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A brief overview of space applications for ultrasonics

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ABSTRACT

Sonics and space are two topics which are not commonly considered together. However, sonic and ultrasonic models, devices and systems have space applications in both science and engineering, as well as showing promise in fields such as cleaning, healthcare and construction. This short paper describes some of these activities and appears as results start to come in from the Curiosity rover, which landed on Mars on the 6th of August, 2012, with over 20 piezoelectric and mechanically-resonant components on board.

Contents

1. Introduction

The exploration of space calls for carrier rockets, often powered by a combination of solid and liquid propellants, to carry payloads into low Earth orbit and beyond. Once in space, scientific payloads must orientate themselves and travel to locations such as the moon, the asteroids, and Mars. Robotic exploration of the subsurface, surface and, where present, the atmospheres of these new worlds are the main activities of today's spacecraft, but in the future people can be expected to follow. These astronauts will need tools, health care and, perhaps, devices to help them hear on the surface of Mars. Sonic, ultrasonic, and piezoelectric devices can be shown to have the potential to assist at every stage of this process.

Secondly, the science of ultrasonics has some commonality with disparate aspects of planetary science. Helioseismology, for example, is the study of oscillations in the sun in the milli-Hertz range, but key concepts, such as the eigenmodes of the behaviour, will be intuitively accessible to students of acoustics. There are very real opportunities for surprising interdisciplinary work and this paper seeks to illustrate just some areas in which the science of vibration, and in particular ultrasonics, can make a valid contribution to the understanding of space.

2. Launching into orbit

Thus far all space missions have begun with the launch of a rocket, and the practicalities of operating a rocket appear to be a reasonable place to begin a discussion of ultrasonics' contribution to space exploration.

Solid rocket propellant often contains both fuel and oxidiser particles in a polymeric binder. The propellant may be poured into the rocket casing where it sets before it is used, during which process it will burn until it is exhausted or extinguished. This means that testing solid motors is exceptionally difficult because the de-

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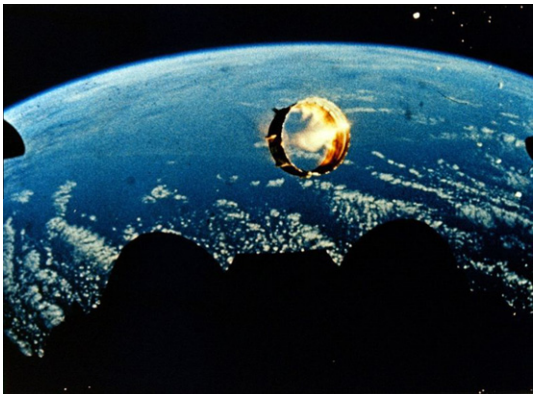

Fig. 1. The interstage adapter ring falls from the base of the second stage of Apollo 6, with ullage motors visible around the sides. This unmanned test flight identified resonances in numerous fuel lines which caused vertical oscillation, known as pogo oscillation, of the entire rocket. These were reduced in subsequent flights (NASA).

vice cannot be test-fired and, instead, high levels of quality assurance must be employed. Ultrasonic inspection of the propellant is difficult due to multiple reflections from the particles and the damping properties of the binder, and to achieve reasonable penetration frequencies below 250 kHz are suggested. This naturally limits the size of deep defect that can be found, but defects in the bond between the propellant and the casing can and are detected [1]. Under some circumstances, ultrasonic techniques can also play a role in determining how fast the flame front passes through the propellant itself [2,3], which is essential in predicting the performance of an inherently unthrottleable motor.

More efficient and more complex liquid motors require careful regulation of the fuel and oxidiser supply. Ultrasonic flow meters can fulfil a role in gauging [4] that is more difficult for traditional hydrostatic or float-based systems to achieve in conditions of varying acceleration and pressure. Also, close inspection of the sides of large liquid–fuelled rockets, such as the Saturn V, can reveal some small excrescences such as those evident in Fig. 1. These are ullage motors, used to maintain a small acceleration during stage separations and thus keep the liquid propellants pooled in anticipation of engine startup. Collecting liquid propellant without ullage motors might be an application for the proposed acoustic 'smart tank', which would both detect and manipulate the vapour/liquid interface using a number of transducer arrays [5].

