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Impact of tubular reluctance motor design parameters on the performance of ground penetrator for space missions

Abstract*. This paper presents analysis results showing impact of particular design parameters on performance of tubular reluctance motor. Investigated motor is a drive system of ground penetrator – devices used in space mission for planetary bodies in situ experiments. Presented results were obtained usingFEM multiphysics model which combines is one simulation three different physical phenomena: electricity, magnetism and mechanics. The main motor features which were analysed includes magnetic circuit geometry, coil and source (capacitor) parameters.*

Streszczenie.*W artykule zaprezentowano wyniki analiz ukazujących wpływ parametrów konstrukcyjnych tubowego silnika reluktancyjnego na jego osiągi. Analizowany silnik jest układem napędowym penetratora gruntu – urządzenia używanego w misjach kosmicznych do badań powierzchni ciał niebieskich. Przedstawione wyniki uzyskano na podstawie bezpośrednio sprzężonego modelu numerycznego wykorzystującego Metodę Elementów Skończonych (MES). Opracowany model umożliwia jednoczesną symulację trzech różnych zjawisk fizycznych: elektryczności, magnetyzmu I mechaniki. Główne parametry, których wpływ na osiągi silnika został przeanalizowany to geometria obwodu magnetycznego oraz parametry cewki i źródła zasilania – kondensatora.(****Wpływ parametrów konstrukcyjnych tubowego silnika reluktancyjnego na wydajność penetratora gruntu dla misji kosmicznych)***

Keywords: tubular reluctance motors, FEM, Multiphysics, space technology
Słowa kluczowe: tubowe silniki reluktancyjne, MES, analizy problemów bezpośrednio sprzężonych, techniki kosmiczne

Introduction

Ground penetrators are devices designed as a carrier of different sensors for in situ investigations of subsurface layers of planetary bodies [1]. In this article authors focus on new generation of mole type ground penetrator driven by an electromagnetic direct drive. This device is a low-speed penetrator capable of soil/regolith underground motion/mobility. Its principle of operation 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 and prototypes of KRET-1 and KRET-2 [2] mole penetrators developed by Space research Centre of Polish Academy of Sciences. All of them have stroke mechanical energy accumulated in their driving springs.

The device, which is a main subject of this article is the first mole type ground penetrator, in which the electromagnetic linear drive system will be implemented. The major novelty of this concept is twofold – the penetrator will have much higher reliability of the drive, and its new drive system is feasible to have power settings. The first advantage would be a consequence of a mechanical simplicity of the drive. Foreseen is only one linear motion of the hammer instead of a number of motions that are typical for spring driven systems consisting of: electrical motor, reduction gear box, rollers and screw-shaped surface or helical screw, nut, special latch and release clamp. 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 can be realized through electrical power supply. Since the mole penetrator is foreseen as a carrier of a sample return system, electronics and sensors, its power settings regulation will allow accommodating the power to the concrete soil mechanical properties and in many cases saving sensitive components from the higher, more destructive overloads. This is possible through major modification of the previous electromagnetic drive technology introduced in MUPUS penetrator (40 cm rod) onboard PHILAE for the Rosetta mission [3], CHOMIK sampling device for Russian Phobos-Grunt [4] and now also prototype HEEP [5].

The research problem presented in this article is determination of influence of electromagnetic direct drive system (tubular reluctance motor) design parameters on performance of the mole kind drive penetrator. The tool developed for the purpose of this study is direct coupled multiphysics FEM model.

Design description

Concept of the electromagnetic direct drive [6, 7] (tubular reluctance motor) is presented in figure 1

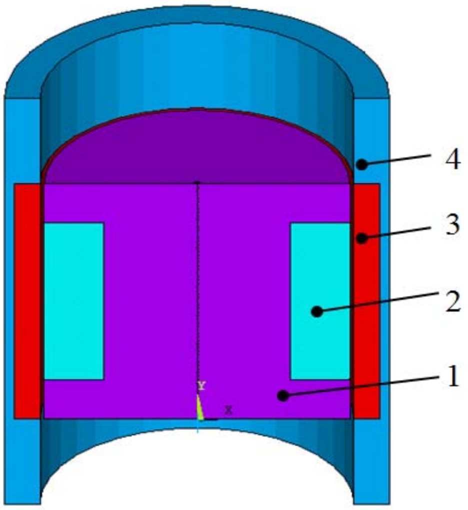

Fig.1. Linear Tubular Reluctance Motor concept – one section of the drive system. 1- core, made of ARMCO-B steel; 2 - coil, copper; 3 – armature, the same material as core; 4 – armature housing made of non-magnetic material

