A Multi-Sectioning, Reconfigurable Electromagnetic Hammering Propulsion for Mole Penetrators

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Abstract

This paper presents a new generation electromagnetic direct drive for low-speed penetrators, which makes them capable of underground mobility within regolith while carrying scientific instruments (such as sampling tools or thermal sensors) in planetary missions, where Mars and the Moon are the mostly foreseen destinations. The propulsion combines new ideas and earlier achievements, both of which had influence on the concept and would demonstrate the technology. A laboratory model device was successively developed and tested. Its principle of operation is based on electromagnets arranged in stock and supplied with high impulse power by rechargeable and dischargeable capacitor.

Introduction

Principle of operation of penetrators is based on interaction of three masses of the device (hammer, casing and counter-mass), between which the energy exchange is performed and as a result hammering action is achieved. Examples of mole-type penetrators include: mole penetrator for the Beagle II mission, HP3 mole penetrator for the Exo-Mars mission (under development), and prototypes of KRET-1 and KRET-2 [1] mole penetrators developed by CBK PAN within ESA PECS projects. All of them have stroke mechanical energy accumulated in their driving springs. EMOLE is the first mole-type penetrator in which the electromagnetic linear drive system has been implemented. Since the mole penetrator has been foreseen as a carrier of a sample return system, electronics and sensors, its power settings regulation has allowed accommodating the power to the concrete soil mechanical properties and in many cases saving sensitive components from higher, more destructive overloads. This was possible through major modification of the previous electromagnetic drive technology introduced in the MUPUS penetrator [2] (40-cm rod) onboard PHILAE for the Rosetta mission, CHOMIK sampling device for Russian Phobos-Grunt and the prototype High Energy and Efficiency Penetrator. Thanks to the EMOLE project, new and more accurate simulations are being performed confirming that the novel concept of splitting a large MUPUS-like coil into stack of small coils is feasible without losing (or possibly even gaining) the energy performance in comparison to mechanical moles.

Principle of Operation

Like in the previously presented solutions, the propulsion principle of operation is based on the interaction of three masses of the device but unlike in all the previously developed mole penetrators, the force is generated by a set of reluctant electromagnets arranged in stock and supplied with high impulse power in sequence rechargeable and dischargeable capacitor.

The major novelty of propulsion concept is twofold – the penetrator has much higher reliability of the drive, and its new drive system is able to have power settings. The first advantage is a consequence of a mechanical simplicity of the drive. Foreseen is only one linear motion of the hammer instead of a number of motions, which are typical for the spring driven systems consisting of an electrical motor, reduction gear box, rollers and screw-shaped surface (based on Gromov idea) or helical screw, nut, special latch

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and release clamp (based on CBK PAN idea). An additional common disadvantageous feature of the existing mechanisms is their permanent, maximum stroke setting without gradation of the stroke value. In the proposed electromagnetic drive, equipping it with the power settings function has been realized through electrical power supply.

Preliminary Tests [3]

The concept's verification test-stand was developed and a single electromagnetic drive section (one coil) was tested on this test-stand. Geometrical and mass proportions are retained in accordance with the actual full design. Velocity of the hammer was measured using a linear encoder and magnetic tape. For the purpose of the tests, the Counter Mass remained fixed, and as the result full stroke energy was transferred to the Hammer Assembly.

