A Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill includes a horn actuator having high power piezoelectric materials and a flexure pre-stress to increase the actuator's effectiveness. The drill is a low mass, low power, compact coring drill measuring 20-cm high by 7-cm diameter and having a total weight of 2 kg including drive electronics. Using an average power of 50-Watts, the drill basalt is expected to cut basalt at a rate of 0.2 cm/min down to depth of 10-cm and create cuttings and an intact core. The drill is expected to operate under different environments including Martian ambient (6 Torr and down to –50° C.), and liquid nitrogen temperatures (77 K) and low pressure (<1 Torr) to simulate lunar polar and Europa conditions. Materials expected to be sampled include Kaolinite, Saddleback Basalt, Limestone, Volcanic Breccia, Siltstone, ice, permafrost and layered rocks with different hardness.

12 Claims, 7 Drawing Sheets
Helical slotted horn

Direction of motion (extension)
FIGURE 3

FIGURE 4

Bit assembly
Cutter
Actuator

Bit mounting
Bit preload bolt
Bit rotating base
Hammering-Twisting horn
Electrodes
Stress bolt
Back ing PZT Stack
Bearing
Bit preload spring
Screws
FIG. 5

Rotary Hammer Actuator

Keyed Free mass

Powdering Bit
FIG. 13

10-cm Basalt core

FIG. 14

10.8-mm diameter by 105-mm long limestone core

FIG. 15
SINGLE PIEZO-ACTUATOR ROTARY-HAMMERING (SPaRH) DRILL

BACKGROUND OF THE INVENTION

Motors that provide rotational drilling motion include conventional drills and the Kumada piezo-motor, described in Sashida T., and T. Kenjo, An introduction to Ultrasonic Motors, Clarendon Press, Oxford (1993) pp. 13-16. This piezo-motor has been documented to have high efficiency of 80%, relatively high torque density of 8.8 Nm/Kg, as described by Kumada A., "A piezoelectric motor," Japanese J. of Applied Physics, Vol. 24, Supplement 24-2 (1985) pp. 739-741. In comparison, Maxon DC Brushless motors have an average efficiency of about 69% and torque density of about 0.2 Nm/Kg, as described in the May 2008 Maxon catalog at page 176.

One application of drills based on rotary motors is in extra-terrestrial drilling such as that performed during U.S. and Soviet lunar drilling missions that took place in the early 1970s. In particular, astronauts who flew the Apollo 15, 16 and 17 missions successfully utilized a rotary percussive core drill, the so called Apollo Lunar Surface Drill or ALSD, designed and built by Martin Marietta, to penetrate up to 3.5 m below the surface. There are, however, a number of differences between the Apollo type drilling missions and future planetary missions including the presence of human operators during the Apollo missions and the available preload in the Soviet lunar drilling platforms.

There is a need for a drilling mechanism that can operate efficiently and reliably in the absence of human operators.

SUMMARY OF THE INVENTION

According to one aspect, the invention features a Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill. The SPaRH comprises a single piezoelectric stack actuator having an electrical signal input port and a mechanical signal output port; a horn transducer structure comprising a plurality of slotted helical members, the horn transducer mechanically coupled to the single piezoelectric stack actuator mechanical signal output port to receive a linear mechanical signal from the single piezoelectric stack actuator and configured to provide an output mechanical signal simultaneously having both a longitudinal mode and a twisting mode; and a rotor/stator interface mechanically coupled to the slotted helical members of the horn transducer, the rotor/stator interface configured to receive from the horn transducer the mechanical signal simultaneously having both a longitudinal mode and a twisting mode, and configured to impart a longitudinal motion and a rotational motion simultaneously to a tool.

In one embodiment, the single piezoelectric stack actuator comprises a flexure horn.

In another embodiment, the single piezoelectric stack actuator comprises a pre-stress bolt.

In yet another embodiment, the single piezoelectric stack actuator comprises a piezoelectric single crystal.

In yet a further embodiment, the rotor/stator interface is configured to hold a removable tool by way of a ball detent holding mechanism.

