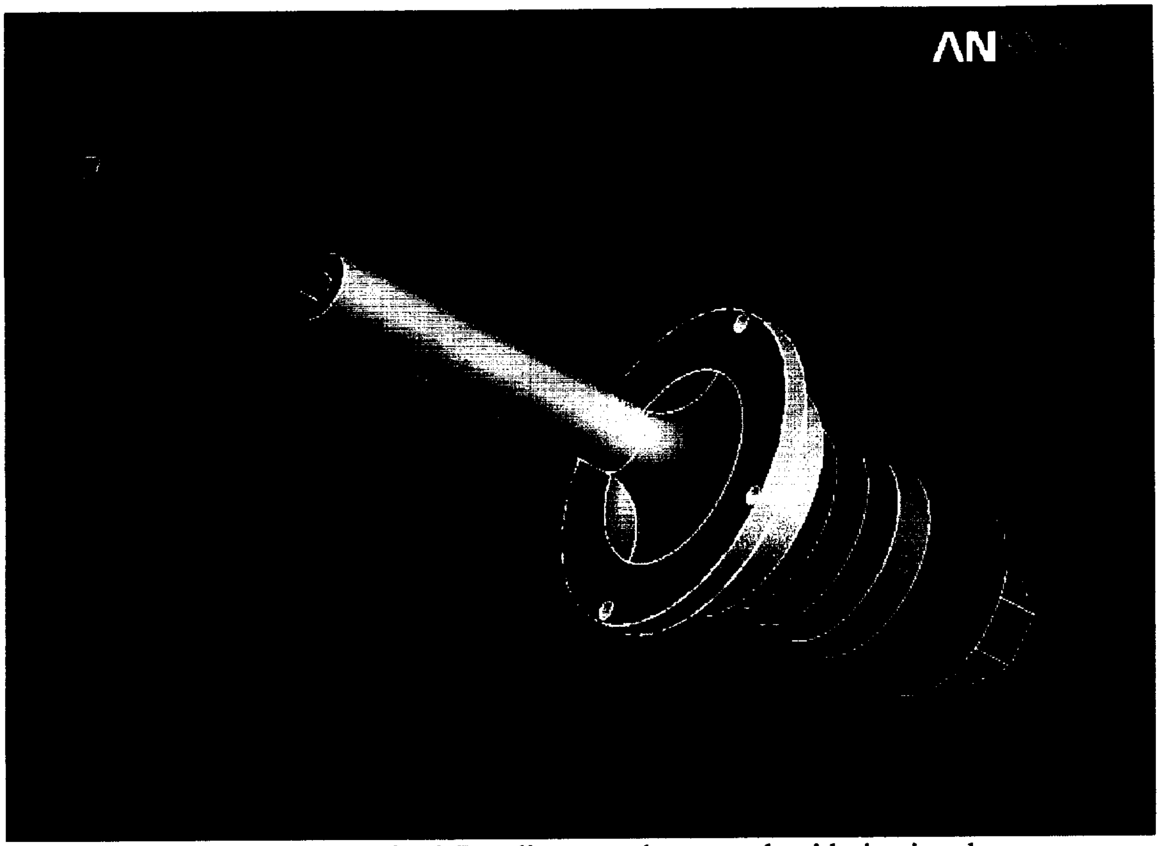


Fig. 2 Baseline transducer stack with titanium horn

The matrix of transducer models was initially determined by the intended application i.e. be small and lightweight enough to work on a rover and perform drilling and coring in various substrates using 5 watts. These constraints forced the transducer stack into a cylindrical envelope 15cm x 6cm. Although the overall weight could have been reduced by using an aluminum horn, which is half the weight of titanium, the titanium 6AL4V-T6 alloy was used instead as the performance and life is approximately ten times greater than that of 2024T4 alloy aluminum.

The back mass material was retained as 1018 alloy steel as its performance was close to some other heavier metals but the performance difference wasn't significant. During the course of the project different piezo crystals were used such as PZT-4, PZT-8, PZ-46, PZT-8M.The baseline unit uses 4 sections of PZt-8.