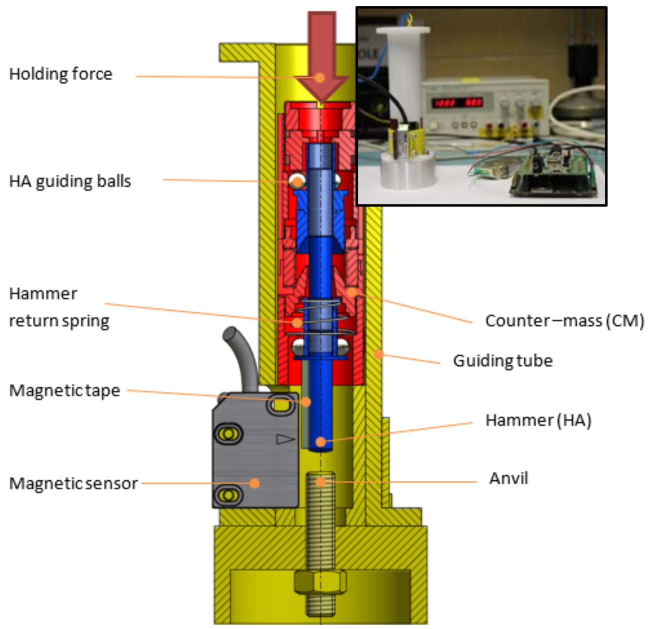

Figure 1. Verification test-stand, in the top right the actual stand with control electronics.

Goals of the test campaign on this test-stand were following:

- to see how coil material influences efficiency of the system,
- to determine the energy fit of the system (meaning at which stored energy the system achieves the highest efficiency),
- to optimize balance between pair of parameters: capacitance and voltage on the capacitor to achieve the most energetic stroke,
- to determine optimal initial gap between hammer and counter-mass for the fixed stored energy value,
- and finally to prove the concept of implementing a coil with 'foot' to the mole-type design and see the outcome of it in comparison to the previously tested concepts.

For these reasons, a single coil with copper wire of 0.4-mm diameter (147 coil turns) was tested to cover all the above mentioned system configurations.

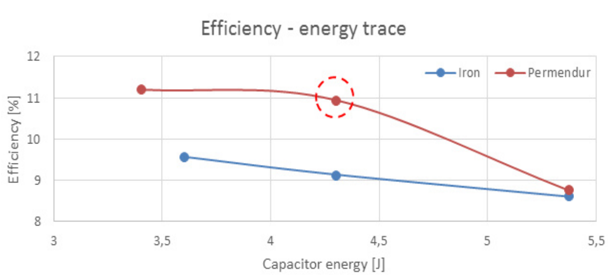

Figure 2. The system's efficiency as a function of the capacitor's energy for Iron and Permendur 49 coils. Dashed circle indicates optimal capacitor energy.

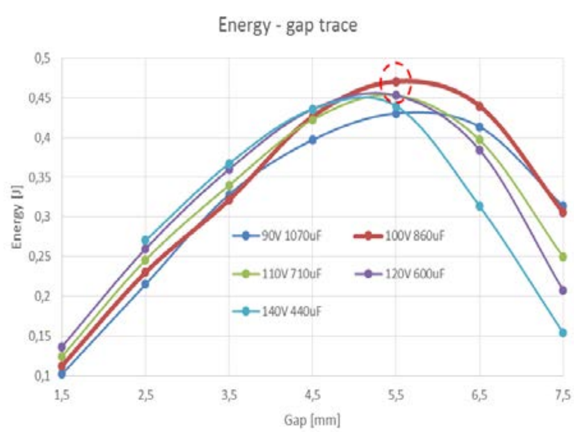

Figure 3. Optimization of Hammer travel gap. Measured hammer kinetic energy for Permendur 49 coil for 4.3-J capacitor energy level. Dashed circle indicates optimal gap.

The results and analysis show:

- It is clear that using Permendur 49 can increase the efficiency of the system by 13-20% with respect to the electromagnet made of Iron coil, see Fig. 2.
- There are no radical changes in the resulting hammer's kinetic energy when taking into account different capacitors settings. Nevertheless, a certain optimal setting can be distinguished for Permendur 49 (see Fig. 3.), which is for 100 V/860 uF.
- When it comes to adjusting the energy level to achieve the most efficient system, it is clear from the test results that by lowering energy on the capacitor we get higher efficiency (at least when approaching down to energy of c.a 3.6 J). Nevertheless, it is energy of 4.3 J that is selected as the optimal.
- Optimal travel gap for hammer was also researched for various capacitors' settings. Fig. 3 shows plots for constant capacitor energy of 4.3 J. For most of the cases, the optimal gap is in the range of 4.5-6.5 mm (with full travel freedom of 8 mm). The selected capacitor settings (100 V/860 uF) have an optimal travel gap of 5.5 mm.

