Paper

MUPUS insertion device for the Rosetta mission

Jerzy Grygorczuk, Marek Banaszkiewicz, Karol Seweryn, and Tilman Spohn

Abstract— An original mechanical device designed to insert a penetrator into a cometary nucleus in an almost gravity-free environment is described. The device comprises a hammer and a power supply system that stores electrical energy in a capacitor. The accumulated energy is discharged through a coil forming a part of electromagnetic circuit that accelerates the hammer. The efficiency of converting the electrical energy to kinetic energy of the hammer is not very high (amounts to about 25%), but the system is very reliable. Additionally, the hammer energy can be chosen from four power settings, hence adjustment of the stroke's strength to nucleus hardness is possible. The device passed many mechanical, functional, thermal and vibration tests and was improved from one model to another. The final, flight model was integrated with the lander Philae and started its space journey to comet Churyumov-Gerasimenko in March 2004.

Keywords— comets, penetrators, hammering device.

1. Introduction

The European Space Agency (ESA) cornerstone mission Rosetta to comet Churyumov-Gerasimienko comprises the main spacecraft that will become a comet companion for at least half a year and the Philae lander [1]. Philae weights about 100 km and includes eight instruments that will measure chemical composition and physical properties of the comet [2]. Space Research Centre participates in the experiment MUPUS (multi-purpose sensors for surface and sub-surface science) [3, 4] that is dedicated to obtain temperature profile of nucleus' subsurface layers to a depth of 40 cm and thermal conductivity of cometary material. The experiment MUPUS is developed by a multinational team led by Prof. T. Spohn from the Muenster University.

The main engineering problems that had to be solved in the design phase were:

- how to insert a 40 cm long penetrator equipped with thermal sensors into the nucleus composed of a porous ice-dust mixture;
- how to deploy the penetrator and its insertion device to a distance of about 1 m from Philae, in order to avoid thermal perturbations caused by the lander.

In this short paper we will address the first issue only.

The cometary environment is very unusual and poses severe requirements on the instrument. First of all, the nucleus is a small body (2–3 km in diameter), with almost negligible gravity (more than four orders of magnitude smaller that on the Earth) and with low pressure and temperature, 10^{-6} bar and 130 K, respectively. The gravity-free condition does not allow using the lander body as an inertial support; it will recoil easily after each stroke of the insertion device, in agreement with the conservation of momentum in an isolated system. In the vacuum and low temperature on the nucleus it is very important to avoid cold-welding effect between metal parts of the device and carefully design all moving and driving subsystems (e.g., motors). Additional constraints are due to sparse lander resources: an average power assigned to MUPUS is 1.5 W, and the instrument should not weight more than 2 kg.

2. Device concept and development

The first issue to be decided about was what type insertion device would be used:

- a single impulse engine (rocket), powered by gunpowder, chemical fuel or high-pressure gas, or
- a multi-stroke system that would slowly insert the penetrator into the nucleus.

For safety reasons and because of uncertainty in our knowledge about the material strength of the nucleus, the first option was abandoned and the hammering concept was chosen. The Philae power supply system delivers energy to its instruments in a form of low voltage electric current. In order to execute hammer strokes energetic enough to penetrate the surface this power must first be stored in the insertion device and then released with maximum efficiency possible. Three kinds of energy storage systems were considered:

- mechanical potential (spring);
- mechanical kinetic (reaction wheel);
- electric (capacitor).

The capacitor has an advantage that there is no need to convert the supplying current to any form of mechanical energy and was, therefore, accepted. Following this choice, an electromagnet was implemented as the hammer accelerating subsystem. The static hollow cylindrical carcass made of iron forms together with a hammer an electromagnetic circuit. The discharge of capacitor converts the current energy to magnetic field and forces the hammer to move inside the iron cylinder to close the circuit.

After having solved the hammer engine problem, one has to consider the basic issue of how to design the mechanical system that would be able to continuously insert the penetrator into the cometary ground without supporting gravity.

The concept applied in the MUPUS insertion device employs three masses: the penetrator, the hammer and the counter-mass. The counter-mass is connected to the other masses with weak springs. A single stroke can be described as a sequence of events:

a) acceleration of the hammer;

b) forward motion of the hammer and slower motion of the (heavy) counter-mass backwards (from momentum conservation);

c) the hammer hits the penetrator and recoils;

d) the penetrator moves forwards, into the ground, the hammer and the counter-mass together move backwards;

e) the penetrator stops or moves backwards for a short time;

f) the counter-mass and the hammer stop.

Since the counter-mass is much heavier than the hammer and the penetrator tube, therfore it moves slower and the average force acting from it through the spring on the penetrator in stages (d) and (e) is much smaller than the forward force pushing the penetrator into the ground just after the hammer hit. In Fig. 1 the insertion scenario during a single stroke is illustrated. The phase 1 in the figure corresponds to event (a) in the scenario. Events (b) and (c) are shown as phase 2, while events (d) and (e) are merged in the figure into phase 3. Finally, the last event (f) corresponds to phase 4.

