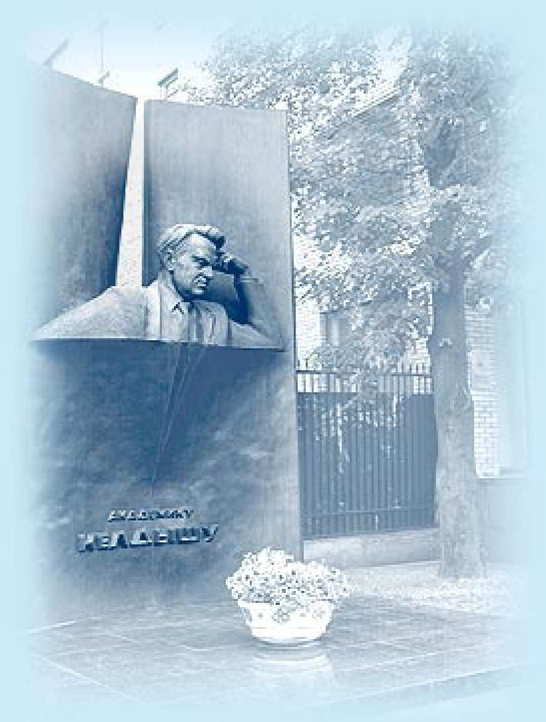

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Preliminary experimental results of a facility to test hysteresis rod parameters: effect of the magnetic field of a permanent magnet.

1. INTRODUCTION

The paper represents the continuation of work described in [1]. In the paper [1] design, sizing and preliminary tests to develop a small facility to carry out experimental investigation on hysteresis rods have been discussed and presented. The facility is based on a simple circuit: there is a transformer which provides the power supply; the transformer has been connected with a variable resistor in parallel with a solenoid. The transformer has been modified to provide a variable voltage of about 19 V (V_p) in input, with a frequency $f = 50$ Hz. Variable resistor provides a maximum resistance about 7.6 kOhm and it is used in the scheme to change the value of the current which flows in the circuit. To test behaviour of hysteresis rods when magnetic field induction amplitude changes we change current in the solenoid.

2. COMPOSITION OF THE FACILITY

Working principle of this facility is based on induction law of Newman-Faraday-Lenz: a variable current flowing in the coil-1 generates in a secondary coil an induced electromagnetic force. The secondary coil (coil-2) is used as a sensor by moving it along the length of solenoid (coil-1) which holds inside the hysteresis rod. Signal of the coil-2 depends also on the position of coil-2 with respect to the field generated by coil-1. Signal is a maximum when cross section of the coil-2 is perpendicular to force lines of field generated by coil-1 and minimum when the cross section is parallel to force lines. To maximize the coefficient of mutual induction it has been chosen the scheme of arrangement sketched in Fig.1.

Solenoid (coil-1) has been realized with a copper wire rolled up at plastic cylindrical body with a diameter of 0.75 cm. Resistor and main coil have been placed on a wood base.

Main purpose of this experimental activity is to analyze the behaviour of a set of different hysteresis rods located in an external magnetic field and to try to develop a modelling for the magnetic permeability of a rod depending by length of the rod.

The rods are made of magnetically soft material and their parameters depend strongly on the manufacturing process and heat treatment. So, it is a difficult problem to predict theoretically their behaviour. Rods efficiency depends not only on their volume, on material used, on technique of heat treatment and on elongation (i.e ratio between length of rod and its diameter) but also on rods arrangement on board of a satellite. It is known [2, 3] permanent magnet field influences on hysteresis rods and hysteresis rods influence mutually each other (demagnetization effect). Therefore, the best arrangement of hysteresis rods in the satellite body is to place them in the plane perpendicular to the magnetic dipole and passed through magnet centre or far from magnet as much as possible; the distance between rods has to be no less than 0.3-0.4 length of rods. But these requirements are not satisfied in the better way when sizes of satellite are very small as in the case of a nanosatellite. Goal of the work is also to establish some empirical design criteria about the arrangement of hysteresis rods and permanent magnet on board of very small satellites.

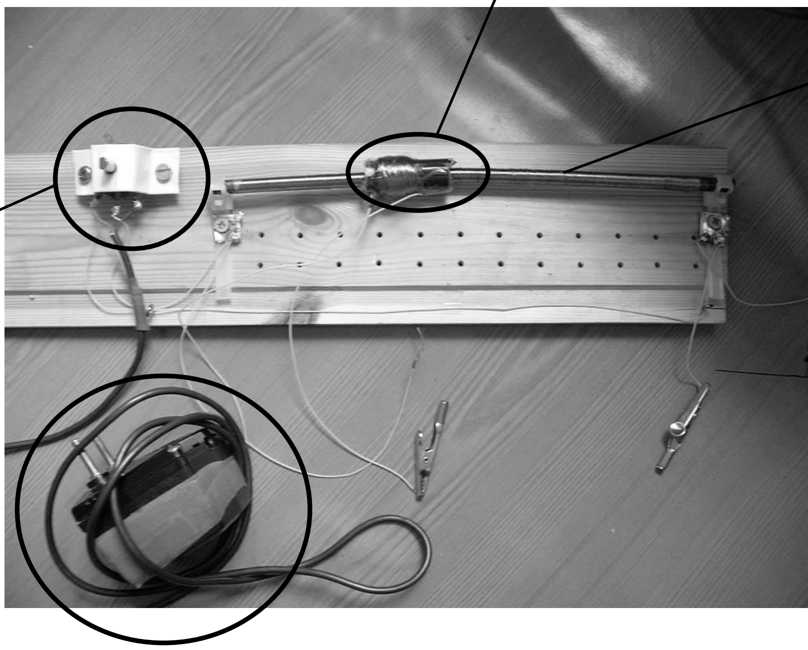


Fig. 1. Final arrangement of the facility developed to carry out test in laboratory on a set of hysteresis rods

Many different problems occur during development and building of the facility. Most part of them have been solved and it allows to carry out some preliminary tests on hysteresis rods but a more accurate analysis is required to interpret behaviour of signal related to rod when voltage applied to solenoid changes. Tests have been performed on two different hysteresis rods. The first rod, named rod-1, has a length of 25 cm and a cross-section of $1\,\mathrm{mm} \times 1\,\mathrm{mm}$ with a square shape. The same rods have been placed on board of MUNIN nanosatellite [2]. Second hysteresis rod, named rod-2, has a length of 13 cm and a cross-section of $2\,\mathrm{mm} \times 2\,\mathrm{mm}$ with a square shape. In the previous part of this experimental activity [1] we verified the magnetizing field in the rod is maximum in the centre of the rod length and minimum in the extremities. Changing the value of current inside of inducing coil (coil-1) hysteresis rod behaviour in different configurations has been evaluated: normal working, approaching to the saturation and saturation. Effect of the relative position between hysteresis rod and Earth magnetic field direction has been also evaluated in all working conditions of the facility. In [1] an analytical representation of signal obtained using coil-2 when hysteresis rod is arranged inside of the solenoid has been obtained. This relation has been calculated on the basis of theoretical considerations for two simple models of the hysteresis but it seems to approximate real signal shape only for values of current which correspond to $H > H_s$ of the rod. To obtain simulation of signal in normal working conditions of the rod and approaching to the saturation, this relation has been empirically modified. Comparisons between experimental and numerical results shown a good approximation but several steps in the interpretation of the experimental results are required. In [1] it have been shown results obtained in laboratory for rod-1. In the paper results of tests carried out on hysteresis rod-2 are discussed and faced with previous results. Then experimental results of the tests carried out on both hysteresis rods to evaluate effects of a permanent magnet located at different distances with respect to the rod and in different positions are depicted.

3. RESULTS OF TESTS CARRIED OUT ON THE HYSTERESIS ROD-2

Rod-2 has a length of 13 cm and a section of $2\,\text{mm} \times 2\,\text{mm}$ with a square shape and elongation $p = 46$. For this rod main parameters are not available but it has been manufactured with molybdenum permalloy of the 79NM specification; its composition includes 79% of Ni, 4% of Mo and 17% of Fe. Main parameters of molybdenum permalloy of 4-79 NM sort used for the manufacturing of rod-2 are available in the Table 1 [2].