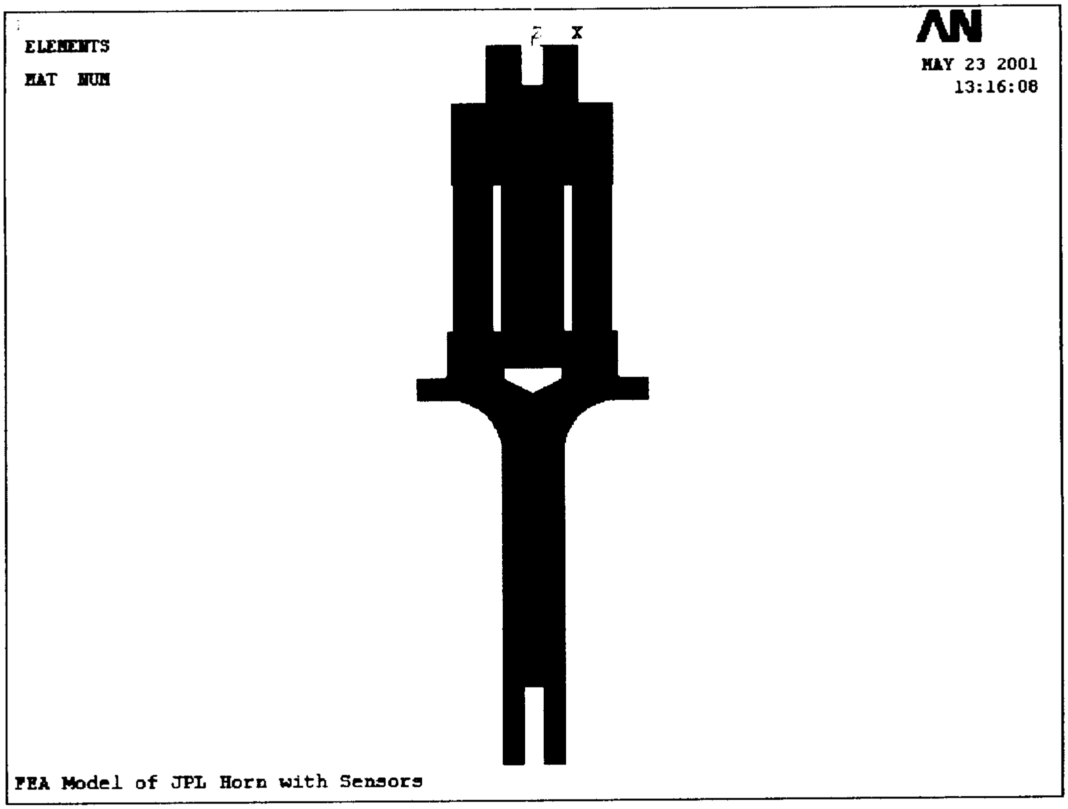


Fig. 3 Baseline stack with Sensors

The current model results and hardware supplied to JPL are in unison with the baseline transducer. The transducer design depicted in Fig.3 can have the inputs/outputs, and component sections varied to achieve the desired stack performance. Once a parametric model is established, iterations can be run to optimize the stack for the desired performance.

JPL also developed a model using ANSYS to better understand the fracture of rocks under impact loading of the USDC. This work was later published for a symposium (SAIRAS –01) in Montreal. Some of this analysis is outlined below.

Free Mass – Drill Stem Interaction

The introduction of the "free mass" to the stack assembly provided a significant increase in USDC performance on all substrates. Although the performance was much better it appeared to be based on almost random output as the size and frequency of the USDC jumps were measured with a high-speed camera and depicted in Fig. 6

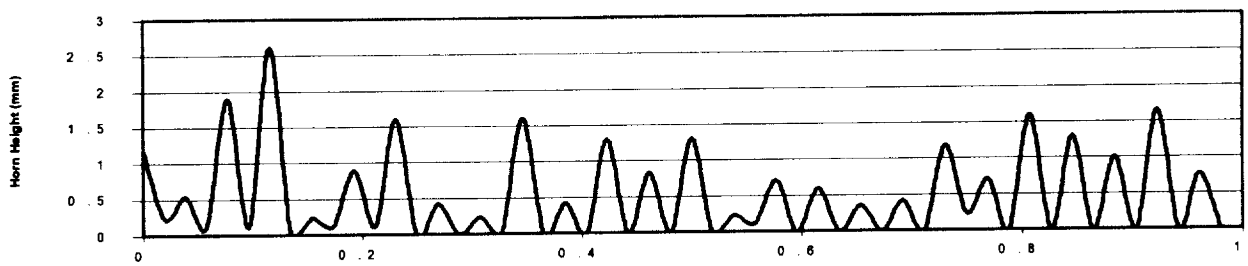


Figure 6 - The horn position as a function of time determined from high-speed camera.

The free mass impacts the top of the drill stem and creates a stress wave that propagates to the bit end. A finite element model was utilized to investigate the impact and resultant stress wave. Figure 7 shows results for the case where a cylindrical steel stem/bit of diameter 3.0 mm and length 100 mm with a concentric top cap of diameter 12 mm and length 6 mm. The impact used in the model is that of a free mass of 2 g with speed 1 m/s. The free mass has a curved surface at the contact area with a curvature of 10 mm. The free mass is assumed to be rigid and the bit end of the drill stem is clamped. Figure 7 shows the displacement of the surface of the free mass and the top surface of the drill stem during impact as a function of time. Figure 8 shows the resultant stress wave as a function of time at the bit end of the drill stem.