In an additional embodiment, the rotor/stator interface is configured to hold a removable tool by way of a flexure detent holding mechanism.

In one more embodiment, the rotor/stator interface comprises a keyed free mass.

In still a further embodiment, the SPaRH further comprises an electronic driving circuit configured to supply an electrical signal to the electrical signal input port of the single piezoelectric stack actuator.

In one embodiment, the SPaRH further comprises a removable tool.

In another embodiment, the removable tool is selected from the group consisting of a powder bit, a coring bit and a rock abrasion bit.

In yet another embodiment, the removable tool comprises an auger.

In still another embodiment, the removable tool comprises a cuttings collection slot.

In a further embodiment, the single piezoelectric stack actuator is configured to be excited in the range of 3 KHz to 100 KHz.

The foregoing and other objects, aspects, features, and advantages of the invention will become more apparent from the following description and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The objects and features of the invention can be better understood with reference to the drawings described below, and the claims. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the drawings, like numerals are used to indicate like parts throughout the various views.

FIG. 1 shows a solid model view of a piezoelectric actuator that simultaneously generates longitudinal-twisting modes to hammer and rotate the bit.

FIG. 2 is a cross-section view of the piezoelectric actuator of FIG. 1.

FIG. 3 is a cross section view of the Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill, according to principles of the invention.

FIG. 4 is a solid isometric view of the Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill.

FIG. 5 is a perspective cutaway view of a rotary hammering sample acquisition system showing the ultrasonic horn, free mass and a powdering bit, and indicating the rotary and hammering motions.

FIG. 6 is an exploded cutaway view that illustrates an embodiment of the sample acquisition system having a pre-stress flexure and keyed free mass with an exchangeable bit.
Getting under the weathering layer of a planet or moon is vital to understanding the origins and history of surface materials. If an intact core can be acquired and analyzed, a better understanding of the physical and mechanical processes that lead to the breakdown of surface material can be achieved. A principal goal of in-situ extra-terrestrial investigations will be to acquire an un-weathered material to elucidate concepts of planetary formation and geological processes. The exact nature of the weathering layer on different bodies in the solar system depends on several factors including the length of time the rock has been on the surface, and the nature of the weathering (solar wind on the moon, galactic cosmic rays on comets, and atmospheric-rock interactions on Mars). It is expected that the maximum depth of the weathering layer on Mars would be on the order of 2-5 cm. Therefore, it is expected that sample acquisition hardware should be able to achieve at least these depths to acquire un-weathered samples. In the lunar polar region, a desiccated outer 1-5 cm could exist over the volatile-rich material. This material would not be loosely consolidated but have a non-negligible compressive strength. Any mission sent to explore these locations would likely have to achieve depths greater than 5 cm to increase probability of identifying volatile material.

The Technical Problem

The search for present or past life in the universe is one of the most important objectives of NASA’s exploration missions. Drills used as subsurface samplers of rocks, ice and permafrost are essential tools for astrobiology studies on other planets and moons. Increasingly, it is recognized that drilling via a combination of rotation and hammering offers an efficient and effective rapid penetration mechanism with the capability to use the rotation as an intrinsic method for removal of cuttings from the borehole while benefiting from the impact and shear forces for fracturing the penetrated medium. The conventional drills that use a single actuator are based on a complex mechanism with many parts and their use in future missions involves a serious risk of failure. Conventional drills may require lubrication that can introduce contamination into the samples that are recovered, which has the potential to cause erroneous analytical results on those samples.

A Solution

A compact drill is disclosed that uses low axial pre-load via vibrations that fractures the rock under the bit kerf and rotates the bit to remove the powdered cuttings while augmenting the rock fracture via shear forces. The vibrations fluidize the powdered cuttings inside the flutes around the bit, which reduces the friction with the auger surface. This mechanical action reduces the consumed power and the heating of the drilled medium, which helps to preserve the produced samples in a pristine condition.