Results obtained for rod-2 confirm the same behaviour of the rod-1. The shape of the signal is similar but much more irregularities appear and values of amplitude are greater. As for rod-1 tests have been performed on the hysteresis rod-2 changing the value of the current inside the coil-1. A summary of main values is available in Table 2 where V_{coil} is the voltage applied to the coil-1, I_c the current which flows in the solenoid H and B are respectively the magnetic field intensity and magnetic induction flux inside of the coil-1. For voltage values $V_{coil} = 0.5$ V, $V_{coil} = 1$ V and $V_{coil} = 2$ V has been verified that signal shape generated by coil-2 in the oscilloscope without rod inside of the solenoid follows cosine law as theoretically calculated assuming that $I_c = i_0 \sin \omega t$. The shape of signal related at the rod-2 when $V_{coil} = 0.5$ V and $V_{coil} = 18.33$ V is sketched in Fig.2.

Table 1. Parameters of molybdenum permalloy of 4-79 NM sort used for the manufacturing of rod-2 and elongation of rod-2

Composition	Initial magnetic permeability μ_{r_in}	Maximum magnetic permeanility $\mu_{r\_\max}$	Coercitive Field H_c, [A/m]	Saturation flux density B_s, [T]	Saturation Field H_s, [A/m]	Elongation of rod-2 $p = l/d$
79% Ni, 17% Fe, 4% Mo	60000	164000	0.96	0.74	12	46

Table 2. Main values of different configurations for test on the hysteresis rod-2

V_{coil} (V)	i_c (mA)	H_{coil} (A/m)	B_{coil} (T)
0.5	3.73	37.30	$4.7 \cdot 10^{-5}$
1.0	7.46	74.63	$9.3 \cdot 10^{-5}$
2.0	14.90	149.25	$18.7 \cdot 10^{-5}$
18.3	136.6	1366	$1.7 \cdot 10^{-3}$

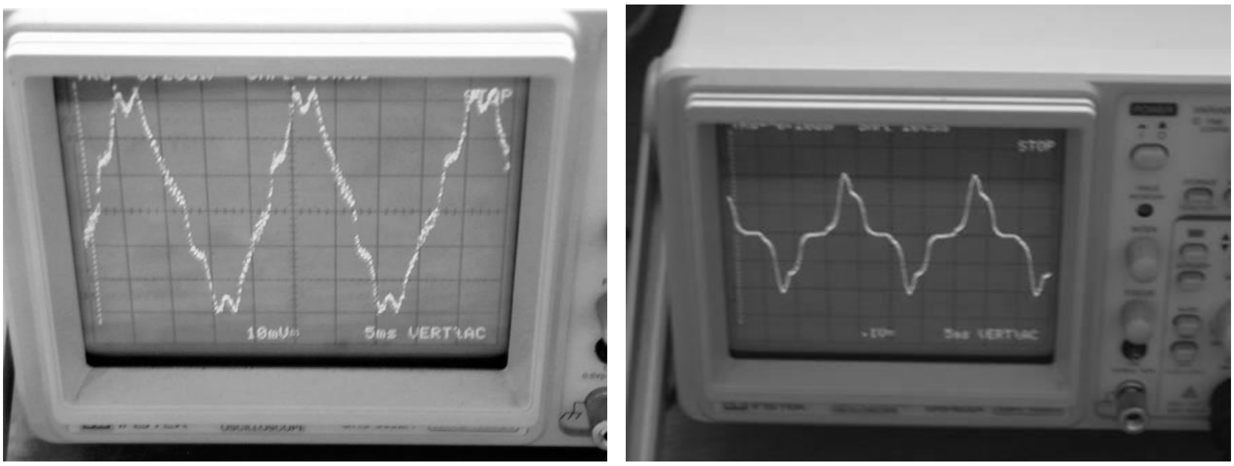


Fig. 2. Results of the tests on the hysteresis rod-2: (left) signal for Vcoil=0.5V; (right) signal obtained for Vcoil=18.33 V

Test in a metallic box showed that these irregularities do not depend by noise and we have a hypothesis about their dependence by characteristics of the rod related to technological heat treatment and manufacturing process. Also in the second case measurements have been replicated in different configurations changing inclination of coil-1 with respect to the Earth magnetic field. Its direction has been established with a compass. Measurements have been obtained for a random inclination (Series-I random B_E), in the perpendicular direction of coil-1 with respect to the Earth magnetic field direction (Series-II perpendicular B_E) and in the same direction of Earth magnetic field (Series III-parallel B_E). Results are collected in Fig.3, Fig.4 and Fig.5 respectively for $V_{coil} = 0.5$ V, 1 V, 18.33 V. In these diagrams one can see the trend of magnetic field inside of rod-2: X axis represents the length of hysteresis rod, Y axis represents experimentally values obtained during tests in laboratory along the rod-2 for induced voltage in coil-2. Diagram shows three sets of measurements with different positions of the facility with respect to the Earth magnetic field direction.

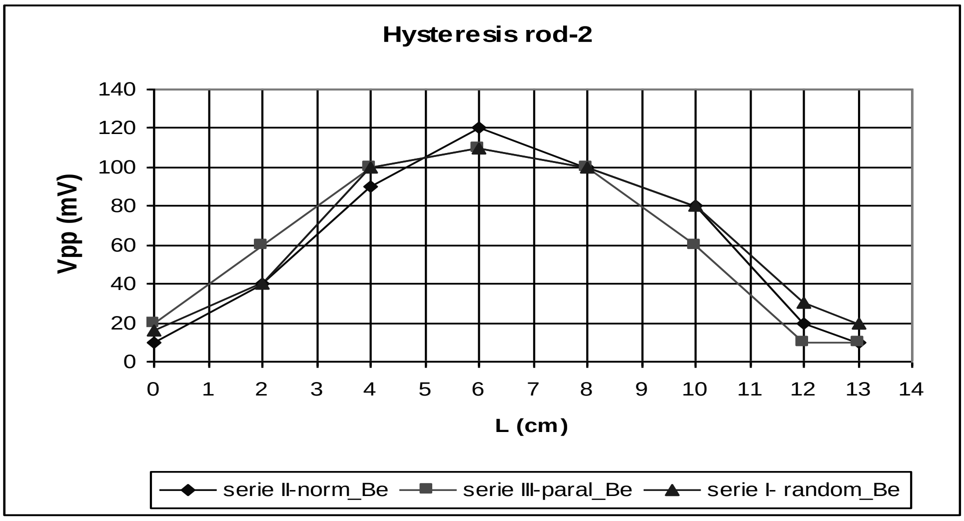


Fig. 3. Three sets of measurements with different positions of the facility with respect to the Earth magnetic field direction. Results for rod-2, Vcoil=0.5 V.

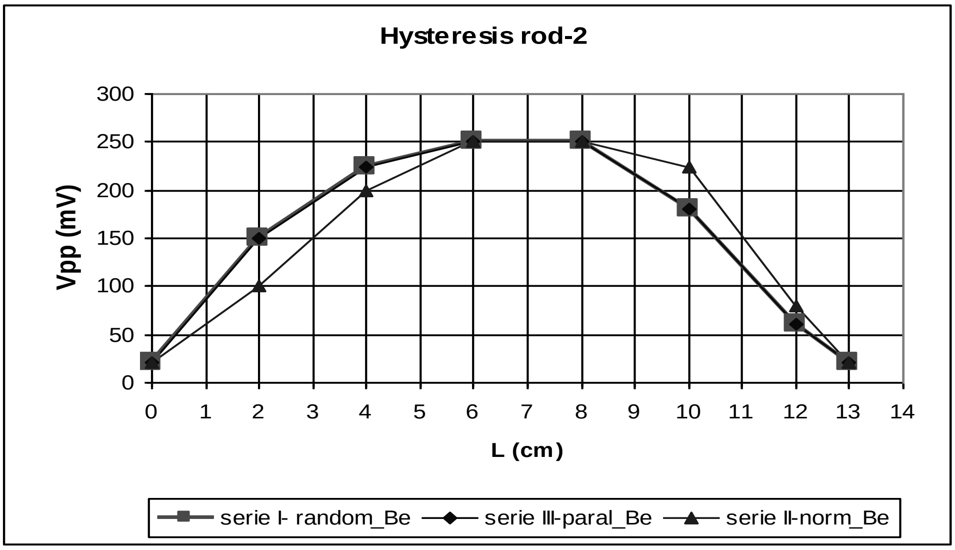


Fig. 4. Thee sets of measurements with different positions of the facility with respect to the Earth magnetic field direction. Results for rod-2 when Vcoil=1V.