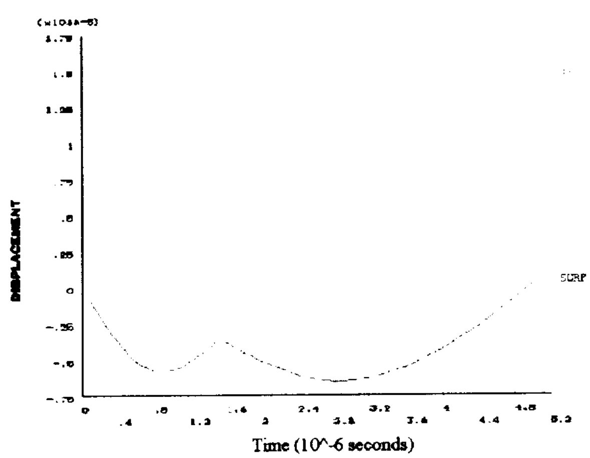


Figure 7 - The displacement as a function of time of the free mass and the top surface of the drill stem after impact.

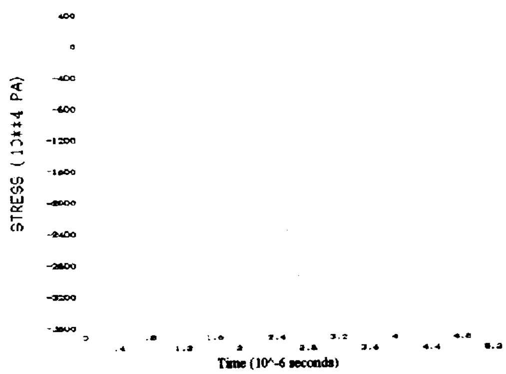


Figure 8 - The stress as a function of time of the free mass and the top surface of the drill stem after impact.

Bit Rock Interaction

In order to better understand the fracture of rocks under impact loading from a drill or a corer, a finite element model was developed using ANSYS. For the purpose of simplifying the problem, the rock is modeled as a circular cylinder with bottom surface fixed and the drill/corer impacts at the center of the top surface. This simplification makes the problem axis-symmetric. By using the axis-symmetric elements available in ANSYS, the original three-dimensional problem is now reduced to a two-dimensions. The element size is made very fine near the drill/corer bit, and becomes coarser and coarser as it goes further away from the bit. Figure 9 shows a typical mesh for the problem outlined above.

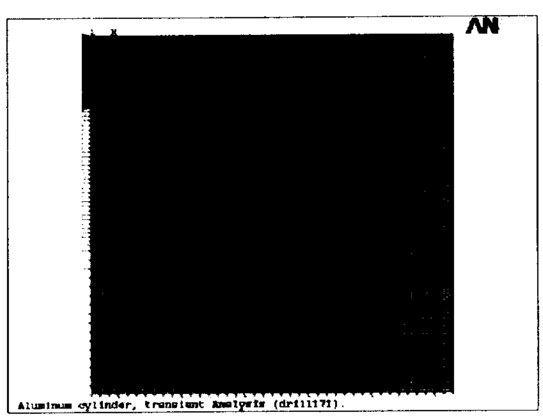


Figure 9- The mesh used to solve the bit rock interaction

Preliminary results were derived by assuming that the circular cylinder is made of isotropic material with a Young's modulus of 10 GPa and poisons ratio of 0.3. The impact loading from the drill has a peak value of .1 GPa and duration of 2.5 μsec, as shown in Figure 8.

Contour maps of the maximum principal strain were plotted and used as indication of fracture of rocks. It also shows how the elastic waves propagate in the rock. Figures 10 show the contour maps for the cylinder for drilling and coring, respectively. The drill bit is 3 mm in diameter. The corer has an inner diameter of 2 mm and an outer diameter of 3 mm.

The results show qualitative features of the rocks fracture under ultrasonic drilling or coring. From Figure 10 we find that the highest principal strain occurs at the edge of the drill bit. Also, the highest principal strain appears at both the outer and inner edge of the corer. It implies that the fracture is likely going to happen at the edge, which is confirmed by viewing the high speed filming during drilling. By comparing the various strain profiles in Figure 10, we find that the maximum principal strain under coring is higher than that under drilling, and the area of high principal strain under coring is

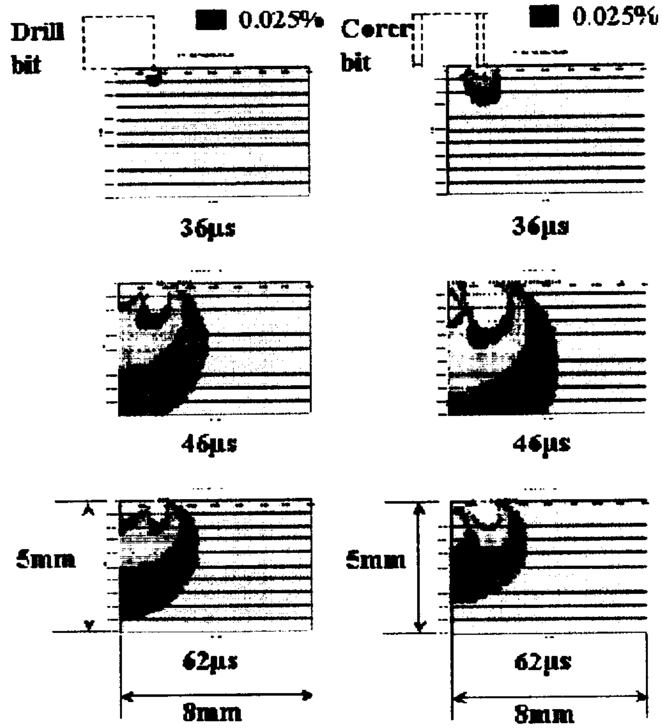


Figure 10 - The principle strain profile at various times after impact of the free mass on the drill stem for a drilling bit and a coring bit.

also larger than that under drilling. It implies that with the same outer diameter and under the same loading, a corer will drill faster than a solid drill of the same diameter. This is confirmed by experiments.