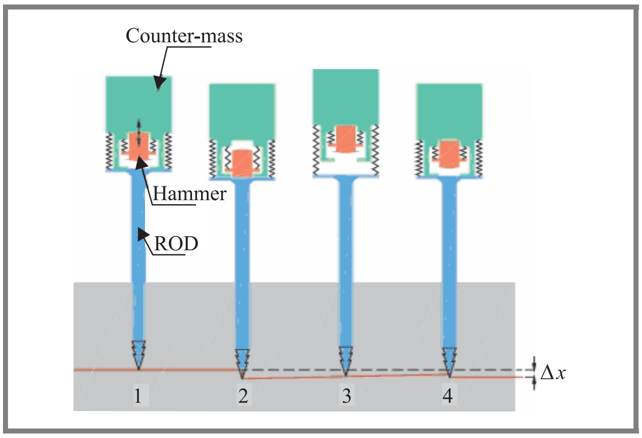

Fig. 1. Four phases of insertion during a single stroke: 1 – hammer acceleration; 2 – hammer hits the penetrator and recoils; 3 – the masses move backwards; 4 – the motion stops.

In Fig. 2 time dependence of the force acting on the penetrator is shown. The energetic phase of penetration, in which the force exerted on the penetrator is large, is followed by a much slower (due to the counter-mass inertia) recoil that tries to pull out the penetrator with a much weaker force. If this latter force is below the level of friction/anchoring force between the medium and the penetrator, then the penetrator will not be pulled out of the ground during recoil. An elementary analysis of the efficiency of momentum exchange in hammer-penetrator collisions as well as of push in and pulling out forces acting on the penetrator from the counter-mass shows that the mass distribution between the penetrator, the hammer and the counter-mass should be close to the relation 1:1:10. In practice, the masses are limited by functional constraints, choice of material, geometry, etc., therefore it is difficult to reach the ideal proportions. In the final, flight model of MUPUS the penetrator weights 60 g, the hammer 30 g, and the counter-mass 350 g.

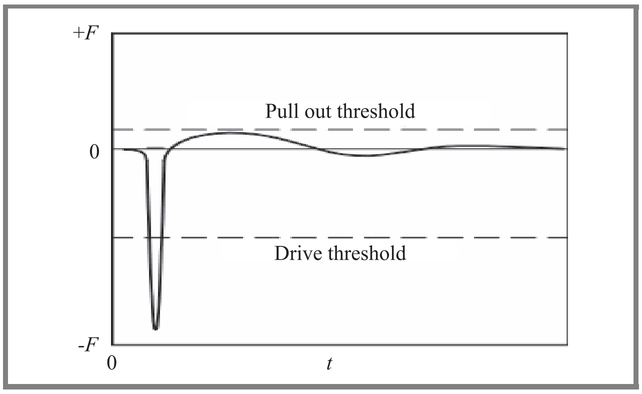

Fig. 2. Time dependence of the force exerted on the penetrator during a single stroke. The first part corresponds to the hitting of the penetrator by the hammer. The second part shows the pulling out force that acts during the recoil.

The last problem to consider is how to support the hammering device during the initial stage of insertion, when the penetrator is not yet stuck in the ground. Here, the deployment device composed of two expandable tubular booms comes to the rescue. It links the insertion device with the lander with a force of about 1 N that is strong enough to bring the penetrator tip back to the ground after the recoil following the stroke. The penetrator tip is equipped with a set of anchoring whiskers, which efficiently increase the resistance of the penetrator against the pulling out force.

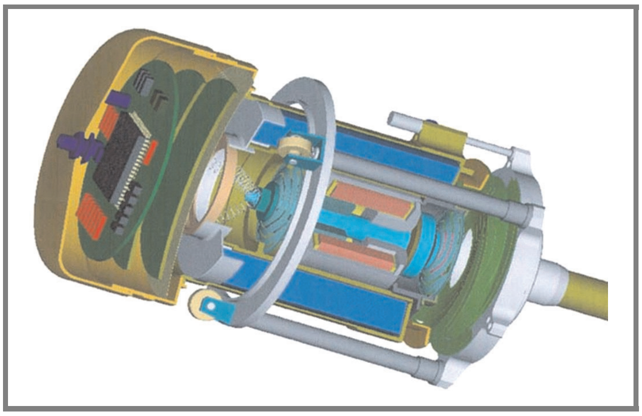

Fig. 3. Cross-section of the hammering device. Only the upper part of the penetrator rod is shown.

The cross-section of the hammering device is shown in Fig. 3. The housing contains the capacitor that surrounds the electromagnet with the hammer inside it. Above, there is an electronic compartment with the hammer controlling circuits and chips.