Of course, not all aspects of sonics in carrier rockets are positive. Combustion instability can arise when an oscillation between combustion, chamber pressure and propellant supply takes place, particularly where combustion is pressure-dependent. These instabilities can occur well into the kHz range, and the addition of Helmholtz resonators [6] or baffles like those in

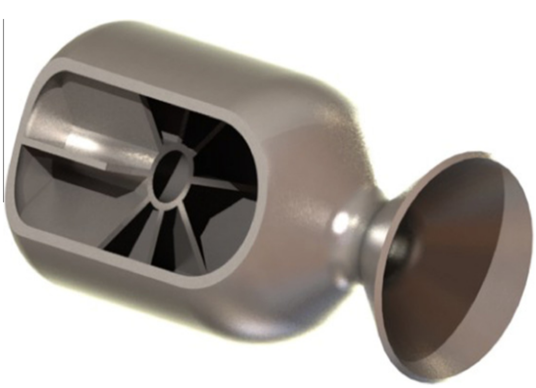

Fig. 2. Baffles such as those suggested above are a mechanism by which the resonance of a combustion chamber can be modified.

Fig. 3. Water released from the white water tower minimises reflection of engine noise from the ground back towards the spacecraft (NASA).

Fig. 2 [7] may be required to modify the resonance of an affected chamber. At the moment of lift-off, however, the presence of launch pad structures can reflect the enormous noise of even well-designed engines upwards, where damage may be caused to the vehicle. For this reason huge quantities of water are released onto the pad during lift-off, as shown in Fig. 3, blurring the interface between jet and pad and thus helping to reduce the echo.

3. Travelling through space

Once they arrive in Earth orbit, spacecraft may need to point in the correct direction and fire small thrusters to move towards their targets. Ultrasonic and piezoelectric systems have a role to play in support of both manoeuvring and propulsion.

Firstly, pointing a spacecraft in a desired direction is relatively difficult due to there being no medium to react forces against. To overcome this, a flywheel (in context, usually called a momentum wheel) can be spun in one direction to cause the spacecraft to turn in the other, with the pointing precision being dependent upon the accuracy of the motor, or perhaps magnets, which spin the wheel. Naturally, three wheels provide three-axis control, with the obvious solution of a momentum sphere being considered, in the earlier phases of the space age at least, to suffer from very severe problems associated with the complexity of the bearing [8]. However, spherical-cap transducers have been suggested as mounts for a momentum sphere, solving the problems of both location and actuation simultaneously by the combined application of magnetic systems for stabilisation and ultrasonic motor effects for motive force. Such a device is designed to provide crisp, 3D pointing capabilities to spacecraft as small as CubeSats [9].

To actually travel through space, however, some form of momentum transfer beyond the spacecraft itself is needed. For smaller spacecraft relatively low amounts of propellant are required and MEMS systems are indicated. Piezoelectric materials have been proposed as suitable valve actuators. Laminations reduce the voltage required to manageable levels and yet enormous forces can be brought to bear on tiny valve seats, reducing the leak rates from small reservoirs [10]. Of course, many spacecraft propulsion systems are themselves pulsed, to ensure that the propellant is accelerated to the highest possible exhaust velocity. Force dynamometers with frequencies in the kHz range have been built to characterise the performance of these systems [11], and providing the tiny amounts of propellant needed for each pulse is an obvious application for ultrasonic atomisation devices [12].

4. Our destinations

The environment that piezoelectric or similar devices will have to work in depends on their final destination. Some missions, such as the Space Interferometry Mission, were or are designed to operate in near-Earth space where temperatures are relatively benign. Missions to Venus will have to cope with +460 °C and Mars experiences temperatures as low as −140 °C, but yet there is evidence to suggest that, although performance may be affected, piezoelectric materials can be developed to operate under these conditions [13]. In transit to locations such as these piezoelectric devices might also be used to pass power through sealed hulls [14] and monitor hypervelocity impacts from space debris or micrometeoroids on the spacecraft itself [15].

Of all the possible destinations, Mars is probably one of the most promising sites for extraterrestrial life in the solar system and is, of course, a leading target for planetary probes. Indeed, the survival of robust terrestrial life on Mars cannot be ruled out and ultrasonic devices have a role to play in decontamination in addition to the sterilization required for fuller planetary protection [16]. On the other hand Martian life, if it ever existed in its own right, might have retreated underground as the planet has become drier. Accessing the subsurface is one of the most high-profile opportunities for ultrasonics in planetary exploration today because the low gravity and relatively poor force-reaction qualities of the average planetary lander make low-force cutting techniques with which we are familiar extremely attractive.

Although traditional ultrasonic cutting has a place in solar system exploration, for example in excising particles captured by aerogels in missions such as Stardust [17], hard materials such as rock do present very particular difficulties. Their high compressive strength can mean that the impulse of each impact of an ultrasonic tool is not delivered at sufficiently high pressure to shatter the rock, and the refinement of ultrasonic/sonic (or high-frequency/low-frequency) drilling is therefore suggested instead [18]. In this approach, illustrated in Fig. 4, ultrasonic vibration is used to excite the lower-frequency velocity of a free-mass, which in turn is used to hammer against the drillbit. The on-going improvement of this system is an area of intense research, with a number of new techniques to achieve bit rotation being discussed very recently [19,20] to take advantage of longitudinal–torsional vibration and hence deliver a drillbit that has both percussive and rotary actions. For this reason, research into modal coupling continues to be reported today [21]. Similar systems have been suggested as effective piledrivers, to help landers climb, walk, or secure themselves in low gravity [22], and ultrasonic systems have even been suggested to weigh [23] and remove [24] dust, for which Mars is well known. A typical Martian scene is shown in Fig. 5.