The results have show how drilling and coring can be achieved with little or no preload. The next challenge is to integrate each of the models to determine the limits and optimization of the USDC. A more complete description of the modeling of the horn/free mass/drill interaction can be found in recent publications [i], [ii], [iii]

OBJECTIVE

2. **Breadboard the next level signal generator that employs a microprocessor to use system feedback in optimizing and controlling input power to the piezo electric resonator.**

Work Performed

The next level generator was designed using the H-bridge inverter topology. This Class D amplifier design was chosen primarily for its high efficiency (>90%). The drive signal was generated using a phase-lock loop circuit made up of a microprocessor controlled frequency synthesizer and a VCO. Feedback from the VCO generated the error signal to complete the loop. The gating signal from the VCO was pulse width modulated with a comparator delay circuit and then sent to an H-bridge driver IC. The H-bridge driver IC set-up the necessary isolation for the stages of the H-bridge, with a boost capacitor circuit. A sense resistor was used to determine the tuning of the transducer. The low voltage power supply was set-up using an IC regulator, which was fed from the 12V bulk supply. Software was created to set the frequency, set the pulsing duty cycle, and to process the feedback tuning algorithms. The software cycle included a tuning routine, which swept through a range of frequencies (ie.19 kHz-25kHz) and polled the A/D converter for the voltage level across the sense resistor. To increase the resolution of the sweep and to reduce the time in the sweeping process, the first sweep was set-up to range from 19 kHz to 25 kHz in 100 Hz increments. Then the narrow sweep used the results from the broad sweep to vary +/- 200 Hz of the determined resonate frequency at 10 Hz increments.

During the normal cycle the software polls the A/D converter to make an adjustment based on a change in frequency due to temperature or loading. The software has the ability to adjust the pulsing duty cycle to regulate the power; this was not implemented in these early versions of the generator. Included in the hardware and software functionality were RS-232, EEPROM memory, display port, and several open I/O ports which were being used to support testing and data streams for retention and analysis.

The performance of an ultrasonic system is dependent largely on the ability of the generator to provide a signal where the system will be most efficient as previously determined by the stack finite model. The system is most efficient when the signal provided to the transducer is of the same frequency as the natural resonant frequency of the transducer and the load combined. The resonant frequency of the system varies with the type of load, temperature, etc. therefore, to keep the system running efficiently, it is important to keep a track of this resonant frequency as it varies. This generator system can be made to generate the exact frequency that the system will be resonant at.
The sensors integrated into the transducer for optimizing the performance of the drilling/coring are made of PZT-8 material with ID/OD dimensions the same as the driver

ceramics except much thinner, with thickness of approximately 0.0625 inches. These ceramics are a part of the stack and are sandwiched between the driver ceramics and the back mass. When the transducer is activated with the correct signal from the generator, it vibrates at is fundamental resonant frequency. The displacement at the tip of the transducer is maximum at this frequency. Displacement in the driver ceramics results in displacement of the sensor ceramics, which generates a corresponding voltage, that is proportional to the amount of displacement.

The best way to track the change in the resonant frequency of the system is by activating the transducer with different frequency signals and then registering the voltage produced in the sensor ceramics. The frequency that produces the maximum displacement and voltage is the resonant frequency of the system. Since the frequency normally shifts only around the nominal resonant frequency, sweeping between a small range around the nominal resonant frequency will detect changes.

Tests were conducted to prove this principle on the transducer stack. The test results showed that the maximum tip displacement of the transducer was corresponding to the frequency that produced the most voltage in the sensors. The drilling performance, which is directly proportional to the tip displacement, could therefore, be related to the maximum voltage generated in the sensors. This relationship is depicted in Fig. 11 below.