The disclosed drill comprises an actuator that simultaneously impacts and rotates the bit by applying force and torque via a single piezoelectric stack actuator without the need for a gearbox or lever mechanism. This reduces the fabrication cost and complexity of the drill.

The piezoelectric actuator generates impacts and shear forces to fragment the drilled medium directly under the bit kerf by exceeding the tensile and/or shear strength. The percussive impact action of the actuator leads to penetration of the medium by producing a zone of finely crushed rock directly underneath the impacted location. This fracturing process is enhanced by the shear forces from the rotation and
An advantage of the described mechanism is the ability to produce cores that have high likelihood of sustaining mechanical stability. Furthermore, the powdered cuttings produced are very fine powder that is not expected to sustain crystallographic structure modification.

The actuator that is shown in FIG. 1 represents a combination of a horn for power ultrasonics using vibratory motion as in our Ultrasonic/Sonic Driller/Corer (USDC) design and a novel ultrasonic motor configuration. The horn has a helical slot configuration (shown in FIG. 1 and FIG. 2) in order to cause rotation. Upon impacting the bit, the horn introduces longitudinal forces along the axis of the actuator and tangential force causing twisting action that rotates the bit. In addition, bending moments at the horn tip at other frequencies can potentially be used to produce only rotation and little hammering. The longitudinal component of the vibrations of the stack introduce percussion impulses between the bit and the rock (or workpiece), which fracture the rock when the ultimate strain is exceeded under the bit.

The actuator of the drill comprises a piezoelectric stack that vibrates a horn. The stack preferably is configured by a flexure (or in some embodiments, by a pre-stress bolt) between the backing and the horn in order to prevent it from being subjected to tensile stress that will cause it to fail. The backing is designed to transfer the generated mechanical vibrations in the stack towards the horn direction. The horn is configured asymmetrically with helical segments (see FIG. 1 and FIG. 2) in order to cause rotation. Upon impacting the bit, the horn introduces longitudinal forces along the axis of the actuator and tangential force causing twisting action that rotates the bit. In addition, bending moments at the horn tip at other frequencies can potentially be used to produce only rotation and little hammering. The longitudinal component of the vibrations of the stack introduce percussion impulses between the bit and the rock (or workpiece), which fracture the rock when the ultimate strain is exceeded under the bit.
Drill is expected to be mounted on an arm or body mounted on a 100 kg class rover because it is compact and lightweight and generates low reaction forces.

Parameters of interest in developing a drill include drilling efficiency, drilling power, drilling energy, mechanism lifetime capabilities, core/sample quality, and range of operating environments.

In a preferred embodiment, the Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill which combines rotary and hammering forces as an effective drilling mechanism utilizes three recent advances, including a flexure horn design described in U.S. Provisional Patent Application Ser. No. 61/362,164, and in S. Sherrit, X. Bao, M. Badescu, Y. Bar-Cohen, P. Allen, "Monolithic Flexure Pre-stressed Ultrasonic Horns," (U.S. Provisional Patent Application Ser. No. 61/362, 164, filed on Jul. 7, 2010), that eliminates the need for a stress bolt in the horn and allows for a 50% increase in the energy density; a helical slotted horn that produces impacts and torque on a keyed free-mass; and high power piezoelectric single crystal materials with high coupling factor (k_{33} = 0.9) and mechanical Q (>400) and actuator figures of merit that are 5 times those of standard PZT. In one embodiment the helical slotted horn has slots oriented at a 45 degree angle to the central axis of the horn, so that the hammering force and the rotational force are approximately of the same magnitude. By changing the angle of the slots in the slotted horn, one can partition the applied force or power to the hammering force and the rotational force in a desired proportion.

The Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill simultaneously impacts and rotates the bit. The required forces to produce these two motions are produced by a high power single crystal piezoelectric stack actuator that does not require a gearbox. This design is expected to achieve a reduction in cost, mass and complexity. The applied forces and torque can be optimized to produce a highly effective rotary-hammer drilling/sampling mechanism by modeling design features using finite element method (FEM), for example using ANSYS Multiphysics (available from ANSYS, Inc., 275 Technology Drive, Canonsburg, Pa. 15317).