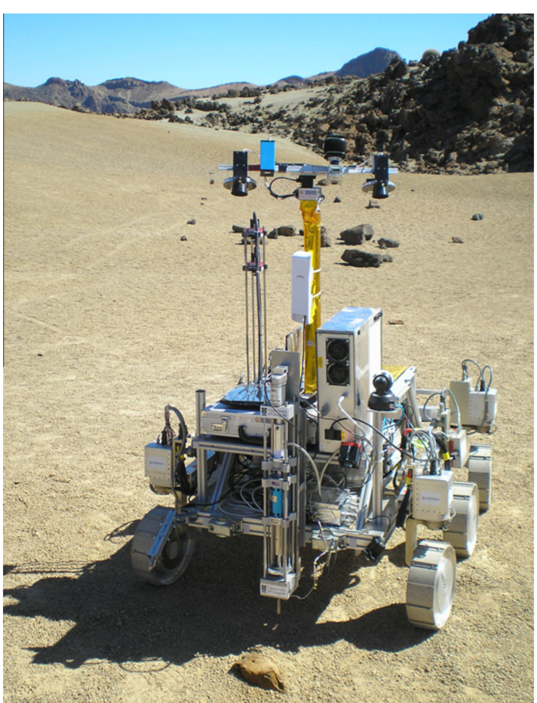

Fig. 4. Ultrasonic drilling using the high-frequency/low-frequency technique at a planetary analogue site.

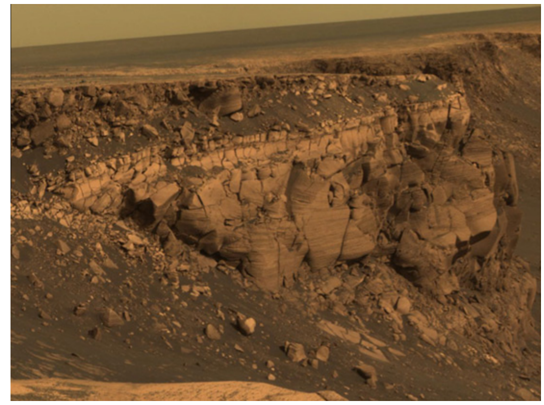

Fig. 5. The lip of Victoria Crater, Mars, from the rover *Opportunity*. Ultrasonic tools could help future spacecraft to penetrate the rock, analyse samples, and remove excess dust (NASA).

5. Supporting science

Scientific planetary exploration includes the analysis of samples of both the terrain and, where present, the atmosphere. For example, analysis of surface moon rock recovered during the Apollo missions has indicated that the speed of sound can be surprisingly low [25], which has implications for the study of the lunar interior [26]. An important aspect of this science is the determination of the Q-factor of the rock, which can be achieved by monitoring the decay of ultrasonic vibration in the material [27].

As well as providing direct measurements, however, sonic systems can also serve to enable further instrumentation. The recently-arrived Mars Curiosity rover contains a sample analysis wheel with 32 chambers, 27 of which are available for samples delivered from the non-ultrasonic drill tool, the remainder containing fixed control materials. The wheel can pass each sample in turn past an X-ray source, and diffracted or fluoresced X-rays are recorded to infer the properties of the sample. Piezoelectric devices are used to energise vibration modes in the walls of the chambers to agitate the samples and randomise the orientation of minerals and crystals, as well as to help empty the chambers after use. The chambers themselves are arranged in pairs, as shown in Fig. 6, with each pair having a resonance at 2.15 kHz [28]. These agitation devices are the most advanced acoustic devices to have flown into space to date but perhaps, in the future, ultrasonic devices will even play a role in the search for potential biomarkers such as amino and carboxylic acids [29].

The Martian wind, which can sometimes form dust-devils like the one shown in Fig. 7, and the atmosphere in general are also important subjects for study. Although it is likely to attenuate sound perhaps 100 times faster than the terrestrial atmosphere [30], ultrasonic anemometers have been proposed to resolve Martian winds, and even vortices, in 3D [31].