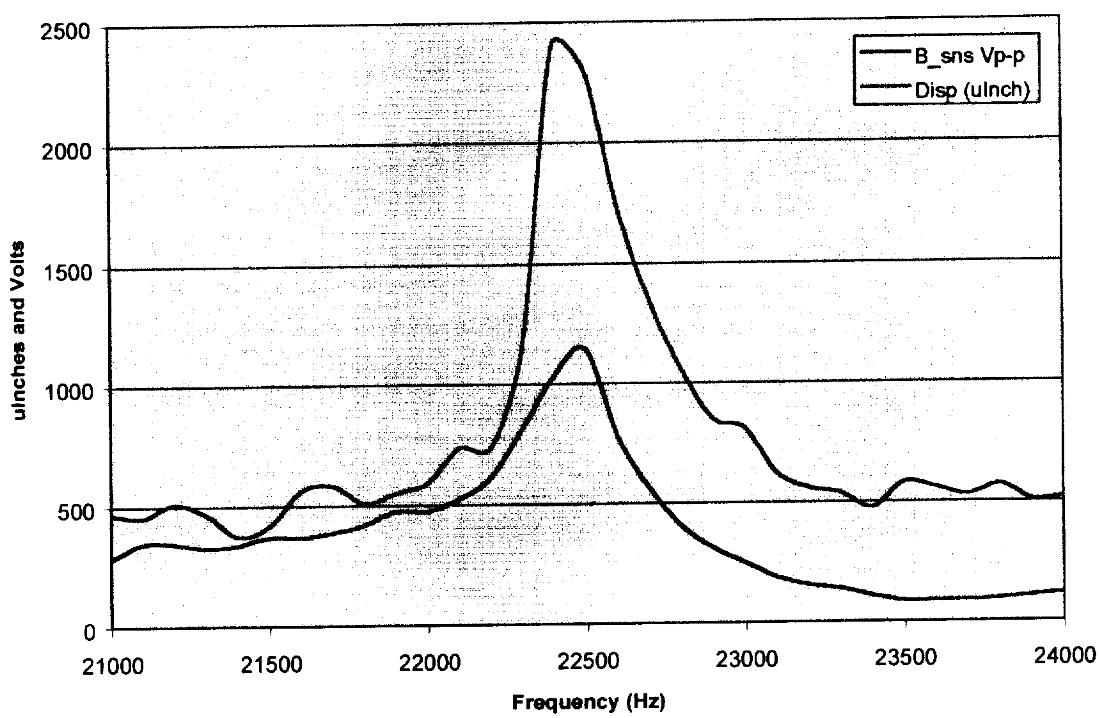


Fig. 11

The signal generator was reduced in size and weight until it was decided that JPL would take this next step to integrate the circuitry on an FGML that would be used to control the robotics and other elements of a rover. The final version is 3x5 inches and weighs fewer 45 grams. Figure 12 demonstrates the size and scale of this generator revision.

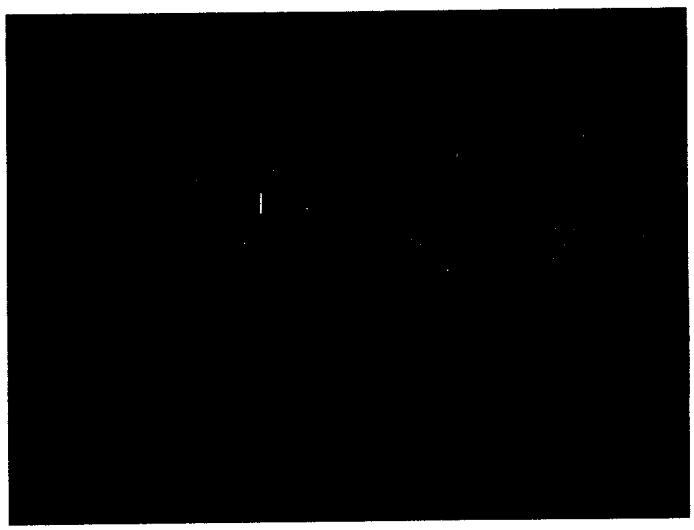


FIG. 12

OBJECTIVE

3. **Develop a power retention system that will accumulate power at 5 watts for appropriate delivery to the generator amplifier.**

Work Performed

The power retention system was simplified to a bank of electrolytic capacitors once the amplifier topology was chosen. Since the H-bridge topology requires a constant DC voltage power supply this approach was sufficient. The power regulation was accomplished by modulating the duty cycle pulse at a percentage of the power of a continuous wave signal. According to the design, the continuous power draw of the load is 50W. Therefore, to drive the load at 5W, a pulsing duty cycle of 10% is necessary. This was experimentally confirmed. A current sense resistor senses current to the load, and voltage divider circuit senses the voltage across the load. These parameters are fed to the microprocessor through an analog-digital converter allowing the software to make adjustments to the duty cycle as necessary to maintain a constant 5W. Tests were conducted with this configuration and the drill rate was found to meet the established criteria.

OBJECTIVE

4. **Evaluate and integrate sensors to expand system capability and contribution.**

Work Performed

The inclusion of ceramic discs as outlined in section 2 was the primary sensor application. During the research to optimize the system by using this sensor and other concepts. It was discovered that the integration of a free mass, or FCC (frequency compensation coupler), dramatically increased the drilling performance by reducing the frequency of the probe or end effector. This free mass is shown as a component in the assembly drawing in Figure 13.