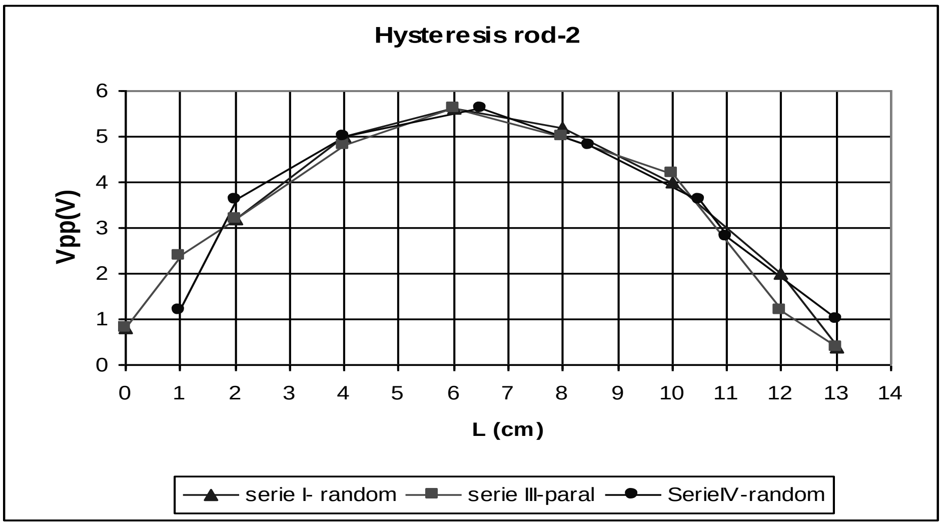


Fig. 5. Three sets of measurements with different positions of the facility with respect to the Earth magnetic field direction. Results for rod-2 when Vcoil=18.3V.

In the centre of the rod one can see that signal has an amplitude which is in several times bigger than signal in the extremities of rods. A comparison with results obtained for rod-1 shows that when $V_{coil} = 0.5$ V the amplitude of signal for the two rods is about the same changing from 20 mV in the extremities until 100-120 mV in the centre of the rod. Rod-1 and rod-2 show the same trend when voltage applied to coil-1 changes with some differences related to the amplitude of the signal measured with the coil-2. When $V_{coil} = 1$ V amplitude is a little bit greater for rod-1 changing in the range 25 mV-300 mV from the extremities until to the centre of rod-1 and in the range 25 mV-250mV for the rod-2. When $V_{coil} = 2$ V the behaviour is confirmed. Signal achieves amplitude about 600 mV in the centre of rod-1 and about 450 mV in the centre of rod-2 (Fig.6). When $V_{coil} = 18.33$ V the behaviour changes: amplitude of signal reaches 5.5V in the centre of rod-2 and about 3.5V in the centre of rod-1.

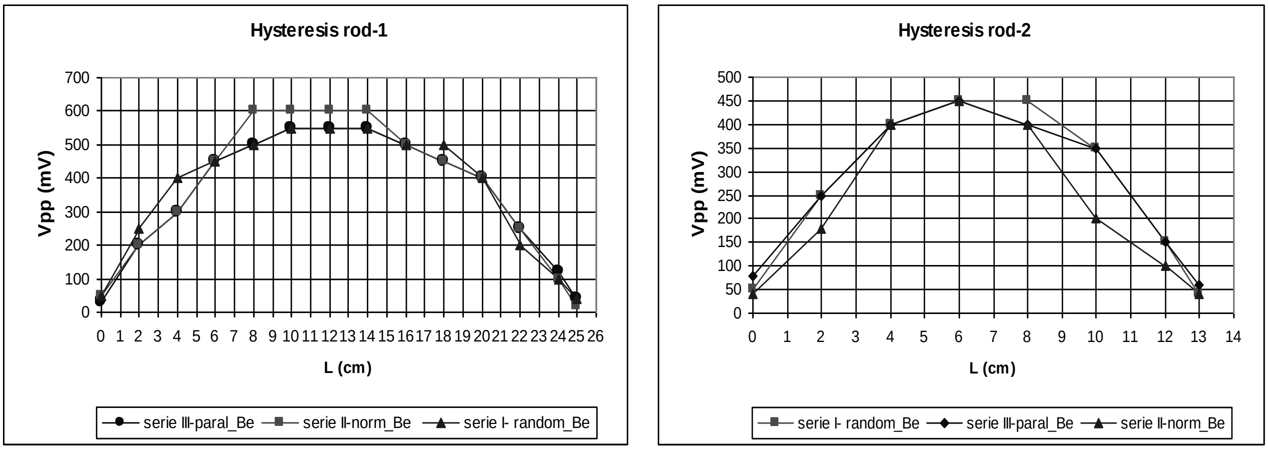


Fig.6. Comparison between results obtained for the rod-1 and rod-2 when Vcoil=2V. 3 set of measurements with different positions of the facility with respect to the Earth magnetic field direction

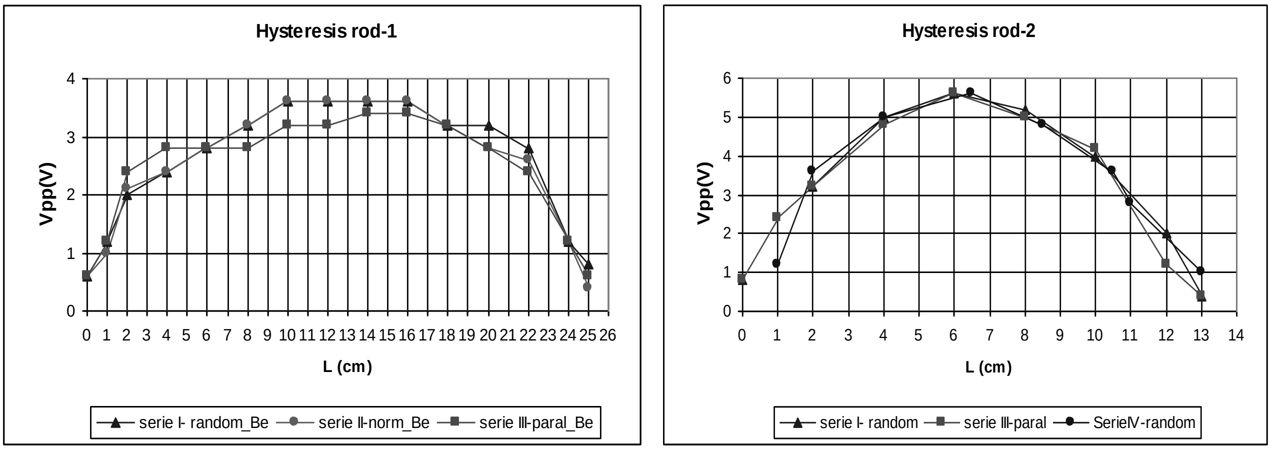


Fig. 7. Comparison between results obtained for the rod-1 and rod-2 when Vcoil=18.33 V. 3 sets of measurements with different positions of the facility with respect to the Earth magnetic field direction

Comparison between curve related to the rod-1 and curve related to the rod-2 when $V_{coil} = 18.33$ V is available in Fig. 7. This testing evidences a different answer of the two rods manufactured with the same magnetically soft material at the same conditions in input perhaps due to the different hysteresis cycle which is affected by many factors, most important of which are heat treatment, fabrication and stress.

4. NON-LINEARITY IN FERROMAGNETIC MATERIALS: PERMEABILITY CURVE AND EMPIRICAL RELATIONS

One of the purposes of the work is to observe Lissajous's pictures [1] generated by two signals at the same frequency and to try to establish the relationship between inclination of Lissajous's pictures which depends by difference of phase of two signals and rod permeability along its length. Nevertheless, the non-linearity of the ferromagnetic material which composes the rod limits the possibility to see a regular ellipse of Lissajous on the screen of oscilloscope. Irregular pictures have been obtained approximating an ellipse. More careful investigation is necessary in this direction: the first step is to describe mathematically the magnetic permeability when field H changes. In Fig. 8 the curve of first magnetization and trend of magnetic permeability for a magnetic material are available. This curve of first magnetization is a function $B = f(H)$ for a material which is magnetized for the first time; it shows the non-linearity of ferromagnetic materials.