Design Features

Mechanical design description

The drive consists of 5 electromagnetic driving sections in which coils, ferromagnetic cores and magnetic separators are concurring to the counter-mass, while armatures of electromagnets with a connection shaft are comprising the hammer. All electromagnetic circuit elements are made of Permendur 49, whereas the magnetic separators are of a tungsten alloy and the connection shaft is made of titanium alloy. The propulsion (counter-mass + hammer) is enclosed in the outer casing assembly and consists of a long, thin wall, titanium sleeve and hardened stainless steel tip.

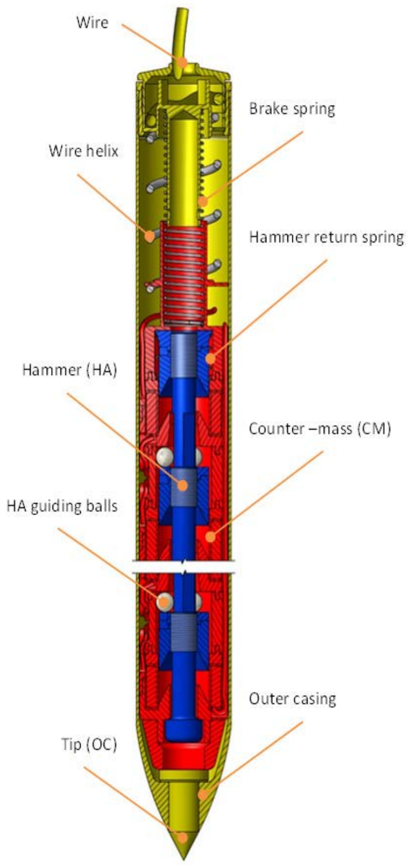

Figure 4. EMOLE CAD model cross-section.

The hammer is guided by two sets of 3 bearing balls inside the counter-mass which provides low friction losses, while the counter-mass is sliding inside the outer-casing tube. As in all the previous penetrators made by CBK PAN, while the hammers starting position (before hit) is set up by a hammering spring, the position of the counter-mass is determined by a brake spring designed in a way that allows the penetrator to work in a non-gravity environment without any support. A cross-section of a CAD model of EMOLE is shown in Fig. 4.

Figure 5. Outer casing, driving sections and return spring just before final assemblage.

The EMOLE is 25 mm in diameter and 250 mm length. The mass of the overall assembly is about 700 g, where the counter-mass mass amounts to 520 g and the hammer and the outer casing are of equal weight of about 90 g.

Electrical design description [4]

The electrical system consists of three parts: control unit (controller), DC/DC converters unit, and electromagnetic drive placed in penetrator. All three parts are designed to operate separately. Control unit, currently in form of a control panel, is used to set signals to turn on the desired mode of operation of the drive electronic system and therefore to control the penetrators behavior. The control unit's interface is able to turn on and off each of the two DC/DC converters as well as to select one of several "gears" – penetrator stroke energy and actuation frequency.

The DC/DC converter unit consists of two DC/DC converters, both in flyback topology. Each DC/DC converter has an overvoltage protection mechanism ensuring safe operation of the device. High Energy DC/DC (DC/DC HE) converter charges large capacitor, stores the energy, which is then released to the electromagnetic drive when it reaches a certain level, set by device operator. The higher the charge (the energy stored), the lower the actuation frequency.

High Frequency DC/DC (DC/DC HF) converter, operates in a similar way as latter DC/DC converter but operates on the energy level ~200 times lower and two orders of magnitude higher frequency. It is galvanically separated from the system ground to operate totally independently from the state of DC/DC HE.