It should be noted, that for the proposed purpose, the drive system will consist of few sections stacked one behind the other and separated magnetically by the core undercutting.Operational stroke is realized by the armature and its housing, called a “hammer”, while core and coil acts as a stator and are called as a counter-mass. It should be emphasized that this specific application requires that both, hammer and counter-mass, are in relative motion which allows proper working in the microgravity conditions. The configuration showed in figure 1 presents position of the hammer and counter-mass at the end of the operational stroke. At this moment there is an impact on the externalpenetrator housing (not included in the figure 1.). After this action both elements return to the starting position by means of springs. After recharging the capacitor to the desired voltage, circuit is closed and the operational stroke (hammering action) is repeated. The average time of charging the capacitor (depending on the desired stroke energy level) in comparison to the hammering action is significantly higher, approximately 10 000 times longer.

The FEM Model

The aim of FEM model is to study impact of design parameters on the efficiency of energy conversion – from electrical energy stored in the capacitor, to the hammer kinetic energy. In other words, from the device point of view the most important factor is the hammer impact energy, which can be produced during one impulse. Investigation of this research issue requires analysis of three different areas of physics: electricity, magnetism, and dynamics. All these areas are influencing each other and should be considered simultaneously. For this purpose 2D axisymmetric multiphysics direct coupled FEM model using ANSYS software [8], which allows creating coupled models [9].

The circuit-magnetic coupling has been included in the numerical model as a simultaneous coupling where the matrix equation is of the form:

$$(1)\begin{bmatrix} [0] & [0] & [0] \\ [C^{iA}] & [0] & [0] \\ [0] & [0] & [0] \end{bmatrix}\begin{Bmatrix} \{\dot{A}\} \\ \{0\} \\ \{0\} \end{Bmatrix}+\begin{bmatrix} [K^{AA}] & [K^{Ai}] & [0] \\ [0] & [K^{ii}] & [K^{ie}] \\ [0] & [0] & [0] \end{bmatrix}\begin{Bmatrix} \{A\} \\ \{i\} \\ \{\varepsilon\} \end{Bmatrix}=\begin{Bmatrix} \{0\} \\ \{0\} \\ \{0\} \end{Bmatrix}$$

where: {A}- magnetic potential vector, {ε} – electromagnetic vector drop, {i} – electric current vector, $[K^{ie}]$ – current-electromagnetic coupling stiffness matrix, $[K^{AA}]$ – vector magnetic potential coefficient, $[K^{Ai}]$ – potential-current coupling stiffness matrix, $[K^{ii}]$ – resistive stiffness matrix

The circuit-magnetic simultaneous coupled effect is accounted by the presence of the off-diagonal submatrices $[K^{ie}]$ and $[K^{Ai}]$.

A different approach has been implemented in magneto-structural coupling. It is defined by the following matrix equation:

$$(2)\begin{bmatrix} [M] & 0 \\ 0 & 0 \end{bmatrix}\begin{Bmatrix} \{\ddot{u}\} \\ \{\ddot{A}\} \end{Bmatrix}+\begin{bmatrix} [C] & [0] \\ [0] & [C^m] \end{bmatrix}\begin{Bmatrix} \{\dot{u}\} \\ \{\dot{A}\} \end{Bmatrix}+\begin{bmatrix} [K] & [0] \\ [0] & [K^m] \end{bmatrix}\begin{Bmatrix} \{u\} \\ \{A\} \end{Bmatrix}=\begin{Bmatrix} \{F\} \\ \{\Psi_i\} \end{Bmatrix}$$

$$(3)\qquad \{F\}=\{F^{nd}\}+\{F^{ac}\}+\{F^{Lo}\}$$

$$(4)\qquad \{\Psi_i\}=\{\Psi_i^{nd}\}+\{\Psi^S\}$$

where: {u} – displacement vector, [M] – structural mass matrix, [C] – structural damping matrix, $[C^m]$ – magnetic damping matrix, [K] – structural stiffness matrix, $[K^m]$ – scalar magnetic potential, $\{F^{nd}\}$ – applied nodal force vector, $\{F^{ac}\}$ – force vector due to acceleration (gravity), $\{F^{Lo}\}$ – Lorentz force vector, $\{\Psi^{ind}\}$ – applied nodal source current vector, $\{\Psi^S\}$ – source current vector

The magneto-structural coupling is sequential. This mean that coupled effect is accounted in the dependency for magnetic and structural part. For this approach at least two iteration are required to achieve coupled response.