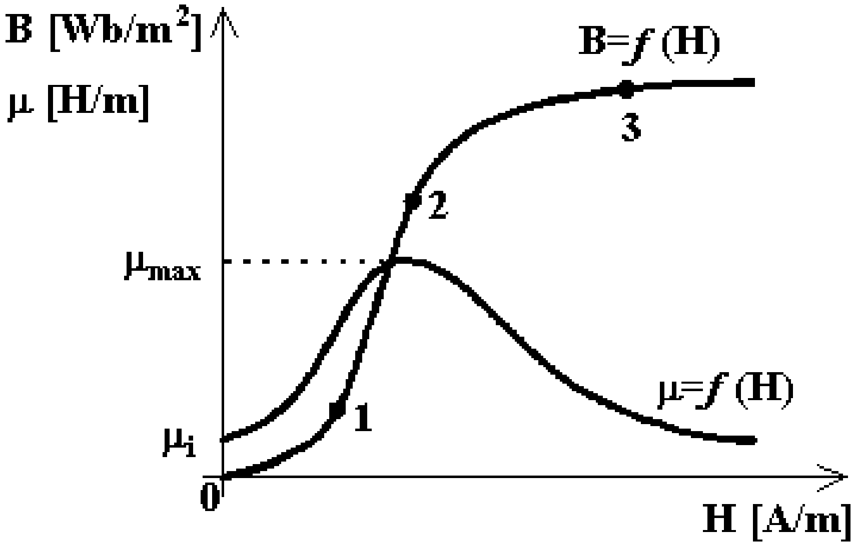


Fig. 8. Curve of first magnetization for a ferromagnetic material

This curve can be described in four parts:

1) 0-1 is typical for small magnetizing fields and it is called "Rayleigh zone". The permeability increases by initial value μ_i and due to Rayleigh we have a formulas which describes a linear behaviour [4]:

$$\mu = \mu_i + \alpha_R H \, . \qquad (3.1)$$

In this formula α_R is the Ryaleigh constant ($\alpha_R = d\mu/dH$) and for material of these rods its value is 350.000 [4]. For most materials permeability curve is in 0-1 a straight line when $B < B_s/10$.

2) 1-2 part is characterized by $\mu_{\max}$ corresponding to knee in the curve of first magnetization of material and by large dB/dH ($dB/dH >> \mu_r$). This area is called "Barkhausen zone" and here domains are instable and change very fast their orientation to rotate in the direction of magnetic field maximum component. This variation is discontinued. On this part we use linear low

$$\mu = \beta + \alpha H \tag{3.2}$$

where parameters β and α are defined through the values of $\mu_{\max}$, H_c and $H_{\max}$ is an external field when magnetization μ has maximum $\mu_{\max}$.

3) 2-3 is the part where the magnetizing field increases and μ decreases; here there is a smaller slope and $dB/dH \approx \mu_r$. This part of curve is described by following relation for μ [4] known as Frolich-Kennelly relation:

$$\frac{1}{\mu} = a + bH \tag{3.3}$$

where for material $a = 0.075 \cdot 10^{-4}$ (this parameter depends on initial permeability) and $b = d(1/\mu)/dH = 1/B_s = 1/8570$ [1/Oe] which corresponds to $1.4 \cdot 10^{-6}$ m/A. For rod-1 $B_s = 0.74$ T it means $b = 1.697 \cdot 10^{-6}$ m/A and $a = 4 \cdot 10^{-5}$. This relation is very useful because shows a linear relation between permeability ($1/\mu$) and field H. In [4] it is available also the following empirical relation (by Kennelly) which should be used for highest fields:

$$\frac{1}{\mu - 1} = a' + b'H\ . \tag{3.4}$$

This relation can be used to determinate B_s.

4) saturation, in this part induction B is about constant and μ it is inclined to value of the initial magnetic permeability.

All empirical relations given imply that curve relating μ approach saturation linearly.

When we place a rod inside of the solenoid the consequence of the permeability is to introduce in this solenoid some currents whose effect is similar to the effect of a current with intensity i which flows into n coils along the solenoid. There is the following relation for this current [5]:

$$in = (\mu_r - 1) n_s i_c \tag{3.5}$$

where n_s is the number of coils for unity of length of the solenoid (N_1/L_1) and μ_r is the relative permeability of material. We assume that $n = n_s$ then the current is

$$i_M = (\mu_r - 1)i_c \tag{3.6}$$

and it is called magnetizing current. This current can be considered as a current which flows in perpendicular coils to the direction of field in the solenoid; it produces a magnetic moment for unity of length of the solenoid:

$$\mathbf{m} = n_s i_M S_1 \mathbf{n}\,. \tag{3.7}$$

Volume of material which presents this moment is $S_1 l$ (l is the unity of length of the solenoid). Magnetic moment for unity of volume is

$$\mathbf{M} = n_s i_M \mathbf{n}\,. \tag{3.8}$$

It is called magnetization vector. This vector allows us to write function $\mathbf{B} = f(\mathbf{H})$ in the form

$$\mathbf{B}(\mathbf{H}) = \mu_0(\mathbf{H} + \mathbf{M}) \tag{3.9}$$

5. EFFECT OF THE FIELD OF A PERMANENT MAGNET ON HYSTERESIS RODS: THEORETICAL ANALYSIS

Consider configuration permanent magnet–hysteresis rod. We suppose magnet has axis of symmetry and its moment is align this axis. Permanent magnet field influences on the rod and there is possible displacement of working point of rod and loses in effectiveness of rod's work. If we want to reduce this effect we have to place rod in an equatorial plane of magnet (passes through geometrical centre of magnet and perpendicular its axis of symmetry) or in parallel plane.

We want to get formula for H_τ component of vector **H** permanent magnet field intensity along the rod. Next symbols are used (Fig. 9)

O – centre of magnet;
P – point of rod in which we analyse field component;
OH (l_S)– perpendicular to rod's projection on the equatorial plane of magnet;
HS (s) – distance between rod and equatorial plane of permanent magnet;
l_t – distance SP.

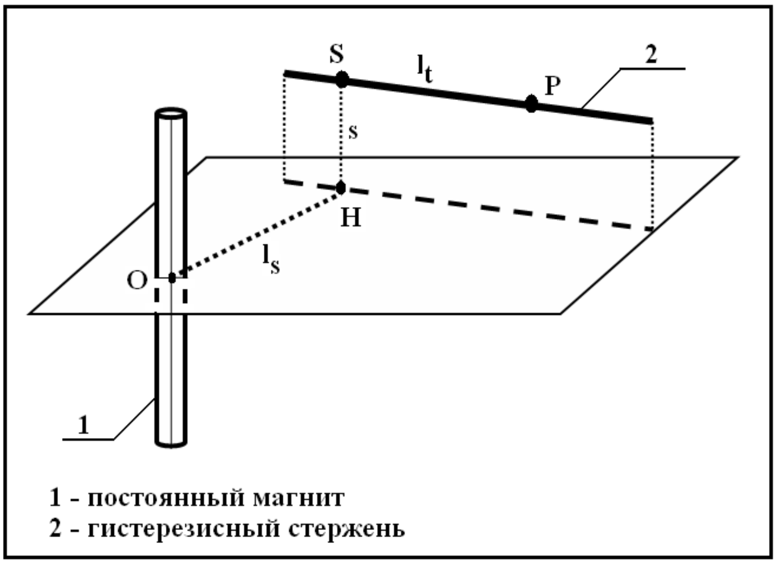


Fig. 9. Placement of hysteresis rod and permanent magnet (1 – permanent magnet, 2 – hysteresis rod)

It is important to say that field component has different signs on the right and left sides from S. We use conception ferromagnetic materials consists of microscopic domains, magnetic domains. Magnetic field are calculated with known formula

$$\mathbf{H} = \frac{3(\mathbf{m},\mathbf{r})}{r^5}\mathbf{r} - \frac{\mathbf{m}}{r^3} \tag{4.1}$$

where r is radius-vector of concerned point P from center of magnet O. Magnitude of magnetic field component alogn rod is

$$H_\tau = \frac{3msl_t}{4\pi(l_S{}^2 + l_t{}^2 + s^2)^{5/2}}. \tag{4.2}$$

Consider a situation then hysteresis rod is in permanent field of magnet and in variable field. Due to field of magnet working point of rod displacements and magnetization is not relative to zero field intensity but relative desplaced value. To calculate the losess of rod work effectiveness we consider parallelogram model of hysteresis. We have two cases.