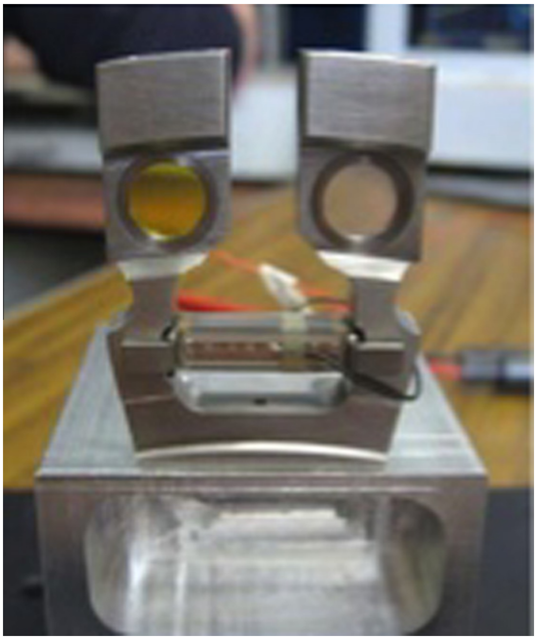

Fig. 6. Two paired chambers from the thirty-two that make up sample analysis wheel, which can be excited by the horizontal transducer between them. The windows are made from different materials to help eliminate systemic errors, and are approximately 8 mm across (NASA).

Fig. 7. A Martian dust-devil from the rover *Spirit*. Ultrasonic anemometry has the potential to return wind-speed data with relatively low sensor-induced error (NASA).

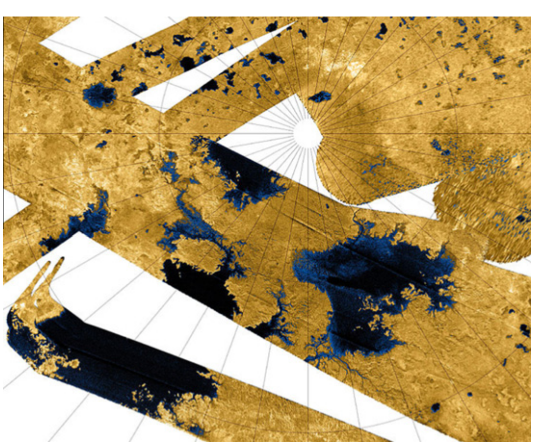

Fig. 8. False-colour image of hydrocarbon-rich lakes on Titan. Sonar sounding of the largest features, comparable in size to Lake Superior, was an objective of the TiME mission (NASA). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 9. An astronaut, André Kuipers, images his own eye with an ultrasound device on the ISS. Prolonged exposure to microgravity appears to have a number of health effects which can be monitored by medical ultrasound (NASA).

However, experience on Earth suggests that acoustic systems are best suited to exploration of the oceans and, while Mars might have lost its water, there is evidence to suggest that Europa, an icy moon of Jupiter, could have a considerable volume of liquid below the surface. Concepts have been proposed to land a receiver on the ice and then bombard the moon from space [32], literally sounding the depths of, perhaps, the largest body of liquid water in the solar system. Other moons, such as Titan, appear to have liquid at the surface in hydrocarbon-rich lakes and seas, as shown in Fig. 8. The planned TiME lake-lander was to have a sonar system [33] to explore these bodies, and maybe ultrasonic thrusters [34] will one day provide future lake-landers with a mechanism to travel across these features.

6. Human exploration

Larger spacecraft, and spacecraft capable of taking astronauts away from the Earth–Moon system, have long been proposed and the application of piezoelectric actuators to control vibration has been suggested for both thin [35] and truss [36] structures since the early 1990s. Ultrasonic leak detectors have been considered to be important safety devices on the International Space Station since the early 2000s [37], and refinements to this system continue to be published in *Ultrasonics* [38]. Astronauts have proven themselves capable, as shown in Fig. 9, of carrying out medical ultrasound procedures in space [39], and there are a wide range of space-related illnesses to which this ability could be turned [40]. The use of ultrasound to diagnose other ailments, perhaps by detecting bubbles associated with decompression sickness, is also mentioned in the literature [41].

One of the most interesting questions for the future might then be how acoustic devices can support the human exploration of Mars. Microphones have already been sent to Mars on two occasions, but in neither case were the sounds of the planet returned. Perhaps future Martian spacesuits will have listening devices to help astronauts speak to each other over short distances without the need for a radio, or even hear dangers such as rockfalls. Such feedback – familiar to readers of science fiction – could help to make the Martian environment feel closer to hand from a psychological viewpoint and thus reduce the sensory deprivation [42] experienced by future explorers.

7. Conclusion

This paper has discussed, at a very high level, some of the areas in which our field is making a contribution to the exploration of space. It has been shown that sonics and space exploration are far from incompatible and that ultrasonic devices are already making a major contribution. Furthermore, there are many challenges ahead – medical, scientific, and engineering – and it seems likely that our research will continue to have an important and on-going role in the years ahead.

Acknowledgement

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