The numerical model includes nonlinearity of ARMOC – B steel magnetic permeability. It should be mentioned that a presented model is 2D and does not reflect essential design feature - core undercutting introduced in order to minimize eddy current presented in figure 4. Therefore, authors decided not to consider eddy current phenomena in the analysis.

To simplify the model and reduce number of elements only two sections (coils) of the linear motor have been modeled. This approach does not effect on simulated physical phenomena and their relations, all relevant features have been contained. Components included in FEM model and their interactions are presented on figure 2.

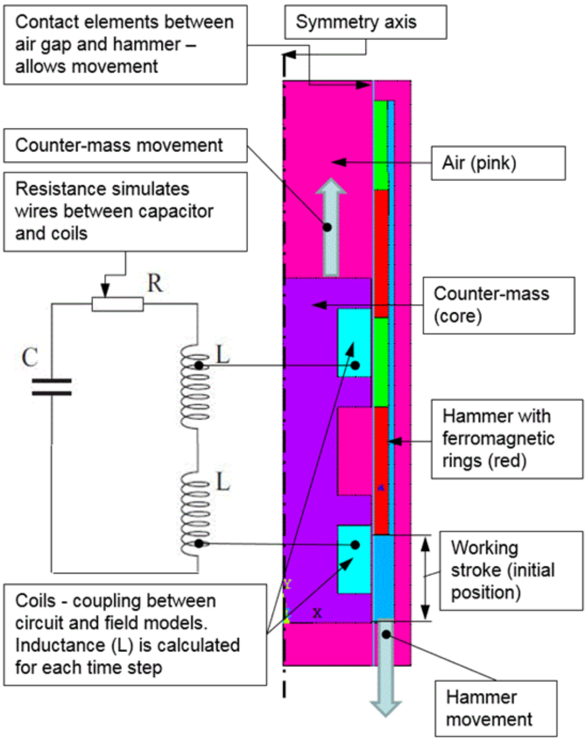

Fig.2. FEM model components and interactions

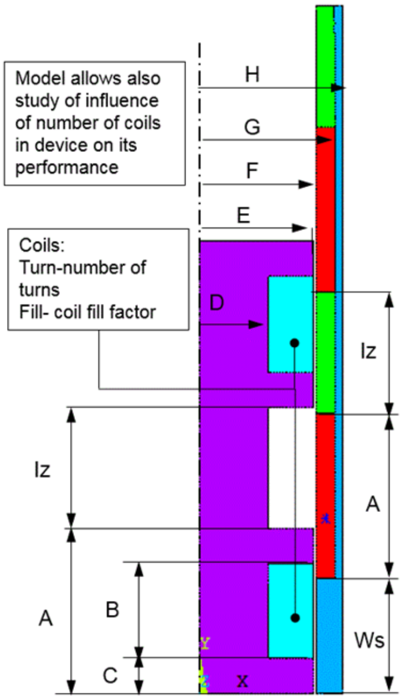

Fig.3. Design parameters, which can be investigated using developed FEM models

The FEM model allows to investigate influence of the tubular reluctance motor design parameters presented in figure 3. It should be mentioned that due to functionality of the whole device and higher level requirementsrestrictions of some parameters were specified and collected in table1.

Table 1. Constraints

Parameter	Value	Unit
Maximum total length of the linear tubular motor	127	mm
Maximum external diameter of the linear tubular motor (H)	22,7	mm
Hammer mass (target)	120	g
Counter-mass	720	g
Energy stored in capacitor	21	J

The laboratory model

In order to validate the numerical results and check drive system concept the experimental model was designed and constructed. This model contains the most crucial components of the device and is presented in figure 4.

The main elements of the hammer are ferromagnetic rings (made of ARMCO-B steel). In addition, the hammer consist of a spacers, made of carbon fiber composite, used to separate the rings and of two ball slides elements, on which bearings ball are guided. The hammer is enclosed in a housing made of a carbon fiber composite. Counter mass consists of a core, made of ferromagnetic material, with two coils wounded around. Coils were covered with insulation to prevent of electrical short cut. At each end of the core two ball sliders, on which the hammer moves, are distributed. It should be mentioned, that the core design includes features (undercutting's) in order to reduce eddy currents (Fig.4).