- Magnetization without displacement (without permanent field) goes on main hysteresis loop to average field intensity. Displacement of working point lead to magnetization goes on a loop which area is equal to area of initial loop and, therefore, in this case there is no losses of effectivness. (Fig. 10).
- Working point displacement leads to losses of effectivness in hysteresis rod work. Loop area decreases (Fig. 11).

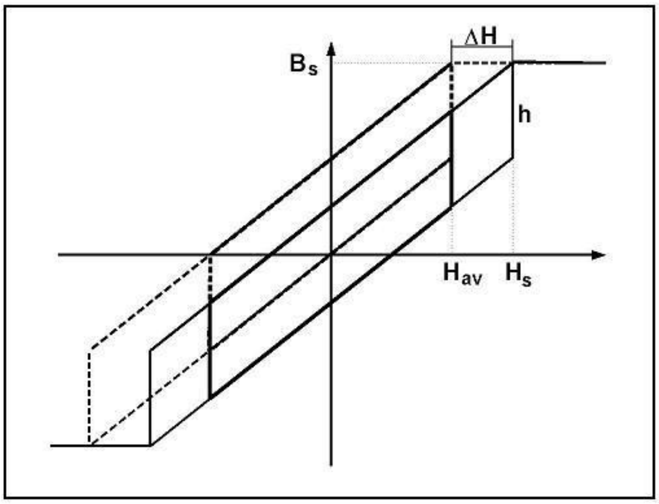


Fig. 10. Working point dicplacement without losses of effectivness

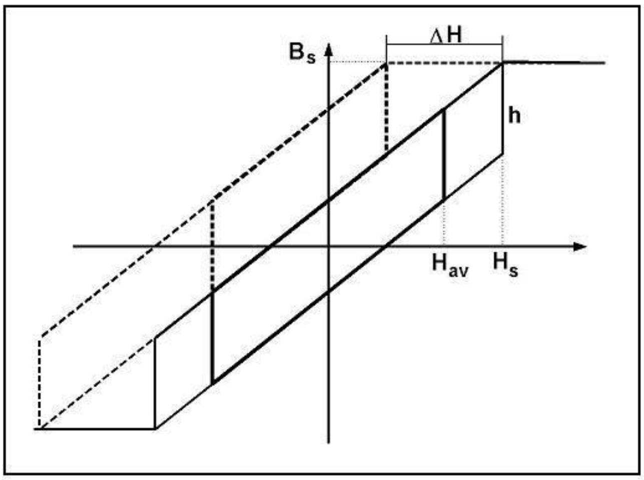


Fig. 11. Working point displacement leads to losses of effectivness

To calculate losess we assume hysteresis loop is parallelogram and permanent field component along rod is the same (it is correct if distance between permanent magnet and rod are bigger than rod's length) or we take some average value of field intensity as working point dicplacement. In this case losess of effictivness depend of relation between three values: satiration intensity H_S, magnetization amplitude H_{av} and working point displacement ΔH. Let $H_{av} = aH_S$ and $\Delta H = bH_S$. Effectivness of rod work is proportional to magnetization loop area ant losess are

$$L(a,b) = 100l(a,b) = 100(1 - \frac{S_{end}}{S_{begin}}) \quad (4.3)$$

where S_{begin} and S_{end} are initial and final hysteresis loop areas correspondingly. Function $l(a,b)$ is defined in area $(0,+\infty)\times[0,+\infty)$, we suppose magnetization amplitude more than 0, otherwise, there is no sense to speak about losess. Function $l(a,b)$ possesses values (Fig. 12)

$$l(a,b)=\begin{cases}1, b\geq a+1\\ 0, \left[\begin{array}{l} b\leq a-1\\ b\leq 1-a\end{array}\right.\\ \dfrac{-a+b+1}{2}, \begin{cases}a-1<b<a+1\\ a\geq 1\end{cases}\\ \dfrac{a+b-1}{2a}, \begin{cases}1-a<b<a+1\\ a<1\end{cases}\end{cases} \tag{4.4}$$

where $a\in(0,+\infty)$ and $b\in[0,+\infty)$.

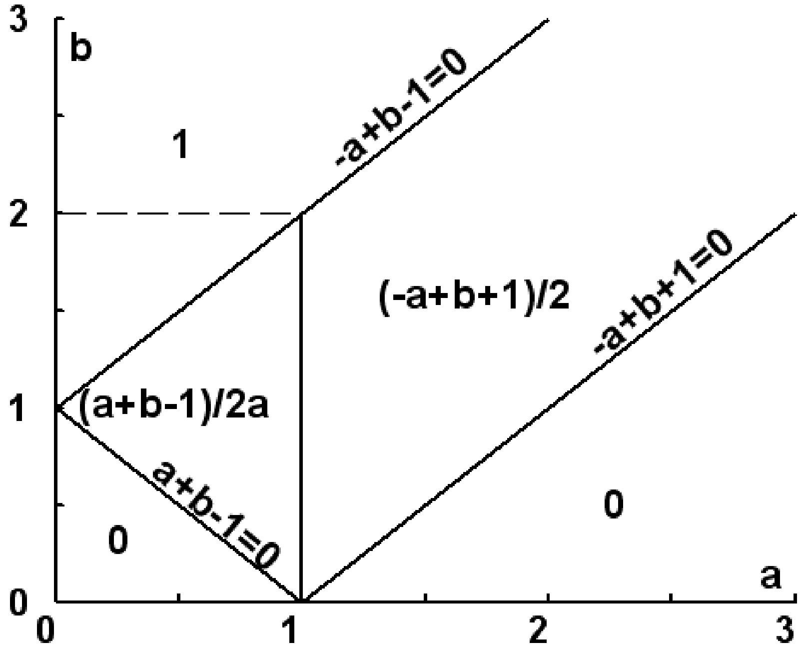


Fig. 12. Function of losses of rod work effectovness under permanent magnet field

6. EFFECT OF THE FIELD OF A PERMANENT MAGNET ON HYSTERESIS RODS: RESULTS OF THE TESTS ON ROD-1

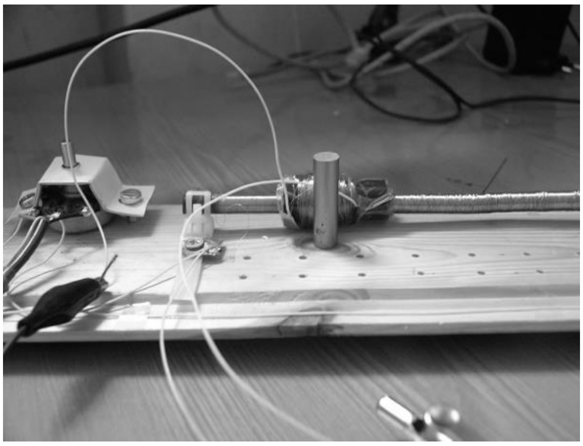
To avoid magnetization of the rods due to the presence of permanent magnet on board of the satellite it is necessary to arrange the rods in the equatorial plane of permanent magnet [6, 7]. Usually to reduce necessary time to stabilize the satellite into orbit one increases number of the rods per axis but arrangement of more parallel rods produce a mutual demagnetizing effect and requires to arrange some of these rods in a plane which is not equatorial plane of the permanent dipole. To evaluate demagnetizing effect (N) of the rods in the design phase one needs simple approximating relations. Different approximating relations for rod demagnetization factor are summarized in [8]. An empirical optimal arrangement criteria for the rods is given in [2, 3]: rod mutual demagnetizing effect can be neglected when the distance among the rods is about 0.3·l where l is the length of rod. In this section we will discuss the results obtained in laboratory about the effect of a permanent magnet on the hysteresis rods. To evaluate this effect different configurations have been employed. Measurements have been carried out changing inclination of the facility with respect to the Earth magnetic field as in the previous measurements on the rods. Measurements have been obtained for a random inclination (Series-I random B_E), in the perpendicular direction of coil-1 with respect to the Earth magnetic field direction (Series-II normal B_E) and in the same direction of the Earth magnetic field (Series-III parallel B_E). In each of these positions tests have been iterated for different values of voltage applied to the solenoid and changing position of the permanent magnetic with respect to the rod: when permanent magnet is centred with respect to the coil-2 (Fig. 13a), when permanent dipole is located in an advanced position (in the left side) with respect to the coil-2 (Fig.13b) and in the last when permanent magnet is located at right side with respect to the position of the coil-2 during measurements (Fig. 13c).