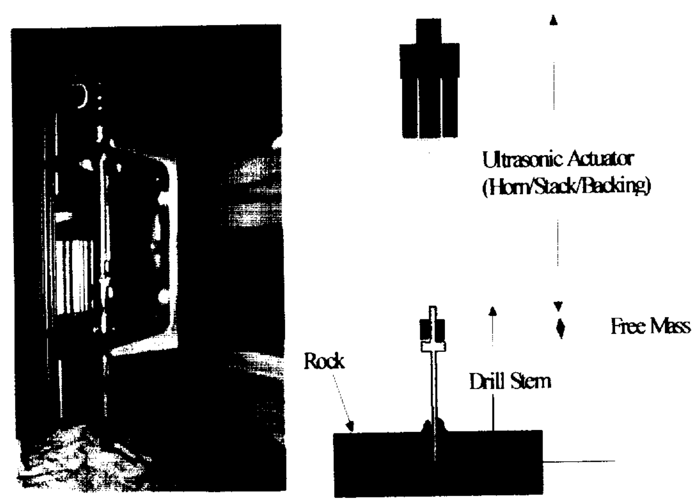


Figure 13 - Photograph and Schematic of the Ultrasonic/Sonic Driller/Corer, which is mounted on a test rig in the photograph.

The baseline horn has its fundamental resonance at 21.5 kHz and the free tip velocity at resonance was determined to be linear with respect to the applied voltage. It ranged from 1 to 10 m/s depending on the acoustic load as is shown in Figure 13. A number of free mass materials and configurations were run with the baseline horn to confirm the relationships of each component to the assembly.

The vibrations of the horn tip excite the free mass, which resonates between the horn tip and the top of the drill stem at frequency of the order of 1000 Hz. Acoustic energy in the free mass resonator is transferred to the top of the drill stem and propagates to the bit/rock interface where the rock is excited past its ultimate strain and fractures. In order to determine the critical issues related to the control and optimization of the drill initial modeling of the acoustic interaction at the various interfaces of the drill was investigated. The three interfaces that were studied are: 1) the interaction of the horn tip with the free mass, 2) the interaction of the free mass with the drill stem and 3) the interaction of the base of the drill stem (bit) with the rock.

Horn Tip – Free Mass Interaction

. The free mass is driven by the horn tip, which vibrates at resonance frequency. A schematic of the model is shown in Figure 14. The tip displacement is harmonic and is described by

$$u = u_0\cos(\omega t + \theta). \qquad (1)$$

The velocity of the horn tip is found by taking the time derivative of the displacement and is

$$v = -\ \omega u_0 \sin(\omega t + \theta). \qquad (2)$$

Assuming the energy loss and time duration of the impact is negligible and the mass of the horn is much larger than

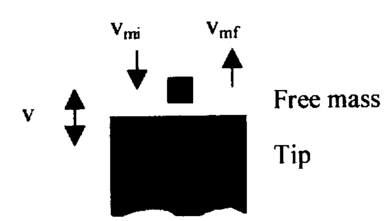


Figure 14 - A schematic of the free mass horn tip interaction model.

the free mass, we find using conservation of momentum and energy that

$$v_{mf} = v_{mi} + 2v$$

where, v_{mi} is the free-mass velocity prior to interaction with horn and v_{mf} is the free mass velocity after interaction with the horn. A computer simulation model that traces the positions of the free mass until it leaves the tip vibration range ($2u_0$) was written. The routine calculates the free mass speed after interaction with the horn. By keeping track of the free mass velocity the routine allowed us to explore this driving mechanism as a function of the horn position as the free mass crosses the plane of full extension (phase). The speed of the free mass as it leaves the interaction region versus position of the horn (position of tip represented as a phase angle t =0 at max displacement) was calculated for various ratios of v_{mi}/v.

For all cases there is a net increase in the free mass velocity after interaction with the horn when averaged over phase. The computer model traces the movements of the free mass and the horn. The movement of the horn is due to the reaction force on the horn tip and the force of gravity. In the calculation the free mass is set to 1 gram, the tip velocity amplitude is set to 1.26 m/s corresponding to displacement amplitude of 10 μm. The horn mass was 800 g (including mass of test-rig). The energy loss of the free mass in each round trip is set as 75%. The ratio of the free mass velocity to the maximum horn tip velocity as a function of time was simulated and the results were used to calculate the motion of the horn. The results show the random characteristics of the movement of the body of the horn. Figure 15 shows the calculated horn tip position as a function of time. The motion is due to the impact interaction with the free mass.

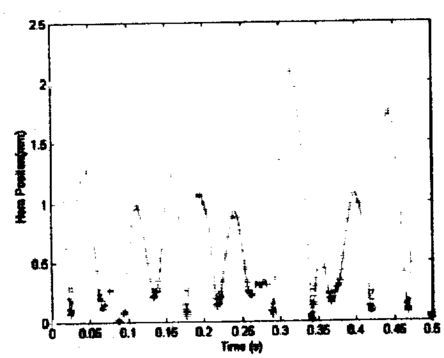


Figure 15 - The horn position calculated as a function of time determined from model.

OBJECTIVE

5. Provide prototype hardware to JPL for design input on modifications required for adaptation to the rover.

Work Performed

Some of the prototype hardware that has been supplied to JPL for feedback and design input has been modified for adaptation to the Sojourner class platform. The free floating drilling/coring probe is held inside the housing in a spring loaded assembly which makes sure that no reactive forces are generated. The rover does not experience any axial or rotary forces when the drill is activated.