The generated stresses are expected to include impact stress and shear stress and are expected to exceed the tensile and/or shear strength of the drilled medium directly under the kerf (or cutting surface of the bit). The rotation can be augmented by an ultrasonic twisting action that is expected to cause a chiseling effect at the rock/bit interface resulting from twisting shear forces. The percussive impact action is expected to lead to penetration of the medium by producing a zone of finely crushed rock directly underneath the impacted locations. The fracturing process is expected to be enhanced by the shear forces from the rotation and twisting action. To remove the formed cuttings, an auger is provided on the bit whose effect is supplemented by vibration. In some embodiments, the powdered cuttings are expected to travel up the flutes to a cuttings collection slot where they are dropped into the tube for collection.

FIG. 10 is a diagram that illustrates how the net force produces a prolonged rotation of the bit as well as an impact. In FIG. 10, the helical extension horn motion can develop an impact and torque at a point (shown as a black dot) on the free mass. FIG. 11 is a diagram that illustrates how the bending horn motion, illustrated by the bending ellipse (helical extension or bending) can develop an impact and torque at a point (black dot) on the free mass. In FIG. 10 and in FIG. 11, the arrow and the ellipse show contact that pushes the free mass up and drags it to right. The normal force is much lower on retraction or on the bottom portion of the ellipse.

Depending on the structure and drive frequency an angled extension or a bending can occur at the horn free mass interface. Because the horn is in contact only when it is in extension the torque is applied only in one direction. The groove horn converts some of the axial vibrations from the piezoelectric stack into twisting motion on the horn surface.

The tangential force produced on the horn surface turns the keyed free mass and bit that is pressed against it via a compressive force of a spring that is fixed to the housing. The bit is interfaced with the horn via the keyed free mass. In addition it is believed that one can optimize the actuation by removing the pre-stress bolt and by using new high power single crystal piezoelectric materials that have been developed for sonor and medical imaging transducers.

To aid the drilling, a crown-shaped cutter on the tip of the bit (that is, a bit comprising a cutter with teeth on its distal end) is expected to be made with specifically designed teeth using an analytical model. Three interchangeable bit types are shown in FIG. 7, FIG. 8 and FIG. 9. For use in unmanned applications such as space exploration, the separation force will be designed to be less than the available arm extension force, so that a robotic device does not become trapped if a bit becomes lodged in a workpiece. We expect to investigate designs of passive and powered core break off and retention mechanisms to break and retain the core in the bit.

High Power Single Crystal Piezoelectric Discs

In some embodiments, the piezoelectric rotary hammer actuator is expected to use high performance piezoelectric materials. Single crystal piezoelectric materials and their methods of fabrication are described at least in U.S. Pat. Nos. 6,491,889, 6,899,761, and 6,942,730 and in U.S. Patent Application No. 2002/0179000, 2003/0164137, 2008/0290315, 2009/0211515, 2009/0212667 and 2009/021829. There are also commercial vendors of single crystal piezoelectric materials. For example, TRS Technologies, Inc., 2820 East College Avenue, State College Pa. 16801 sells PMN-28% PT, PMN-30% PT, and PMN-32% PT single crystals. Piezoelectric single crystals (PMN-PT and PMN-PZT) are available from Ceracomp Co., Ltd., 3F-3309, Post Plant 1, Chungnum Techno Park, Jiksan-eup, Cheonan-si, Chungcheongnam-do, South Korea 330-816. These improved ferroelectric single crystals materials make possible significant changes in the design and ultimate performance of many electromechanical devices. Many ultrasound imaging applications offer greater resolution via the increased bandwidth offered by the high k_{33} exhibited by this material. In some embodiments, single crystal piezoelectric material is expected to be used in high power ultrasonic horn actuators.