Permanent magnet used for testing is the same one arranged on board of the TNS-0 nanosatellite successfully launched in orbit from the International space station (ISS) in March 2005. TNS-0 nanosatellite weights about 4.5 kg and its structure is constituted by a cylinder with a diameter of 170 mm and a length of 250 mm [9]. Value of the moment of the permanent magnet is 2.2 A·m^2.

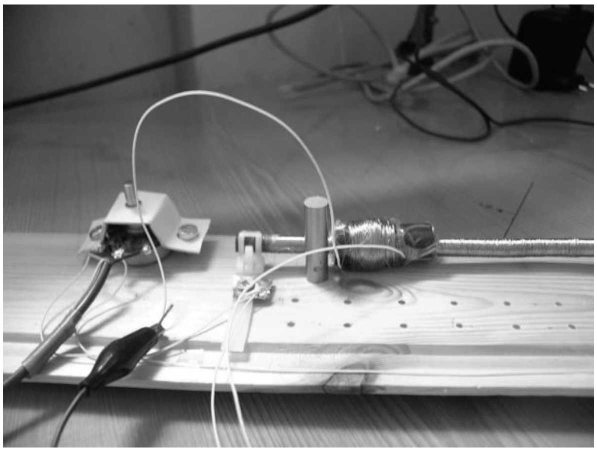
Measurements have been repeated for different distances between permanent dipole and rod. A board to summarize all these configurations is given in Table 3. Sizes of permanent dipole used for testing and configuration for measurements are available in Fig. 14.

Table 3. Main parameters used to change configuration during tests on the hysteresis rods to evaluate the effect of permanent magnet: Vcoil (voltage applied to coil-1), distance between rod and magnet and direction of the facility with respect to the Earth magnetic field

V_{coil} (V)	Distance-l_s (cm)	Direction
0.5	$l_{s\,1}$=1.6 cm	Perpendicular to B_E
1	$l_{s\,2}$=3 cm	Parallel to B_E
2	$l_{s\,3}$= 4.5 cm	Random inclination with respect to B_E



13.a



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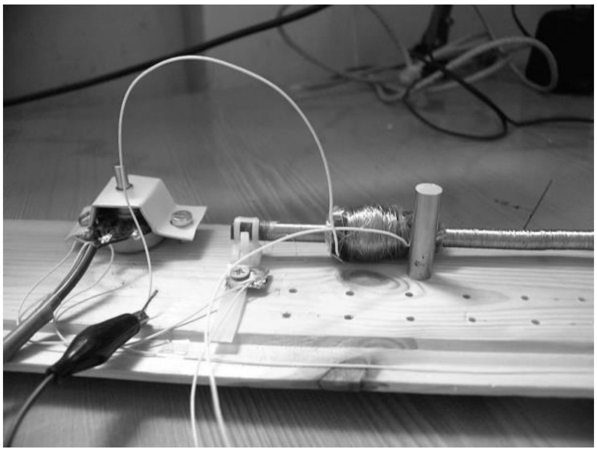

13.c

Fig. 13. Different positions for the permanent magnet with respect to the rod

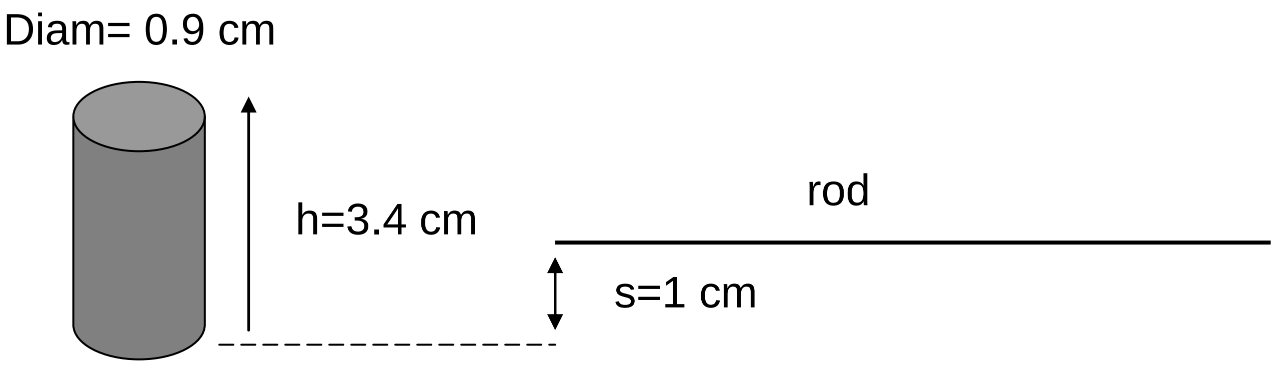

Fig. 14. Configuration for the measurements carried out to evaluate effect of a permanent dipole on the hysteresis rods

Results of measurements carried out on the rod-1 when $V_{coil} = 0.5$ V in the direction of the facility perpendicular to the Earth magnetic field for the configuration of Fig. 13.a are available in Fig. 15. Measurements have been carried out with facility in the direction perpendicular to the geomagnetic field. In the diagram we see that when $l_s = 1.6$ cm the signal measured with coil-2 is pressed at about 20 mV along all rod.

Increasing the distance between dipole and the rod arranged inside the coil-1 effect of dipole decreases as expected. In Fig. 16 and Fig. 17 results carried out when $V_{coil} = 1$ V and $V_{coil} = 2$ V respectively in the direction of the facility perpendicular to the Earth magnetic field with permanent magnet centered with respect to coil-2 are sketched.

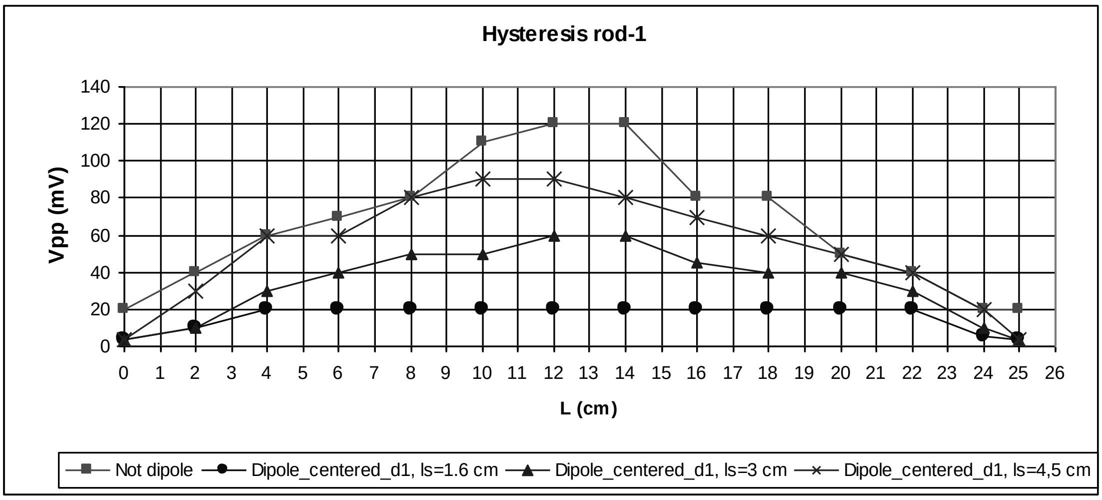

Fig. 15. Permanent dipole located in the middle of coil-2 for different distances between dipole and rod: ls=1,6 cm, ls=3 cm and ls=4.5 cm. Results of the measurements for rod-1, Vcoil=0.5 V

In the Fig. 16 some peaks are visible in the measurements along the rod. Probably this behaviour depends by unintentionally mechanical stress suffered by the rod during different set of measurements when we pushed and extracted rod in the solenoid different times.