The current design housing is a round aluminum body of max 1.5" outer diameter and 1" outer diameter at the cutting tip. The transducer housing design is such that it can be attached to the rover arm easily without any modifications.
Since the drill works on a principle that does not generate any rotary forces so the drill/corer bits do not have to be round in cross section. They can be any shape like square, round, hexagon, star, etc.

The entire drill weighs only around 400 grams. This would help on mounting it on the smallest of rovers with a big arm reach without any chances of tipping over.
Several versions of the generator were supplied to JPL. The first version was designed using two 5x5 circuit boards mounted atop of each other. This satisfied the 5x5x3 requirement but came slightly short of the 300 g weight limit. The next prototype was a surface mount board, which measured 5x3x1 and weighed about 70g. A generator supplied by 120Vac was designed for demonstrations. Two generators were designed that used available I/O to allow the user to vary the duty cycle, therefore allowing the user to adjust the power level and drilling rate manually. The introduction of the microprocessor to the generator design gives Cybersonics the ability to easily adjust parameters and functionality for JPL's current and future work

Although the majority of tests discussed above have been performed on the test-rigs the USDC has been operated successfully from a Sojourner class rover scaled down to be the same weight on Earth as it would be on Mars Figure 16. Drilling and coring were performed from the rover without any mechanical interaction with the body of the rover even when axial loads applied from the rover were large enough to clamp the sonic component of the drill.

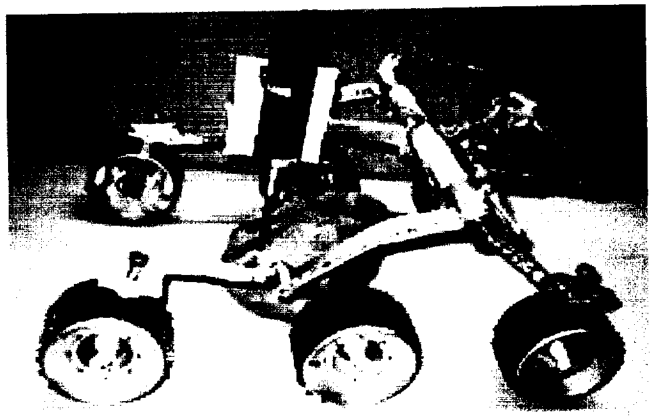


Figure 16. Coring from a Sojourner class rover.

Drilling was also demonstrated from the arm of the Field Integration Design and Operations rover (FIDO) shown in Figure 17. During the tests the USDC drilled into a limestone rock. The drill was removed from the drill-hole and the hole was re-acquired using the FIDO robotic arm.

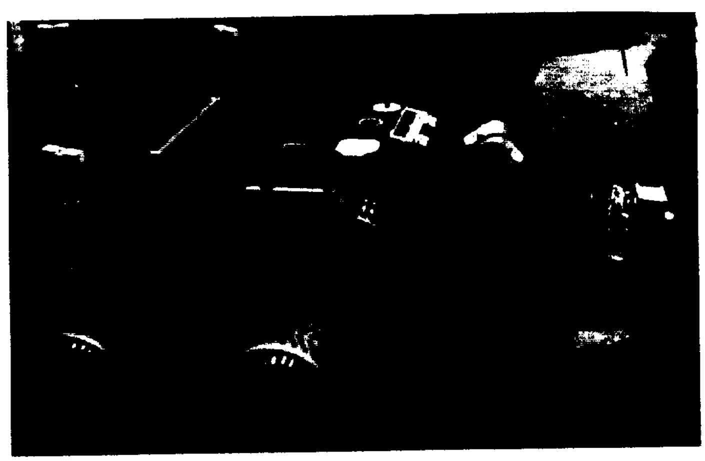


Figure 17. Drilling from the arm of the FIDO rover. The hole was reacquired after the drill and arm were stowed.

Smart USDC

Further iterations of the USDC are leading to a "smart" driller/corer where any number of sensors and feedback systems can be used to configure the system for a given mission or specific task.

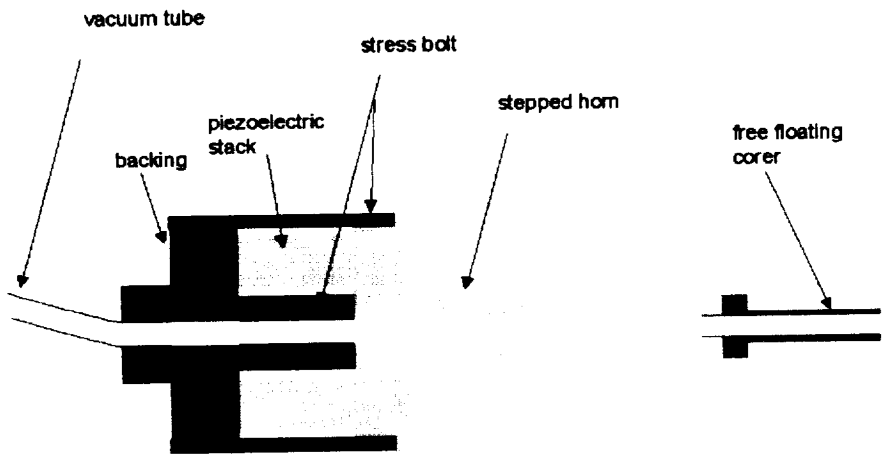


Figure 12. A prototype USDC with the capability for sample extraction through the actuator.