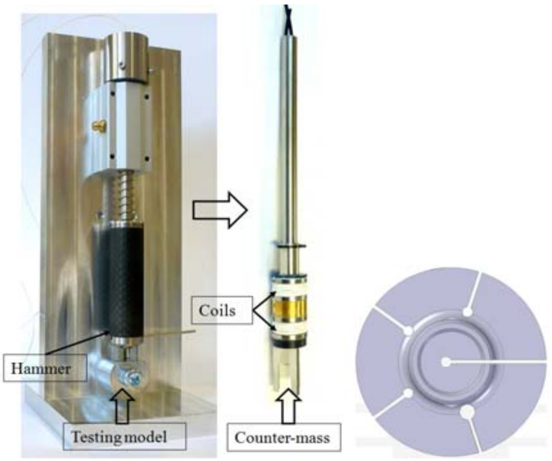

Fig. 4. View of the laboratory model (right) and tope view of core with undercutting introduced in order to minimize eddy current effect (left)

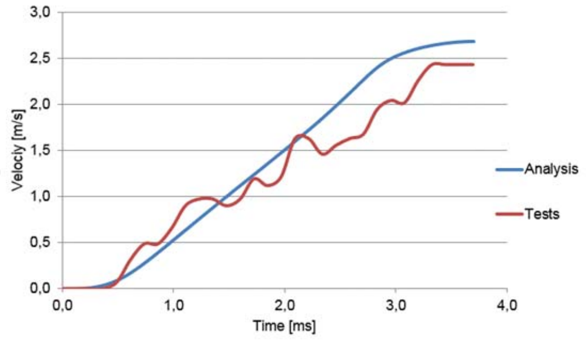

Fig.5. Comparison of tests and analysis results

During laboratory tests, measurements of the hammer movements were executed using fast acquisition camera. As results of conducted tests, function of hammer displacement vs. time was determined. Figure 5 shows comparison between results obtained from the numerical simulation versus experimental results. The agreement is considered to be satisfactory, taking into account test measurements error estimated at 10%.

Analysis of the results

First design parameters, which were researched are number of section (coils) in the motor as well as coils parameters (number of turns, wire diameter). It should be mentioned that all modifications were introduced taking into account design constraints (Table 1.), i.e. change of number of coils imply modification of its length (parameter B in figure 3.), to keep the total length of the motor constant. Moreover, changing of coils length cause modification in size of ferromagnetic hammer's rings (parameter A in figure 3). Figures6.,7.and8.collate kinetic energy of the hammer reached at the end of its movement (stroke). This value has been chosen as the parameter, which describing performance of the penetrator.

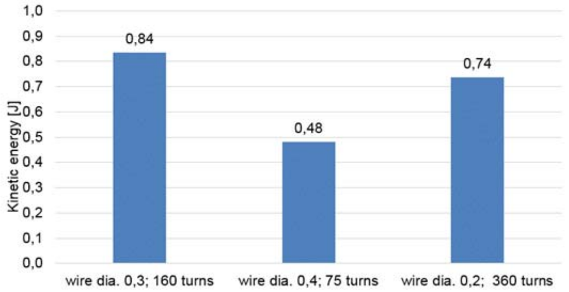

Fig.6. Kinetic energy achieved by hammer for different coils parameters, configuration with 6 coils, wire diameter in mm.

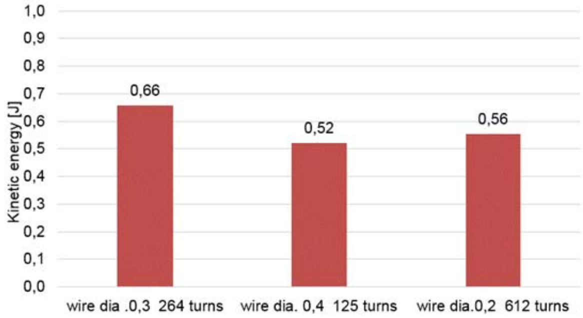

Fig.7. Kinetic energy achieved by hammer for different coils parameters, configuration with 5 coils, wire diameter in mm.

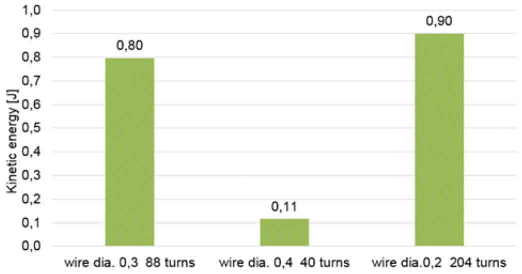

Fig.8. Kinetic energy achieved by hammer for different coils parameters, configuration with 7 coils, wire diameter in mm

The next design parameter, which were researched is value of the working stroke (parameter Ws on figure 3), i.e. initial position of the hammer. Figures 9.,and 10 present influence of working stroke modifications on reached kinetic energy for three versions of coils configuration.