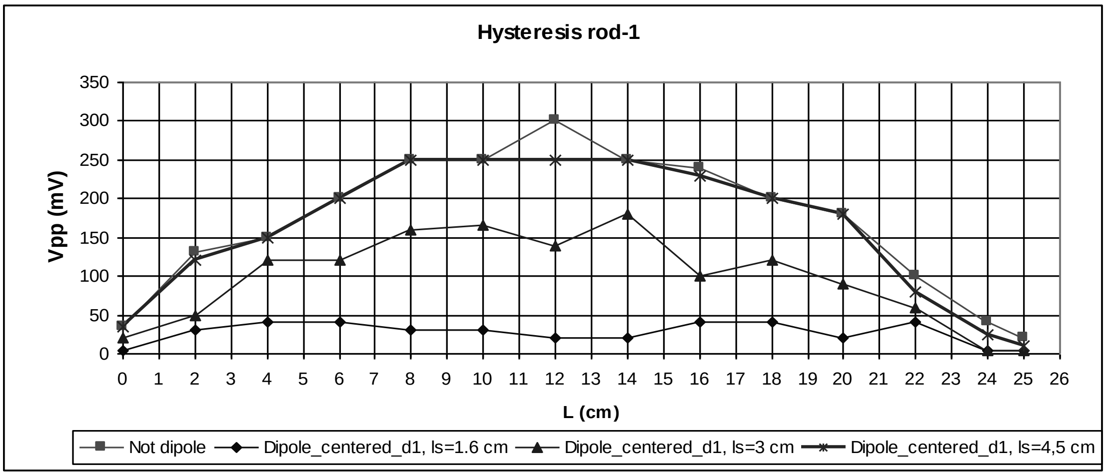

Fig. 16. Permanent dipole located in the middle of coil-2 for different distances between dipole and rod: ls=1,6 cm, ls=3 cm and ls=4.5 cm. Results of the measurements for rod-1, Vcoil=1 V

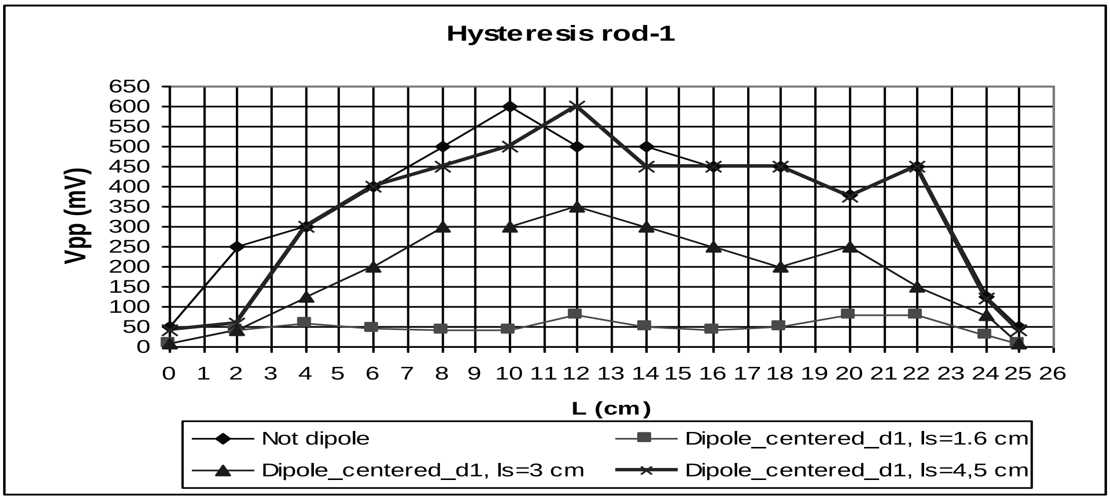

Fig. 17. Permanent dipole located in the middle of coil-2 for different distances between dipole and rod: ls=1,6 cm, ls=3 cm and ls=4.5 cm. Results of the measurements for rod-1, Vcoil=2 V

Comparison among these results shows that in the direction perpendicular to the geomagnetic field when l_s is about 4.5-5 cm effect of permanent magnet can be neglected. Measurements have been replied in the direction parallel to the geomagnetic field changing the value of V_{coil} : results show that in this case to neglect the effect of permanent dipole on the hysteresis rod it is necessary a bigger distance with respect to the previous case about $l_s = 6 - 7$ cm. Tests replied with the facility in a random inclination with respect to the Earth magnetic field confirm this result. In a general direction to neglect the effect of permanent dipole on the rod-1, the dipole has to be located at least 6.5 cm far from the rod. Results of the measurements carried out on the rod-1 when $V_{coil} = 1$ V in the direction of the facility parallel to the Earth magnetic field for the configuration of Fig. 13 (a) are available in Fig. 18.

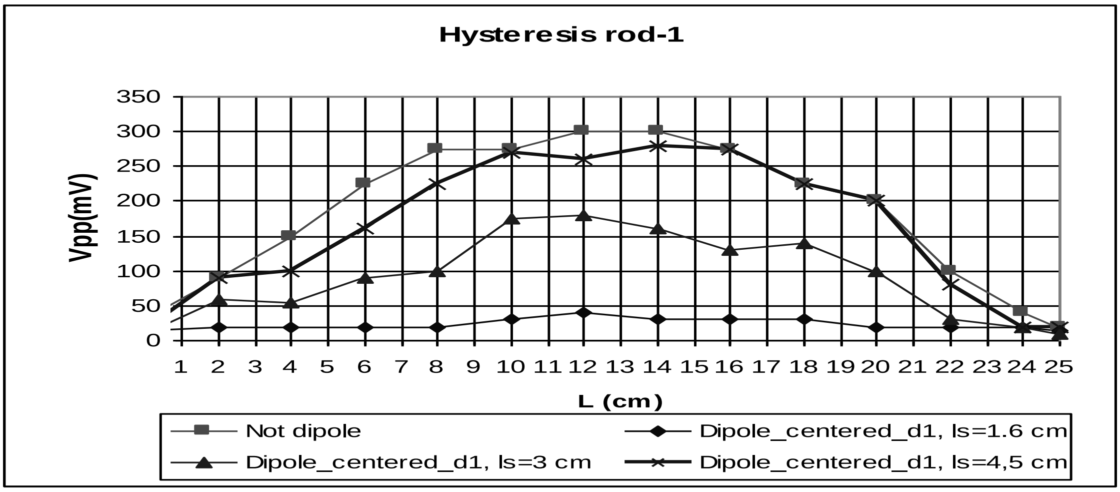

Fig. 18. Permanent dipole located in the middle of coil-2 for different distances between dipole and rod: ls=1,6 cm, ls=3 cm and ls=4.5 cm. Results of the measurements for rod-1, Vcoil=1 V

For easy comparison among results obtained in the different configurations experimental measurements performed for rod-1 when $V_{coil} = 2$ V with the facility located in a random direction with respect to the Earth magnetic field, considering the configuration with the dipole centred with respect to the coil-2 are shown in Fig. 19.