3. Performance and tests

The device was carefully tested, first at the level of subsystems (electromagnet, capacitor, mechanical part, etc.) then as a whole. The electromagnetic circuit was simulated by finite element method (FEM) and its parameters were optimized [5]. The most interesting were the functional tests of insertion into cometary like materials. Those were simulated by Ytong and solid foam blocks. To imitate the gravity free condition, the penetrator was suspended horizontally on a pair of strings (Fig. 4). The blocks were highly porous (up to 90%) that appropriately mimics cometary material but not at all weak; their compressive strength ranged from 0.79 MPa, through 1.75 MPa, to 5–7 MPa (for solid silica foam). The estimated strength of cometary nuclei vary from 25 kPa to 2.5 MPa. Since the test were passed successfully, one can assume that the hammering device would be able to insert the penetrator into the comet as well. The attempts to insert the penetrator into the ice were moderately successful. If its strength did not exceed 3 MPa, the penetrator worked fine. Above this limit, it could only be inserted to a certain depth and then got stuck in the ice.

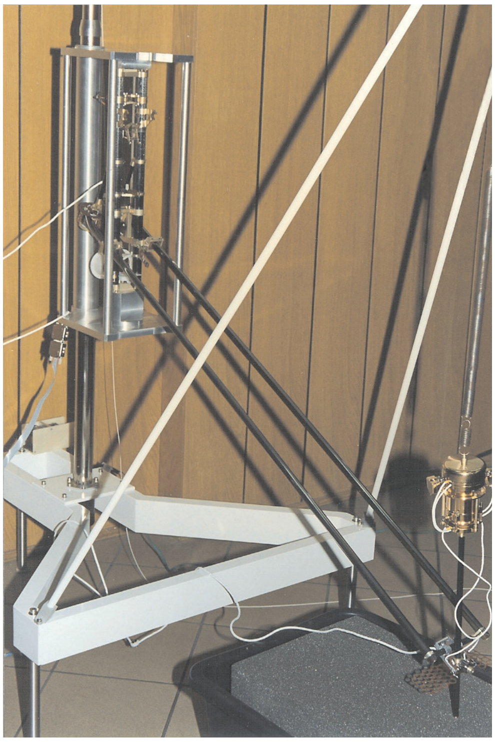

Fig. 4. The stand for functional test of the insertion device (left picture).

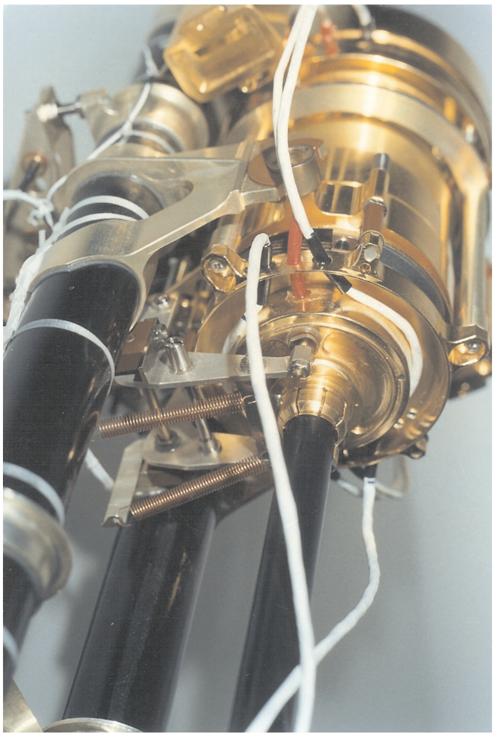

Fig. 5. The flight model of MUPUS insertion device in the stowed position on the lander balcony (right picture).

The functional tests of the insertion device were followed by several other tests of the whole MUPUS device: vacuum-thermal, electrical, vibrational, and electromagnetic compatibility (EMC). The most severe test were applied to the engineering model, so that the final flight model of MUPUS (Fig. 5) were subject to only moderately heavy loads and environmental tests.

4. Conclusions

The MUPUS is one of the most complicated space instruments developed in Space Research Centre. It is also the only so far designed and developed cometary penetrator. It took 6 years to develop the instrument, starting from the first conceptual study in 1996 till the delivery of the flight model to ESA in 2001. The insertion device described in this paper comprises only a pat of the whole experiment. It includes two other scientific elements: IR mapper that is placed on the lander balcony and accelerometer and temperature sensor located in the anchor that will be shot into the nucleus at the moment of landing. Those two units were developed by German and Austrian colleagues, respectively. What concerns Polish contribution, we developed the deployment device, thermal sensors for the penetrator, depth sensor to measure the insertion progress, part of the on-board and the whole hammer electronics, and flight software to control the experiment. The outcome of the tests are the data that are now used in computer simulations [6]. The involvement in MUPUS enabled the Polish team to gain the knowledge and expertise necessary to participate in most demanding space endeavors.

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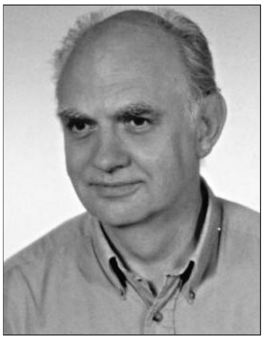

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