Conventional high power ultrasonic transducers use acceptor modified "hard" PZT ceramics, which have piezoelectric d_{33} coefficients of 200-300 pC/N. In general, these components operate around their resonance frequency. Near resonance, the output is proportional to the product d_{33} Q_m. The mechanical quality factor Q_m is an important material parameter when designing high power devices. The relatively low Q of some single crystals (Q_m=100, compared to Q_m=1000 for hard PZTs) has limited their implementation in high power applications. Recently, advances in single crystal ferroelectrics have demonstrated increased Q utilizing two approaches: 1) crystallographic engineering, and 2) acceptor modifications, analogous to hard PZTs.

An equivalent circuit is expected to provide a critical capability in the modeling and simulation of the performance of the piezoelectric actuator. Since the Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill is a dual mode actuator, the analytical model will examine two motional branches to
determine the longitudinal and torsional tip displacement of
the asymmetric horn. The interaction of the bit with the rock
will be modeled using rock fracture theory and a finite ele-
ment approach. The models are expected to be integrated into
an analytical model so that the drill performance can be predicted
by simulation of the drill operation.

In a preferred embodiment the Single Piezo-Actuator
Rotary-Hammering (SPaRH) Drill is expected to be excited
in the range of 3 to 100 KHz frequency range. The actuation
mechanism that amplifies the amplitude of the vibration will
be directly coupled to the drill bit. The analytical model is
expected to take into account the electric, electromechanical,
thermal and mechanical effects and responses. The model
will include the piezoelectric stack, slotted helical horn trans-
ducer structure, rotor/stator interface and drill bit, as well as
the interfaces to the electronic driving circuit and the rock
fracture model. The full analytical model is expected to pre-
dict the drill performance for various design configurations
and types of rocks. Some of the operating parameters that will
be included in the model are the use of different piezoelectric
stack materials and sizes, height to length ratio of the trans-
ducer, and bit parameters such as length and radius. One can
determine the temperature distribution in the drill and most
importantly the temperature rise at the bit/rock interface by
modeling or mathematical analysis. A parametric matrix
study is expected to be performed to optimize the designs,
which then can be implemented using a breadboard.

Experimental Corroboration of the Analytical Model

The analytical model can be corroborated experimentally
to assure its applicability and determine its accuracy as a
performance predictor for the drill system. The JPL drill
testbeds shown in FIG. 12 and FIG. 13 can be modified to test
and demonstrate the Single Piezo-Actuator Rotary-Hammering
(SPaRH) Drill actuation mechanism. The testbeds can include
a mounting fixture with position and preload control to allow testing the effect of various design variables and control parameters. In addition we can use a pulley mecha-
nism and counter mass to off load mass of the drill. The position and axial load on the actuator can be controlled by a
voice coil-spring mechanism. A data acquisition system can
record the piezoelectric actuator drive signal frequency and
power, the piezoelectric actuator temperature, and the voice coil actuator displacement and preload force. The actuator
performance can be examined under various operating con-
ditions. The experimental data will provide values for drilling
rate, lift and vibration and other parameters. The parameters
observed will be analyzed and compared to the predictions of
the analytical model.

Since the piezoelectric stack actuator is the driver of the
Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill, it
should be characterized carefully. Generally, most multi-
layer PZT stacks are designed for precision positioning or low
frequency actuation. The coefficients describing the actuation
generated by the stack in the spectral range of 20 KHz to 40
kHz or the spectral range of 3 KHz to 100 KHz generally are
not available from the vendors and these coefficients prefer-
ablely should be determined. Experimental characterization of
available PZT stacks can be conducted to provide comparison
and to generate accurate input data to our analytical model.
Small signal measurements of the electric impedance spec-
trum can be conducted using an impedance analyzer. A Lab-
VIEW-based computer program can be used to extract the
basic piezoelectric material properties from the measured
data for the single crystal stacks including for example the
electromechanical coupling factor, piezoelectric charge con-
tant, dielectric constant, and mechanical modulus. The char-
acteristic operation under a drive from high power signal
(high electric field and large deformation) will be modeled.
LabVIEW is available from National Instruments Corpora-
tion, 11500 N Mopac Expwy, Austin, Tex. 78759-3504.