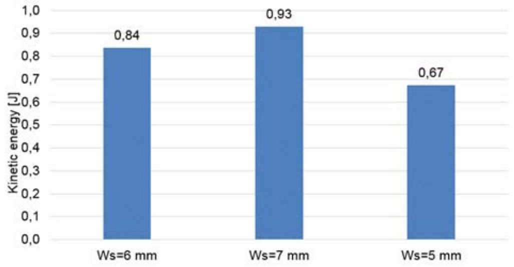

Fig.9. Kinetic energy achieved by hammer for different value of working stroke for configuration with 6 coils

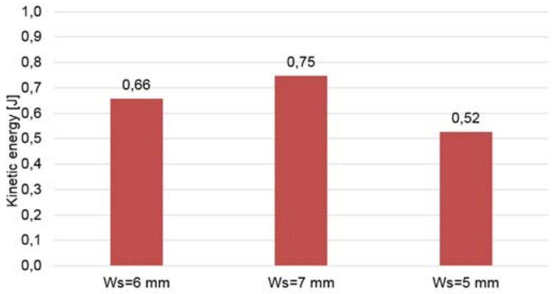

Fig.10. Kinetic energy achieved by hammer for different value of working stroke for configuration with 5 coils

One of the project restriction is available energy stored in capacitor. Below results (Fig.11.) show comparison between different values of capacitors capacitances and initial voltage selected to provide the same stored energy.

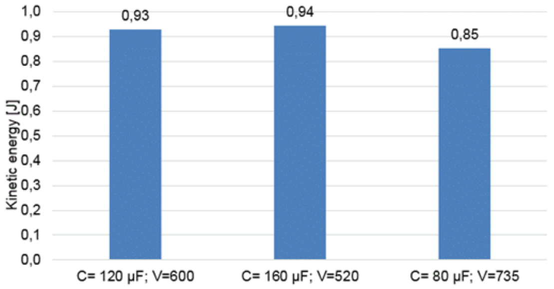

Fig.11. Kinetic energy achieved by hammer for different capacitances and initial voltages for configuration with 6 coils

Conclusions

Information presented in this article concerns use of the tubular reluctance motor in uncommon application – as a drive of penetrator for space mission. The article focus on presentation of analysis showing impact of magnetic circuit geometry, number of coils, coils and source parameters on the device performance. Above data were obtain using FEM multiphysics model, which proved to be very powerful tool for numerical simulations.

The model was validated, by laboratory tests - conformity between results is satisfactory. Number of coils, number of turns and length of working stroke have major impact on kinetic energy of the hummer. Influence of capacitance and voltage is not so significant, if stored energy is constant.

All described researches were conducted in within the framework of the research project, which aim is to develop new type of penetrator for space mission. Presented results will be used in next phases of the project and will allow to design the most efficient device taking into account imposed restrictions.

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REFERENCES

[1] Grygorczuk J. et al. Advanced penetrators and hammering sampling devices for planetary body exploration. *In: ASTRA 2011,* ESA ESTEC, Noordwijk, The Netherlands.
[2] Grygorczuk J, Seweryn K, Wawrzaszek R, Banaszkiewicz M. *Technological features in the new mole penetrator "KRET*". In: 13th ESMATS 2009, Vienna, Austria.
[3] GrygorczukJ, Banaszkiewicz M, Seweryn K, Spohn T. MUPUS Insertion device for the Rosetta mission. *Journal of Telecommunications and Information Technology* 2007;1 50-53
[4] Grygorczuk J. et al. Advanced mechanisms and tribological tests of the hammering sampling device CHOMIK. In: *14th ESMATS 2011, Constance*, Germany.
[5] Grygorczuk J, , Wiśniewski L, Banaszkiewicz M, CiesielskaM,Dobrowolski M,Kędziora B, Przybyła R, Seweryn K, Wawrzaszek, Bieńkowski K, Drogosz M, High energy and efficiency penetrator- HEEP. In: *15th ESMATS 2013, Nordwijk, the Netherlands*.
[6] 6Boldea I., Nasar S.A. Linear Electric Actuators and Generators. *Cambridge University Press, 1997.*
[7] Przyborowski W., Kamiński G. Maszyny Elektryczne, *Oficyna Wydawnicza Politechniki Warszawskiej*, 2014
[8] Kohnke P. ANSYS Theory Reference, Release 5.6. *Ansys Inc. Southpointe,* Canonsburg, USA, 1999.
[9] Gih-Keong L. Design Optimization of Actuators Using ANSYS In: *7th ASEAN ANSYS Conference: Inspiring Engineering* October 2008, Biopolis, Singapore,