Tests [5]

<u>Actual velocity (and kinetic energy) speed measurements on the finalized assembly</u>

The actual velocity of the hammer with a blocked counter-mass was measured on a test stand. For this purpose, the counter-mass was clamped in the test stand (without the outer casing) and the movement of the hammer was captured on a high-speed camera. The measurement was repeated for all five high energy power settings that the electromagnetic drive possesses. The summary for the achieved velocities, resulting energies and expected efficiencies for each PS are presented in Table 1.

Table 1. Summary of results

Power setting	Hit velocity [m/s]	Hit energy [J]	Efficiency [%]
PS-1	3.352	0.49	10.72
PS-2	4.621	0.94	10.62
PS-3	5.774	1.47	11.22
PS-4	6.503	1.86	10.62
PS-5	7.096	2.22	10.28

These results show that the efficiency varies insignificantly between each power setting. The highest efficiency was achieved for the third power setting. Furthermore, this test proved that the stroke energy changes quite equally with the number of the driving sections. It means the amount of sections can be raised or decreased with respect to the direct mission mass or power requirements, and the stroke energy will raise or decrease equally.

<u>Tests in Syar regolith analogue</u>

After determination of the energy generated by five-coils driving system, the EMOLE penetrator was tested several times, on different power settings, in Syar regolith up to depth of about 50 – 60 cm. The summary of these tests is presented in Figures 6, 7 and 8.

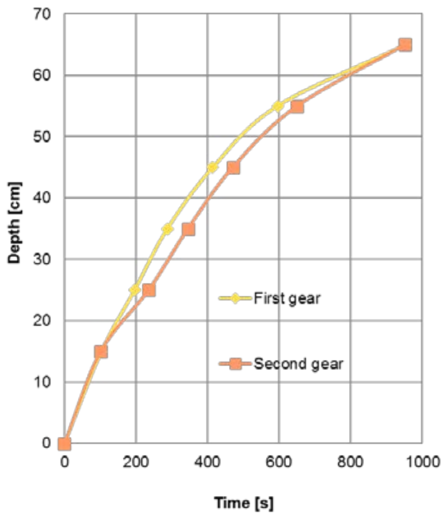

Figure 6. Dependence of time imbedded from depth in Syar regolith analogue.

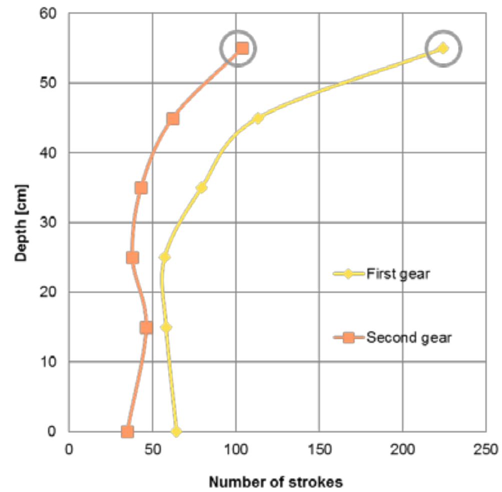

Figure 7. Dependence of number of strokes from depth in Syar regolith analogue. Numbers of strokes are presented for 10-cm depth sections and only first one is for 15 cm.

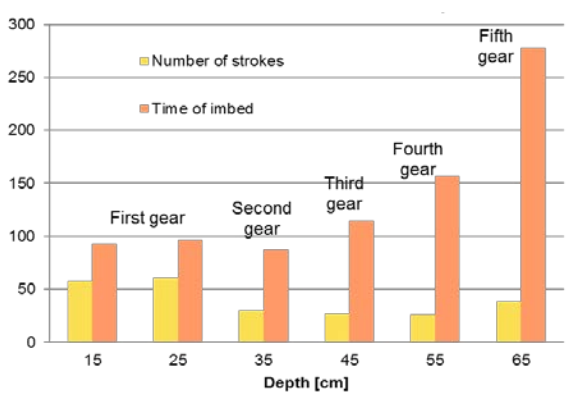

Figure 8. Dependence of number of strokes and time of imbed from depth for five power settings.
EMOLE needed more strokes on higher power levels to reach the next ten centimeters because the bottom volumes of the regolith were much more compressed.