One aspect of the smart USDC relies on the inherent acoustic properties of the device. The sonic component of the USDC can be used a source for sonar to investigate the presence of layers. These layers cause dispersive wave characteristics, small discontinuities cause scattering and attenuation, and large discontinuities (rocks, cavities, etc.) produce reflections. Methods are available to extract geophysical information from the imparted waves, offering effective probing, imaging and providing valuable information about the stiffness constants and other mechanical properties of soil and rocks. In addition the ultrasonic component generated at the horn tip may be used to investigate the acoustic impedance of contacting samples. The horn/actuator is a high Q resonator and when the horn comes in contact with a structure it radiates ultrasonic energy into the structure, which can among other things reduce the resonance frequency and lower the quality Q of the resonance. The degree to which this occurs is a function of the acoustic impedance (product of the density and velocity of sound) in the contacting material.

Assessment of Technical Feasibility

It is apparent that the USDC will have future application for planetary exploration and also provides the "engine" for a variety of tools and medical instruments. How far the base design can be scaled has not yet been determined, but work is ongoing to develop a 3cm diameter driller for deep geological explorations on Mars.

Additionally, baseline units were configured with PZ-46 crystals to determine if the USDC could perform in temperatures ranging to 500C to simulate conditions on Venus. Performance in extreme temperatures could solve a number of problems since conventional drilling equipment cannot operate at extreme temperatures.

Cybersonics has continued to work on refinements of the signal generator, which can now be miniaturized for handheld devices and be powered by standard 120V household current. In addition, there are hand tool concepts in development that can use battery packs now common in drills and sanders.

Other variations of medical grade transducers are being powered by re-charagble batteries and are in use as clinical test instruments on both animals and humans.
In test instrument applications, the de-carbonating of soft drinks can be performed with a Cybersonics instrument that employs an annular probe with an air dispersing end effector that essentially forces the carbon dioxide from soda test samples. The lab technicians are than able to run different tests to confirm the concentration and mix of the various elements in their product. These samples are taken through out the bottling process to assure consistency of the brand regardless of bottling location.

By using the FCC or free mass configuration probe it was confirmed that a polymer based material could be used in place of the traditional stainless steel probe in a medical instrument application. The lead extraction instrument can cut through calcified tissue to free leads trapped in the human vein wall. This procedure has been performed on animals and trials will be conducted on humans this year.

Cybersonics has received a number of inquiries for applications of this technology, and received recognition as one of the Top 100 new designs from R&D Magazine. It is becoming apparent that we aren't the only ones who can see the potential for future applications.

[i] S. Sherrit, X. Bao, Z. Chang, B.P. Dolgin, Y. Bar-Cohen, D. Pal, J. Kroh, T. Peterson, "Modeling of the Ultrasonic/Sonic Driller/Corer: USDC," Proceedings of the IEEE Ultrasonics Symposium in San Juan, Puerto Rico, pp. 691-694, Oct 22-25, 2000

[ii]Y. Bar-Cohen, S. Sherrit, B.P. Dolgin, X. Bao, Z. Chang, D. Pal, R. Krahe, J. Kroh, S. Du, T. Peterson "Ultrasonic/sonic drilling/coring (USDC) for planetary applications," SPIE Smart Structures 2001, March 2001, Newport Beach, CA, paper 4327-55

[iii]Xiaqi Bao, Zensheu Chang, Stewart Sherrit, Benjamin P. Dolgin, Yoseph Bar-Cohen, Dharmendra S. Pal, Shu Du, Thomas Peterson," Modeling and Computer Simulation of Ultrasonic/Sonic Driller/Corer (USDC)" To be published - In preparation

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13. ABSTRACT *(Maximum 200 words)*

The next series of planetary exploration missions require a method of extracting rock & soil core sample. Therefore, a prototype ultrasonic core driller (UTCD) was developed to meet the constraints of Small Bodies Exploration and Mars Sample return Missions. The constraints in the design are size, weight, power, and axial loading. The ultrasonic transducer requires a relatively low axial load, which is one of the reasons this technology was chosen. The ultrasonic generator breadboard section can be contained within the 5x5x3 limits and weighs less than 2 lbs.
Based on results attained the objectives for the phase I were achieved. A number of transducer probes were made and tested. One version only drills, and the other will actually provide a small core from a rock. Because of a more efficient transducer/probe it will run at very low power < 5 Watts and still drill/core. The prototype generator was built it allows variation of all the performance-affecting elements of the transducer/probe/end effector i.e.: pulse, duty cycle, frequency, etc. The heart of the circuitry is what will be converted to a surface mounted board for the next phase, after all the parameters have been optimized and the microprocessor feedback can be installed

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