The performance of the one or more implementations in
broadboard can be tested before conducting rock drilling tests
under various operating conditions. To test the performance
of a drill, a testbed setup is equipped with a signal generator
and power amplifier to drive the drill as well as sensors to
monitor the voltage, current, vibration amplitude, dynamic
stress, and temperature.

The testbed is designed to include a support frame, a slider
to hold the drill, a constant force thrust mechanism to provide
preload, and a position sensor to monitor the drilling depth.
An electronic driver with resonance frequency tracking capa-
bility will be provided and the electric input power can be
measured. The drilling rate under different input power and
preloads can be recorded for analysis. A demonstration using
the arm of the Pluto 100 kg class rover or the DEXTER arm
testbed will be performed in Earth ambient (e.g., under ter-
restrial conditions) to investigate and characterize reaction
forces.

Examples of ~10-cm long basalt and limestone cores that
were produced by the longitudinal vibration of the USDC are
shown in FIG. 14 and FIG. 15. These two cores were main-
tained relatively intact with 2 and 3 segments, respectively.
Further, the USDC was demonstrated to sample powdered
cuttings that are very fine with minimal crystallographic
structure distortions.

The beneficial qualities of the USDC will be maintained in
the Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill
since the impact forces will be designed to be the same or
similar.

Theoretical Discussion

Although the theoretical description given herein is
thought to be correct, the operation of the devices described
and claimed herein does not depend upon the accuracy or
validity of the theoretical description. That is, later theoretical
developments that may explain the observed results on a basis
different from the theory presented herein will not detract
from the inventions described herein.

Any patent, patent application, or publication identified in
the specification is hereby incorporated by reference herein in
every line. Any material, or portion thereof, that is said to be
incorporated by reference herein, but which conflicts with
existing definitions, statements, or other disclosure material
explicitly set forth herein is only incorporated to the extent
that no conflict arises between that incorporated material and
the present disclosure material. In the event of a conflict, the
material from the inventions described herein.

What is claimed is:

1. A Single Piezo-Actuator Rotary-Hammering (SPaRH)
Drill, comprising:
a single piezoelectric stack actuator having an electrical
signal input port and a mechanical signal output port;
a horn transducer structure comprising a plurality of slotted
helical members, said horn transducer mechanism coupled
to said single piezoelectric stack actuator
mechanical Signal output port to receive a linear
mechanical signal from said single piezoelectric stack
actuator and configured to provide an output mechanical signal simultaneously having both a longitudinal mode and a twisting mode; and
a rotor/stator interface mechanically coupled to said slotted helical members of said horn transducer, said rotor/stator interface configured to receive from said horn transducer said mechanical signal simultaneously having both a longitudinal mode and a twisting mode, and configured to impart a longitudinal motion and a rotational motion simultaneously to a tool.

2. The Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill of claim 1, wherein said single piezoelectric stack actuator comprises a flexure horn.

3. The Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill of claim 1, wherein said single piezoelectric stack actuator comprises a pre-stress bolt.

4. The Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill of claim 1, wherein said single piezoelectric stack actuator comprises a piezoelectric single crystal.

5. The Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill of claim 1, wherein said rotor/stator interface is configured to hold a removable tool by way of a ball detent holding mechanism.

6. The Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill of claim 1, wherein said rotor/stator interface comprises a keyed free mass.

7. The Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill of claim 1, further comprising an electronic driving circuit configured to supply an electrical signal to said electrical signal input port of said single piezoelectric stack actuator.

8. The Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill of claim 1, further comprising a removable tool.

9. The Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill of claim 8, wherein said removable tool is selected from the group consisting of a powder bit, a coring bit and a rock abrasion bit.

10. The Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill of claim 8, wherein said removable tool comprises an auger.

11. The Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill of claim 8, wherein said removable tool comprises a cuttings collection slot.

12. The Single Piezo-Actuator Rotary-Hammering (SPaRH) Drill of claim 1, wherein said single piezoelectric stack actuator is configured to be excited in the range of 3 KHz to 100 KHz.

* * * * *