<u>Environmental tests</u>
During the tests conducted in a vacuum chamber, EMOLE was run after degassing (p=0.075 mbar) for about 5 strokes each for all 5 power settings. No problem with launch or any unusual behavior occurred. After gassing the vacuum chamber, the test was repeated again without any problems.

<u>Vibration tests</u>
The last and the most crucial test concerned durability in regards to vibrations. Thanks to the fact that the propulsion is axially symmetric, tests were performed along two axis: one parallel to the axial symmetric axis and the second one perpendicular to it. In these tests the counter-mass and the hammer were locked. One additional test was performed in which the hammer and the counter-mass were held by an external, permanent magnet. During and after vibration tests with locked counter-mass no problems or difficulties were observed. Afterwards, the drive was run without any problems on all power settings what proves its high resistance against overloads. The preliminary vibration tests with unlocked the counter-mass and the hammer that were held only by magnetic field generated by permanent magnet, showing that this kind of solution is able to prevent the driving sections against damage during vibrations that are generated by a starting rocket.

Conclusions

A multi-sectioning, reconfigurable electromagnetic hammering propulsion is the first such type of drive to be used in mole penetrator. The main structural novelty, i.e., use of several electromagnets arranged in stock as a direct hammer propulsion, gave twofold improvements. First of all, owing to the fact that the electromagnets do not need any drive transmissions and they do not have any rotating parts (e.g., a DC motor), the whole instrument became much simpler and more reliable. Secondly, the drive has the ability to adjust hit energy during operation, which can contribute to saving energy and to protection of the scientific instruments from damage. Furthermore, to provide an additional mode in which the typical operation is superimposed with a high frequency and low energy mode, a new electronic control was developed. The simplicity of the direct drive solution, its relevance to the previous flight models of MUPUS (Rosetta), CHOMIK (Phobos-Grunt) and mole penetrator "KRET", along with the experience of CBK PAN, give a path for fast development to a high TRL in a short time.

Variable	Value	Comments
Diameter	25,4mm	1in
Length	254mm	10in
Overall mass	704g	Without power supply wire, with the outgoing wire inside the outer casing, brake spring and bearing balls.
Hammer mass	88g	
Counter-mass mass	52g	
Outer casing mass	90g	
Power consumption	**4W**	12V
Number of coils	5	Can be increased or reduced
Number of wire turns in each coil	147	In each coil
Capacitor parameters	1: 230V; 4,57J 2: 320V; 8,85J 3: 390V; 13,1J 4: 450V; 17,5J 5: 500V; 21,6J	Next power settings in sequence. Discharging voltage and accumulated energy.
Stroke energy, efficiency and duration	1: **0,49J**; 10,72%; **1,6s** 2: **0,94J**; 10,62%; **2,9s** 3: **1,47J**; 11,22%; **4,3s** 4: **1,86J**; 10,62%; **6s** 5: **2,22J**; 10,28%; **7,2s**	Next power settings in sequence. Generated on hammer with fixed counter-mass.

Table 2. Summary of the drive attributes.

EMOLE is a low-speed penetrator capable of mobility within the regolith subsurface and is the first mole-type penetrator that employs an electro-magnetic linear drive system. Lightweight and compact EMOLE either as a whole device or only its new electromagnetic direct drive, may become flexible solution for space exploration missions providing a wide range of the possible applications, e.g.,:

- carrying sensors (e.g., thermal, miniature spectrometers, cameras) underneath the granular matter of a celestial body
- subsurface ground sampling
- anchoring of lander in microgravity conditions
- anchoring (better coupling with the ground) e.g., seismometers
- act as a special actuator for generating high pulse force (1000-2500 N)

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