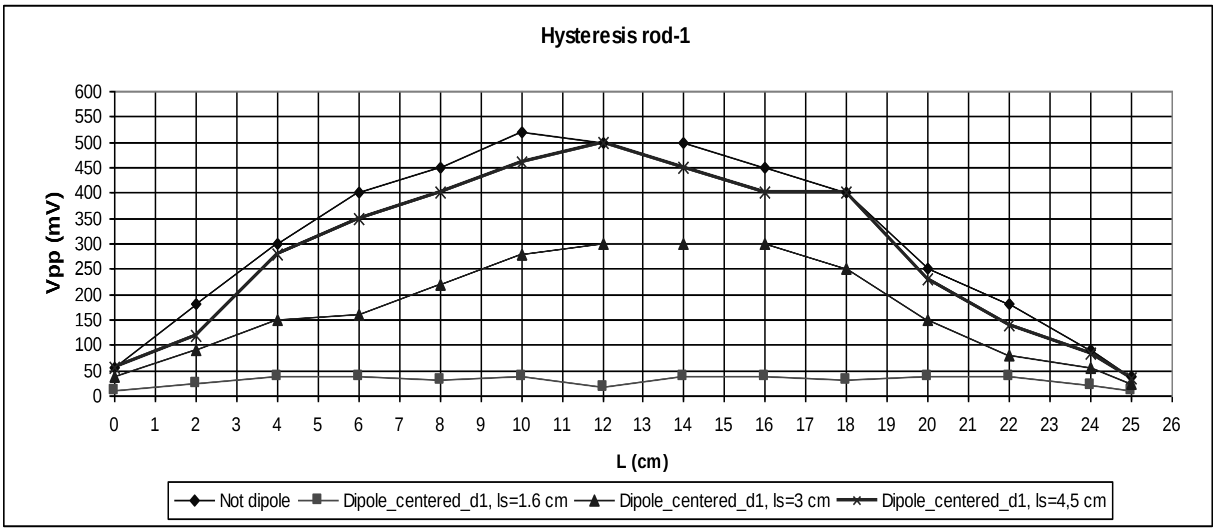

Fig. 19. Permanent dipole located in the middle of coil-2 for different distances between dipole and rod: ls=1,6 cm, ls=3 cm and ls=4.5 cm. Results of the measurements for rod-1, Vcoil=2 V

At this point we carried out a series of measurements to evaluate effect of dipole when its position changes with respect to the rod and coil-2. In Fig. 20 one can see that shape of the signal changes with a translation of peak of the signal versus left. If we rotate the dipole changing the versus of its magnetic moment it is important to notice a different effect on the signal of the rod (Fig. 21).

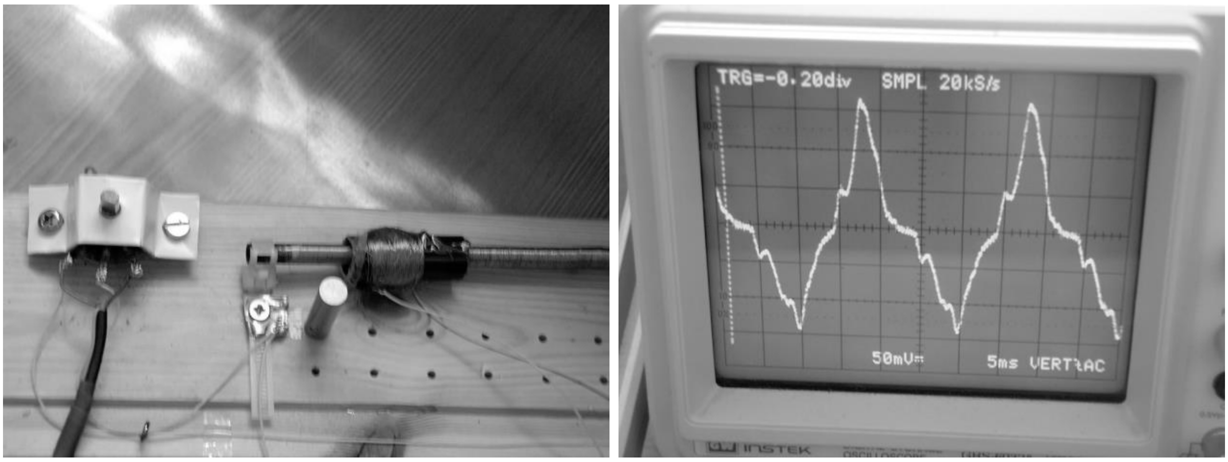

Fig. 20. Effect of the position of dipole with respect to the rod: the shape of signal changes with a translation of peak of the signal vs left

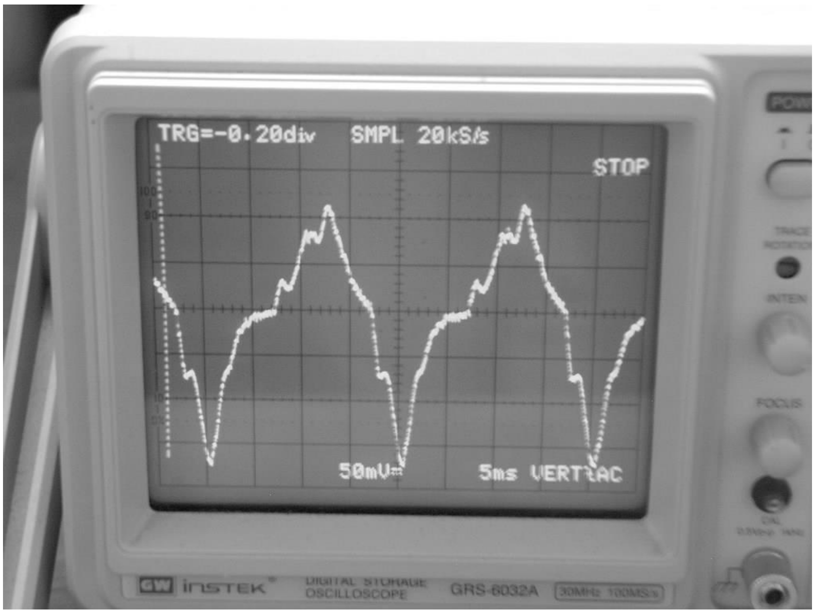

Fig. 21. Changing of the signal generated by rod when dipole is rotated to obtain an opposite versus for its magnetic moment

Comparison of the measurements obtained changing position of dipole when voltage applied to the coil-1 is $V_{coil} = 1$ V with the facility arranged in the perpendicular direction to the geomagnetic field and with the dipole located at 3 cm far from rod are available in Fig. 22. When $l_s = 4.5$ cm in this configuration effect of the dipole can be neglected. Measurements carried out for $V_{coil} = 0.5$ V and $V_{coil} = 2$ V confirm results shown in Fig. 22: effect of dipole does not change in a very significant way when its position changes from the centre to the left side or right side at the same distance from rod.

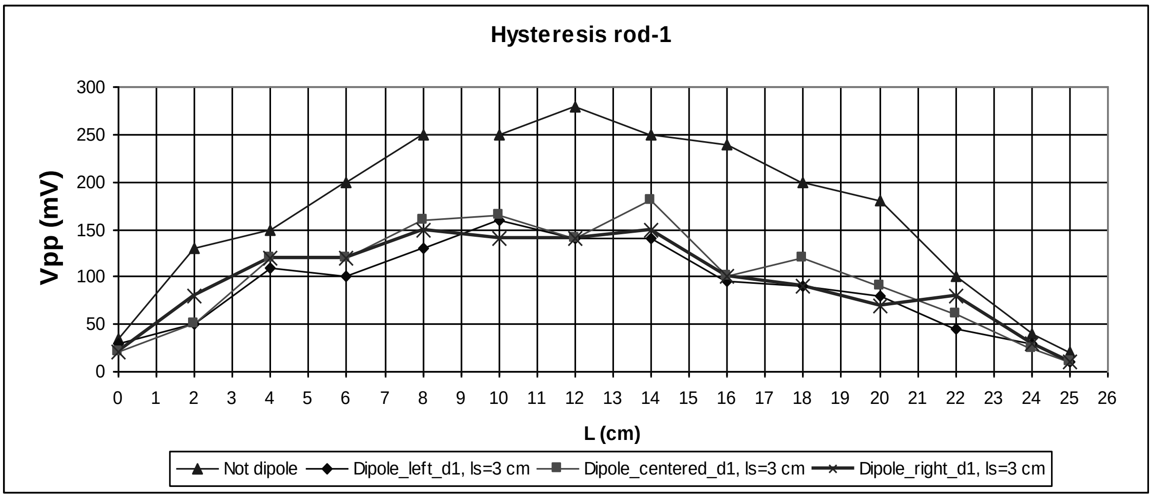

Fig. 22. Permanent dipole located at ls=3 cm in different positions with respect to the rod and coil-2. Results of the measurements for rod-1, Vcoil=1 V

Results obtained when facility is located in a general direction with respect to the magnetic field of the Earth with the dipole located at 3 cm far from rod confirm this result (Fig. 23). Results obtained in the parallel direction of the facility with respect to the magnetic field of the Earth seem to contradict this result (Fig. 24): to interpret and to confirm these results it is necessary to repeat a series of measurements in the parallel direction with respect to the geomagnetic field for this rod. Results and comparison with behaviour of the rod-2 can be useful to analyze these results: effect of a permanent magnet on the rod-2 is the topic of the next section.

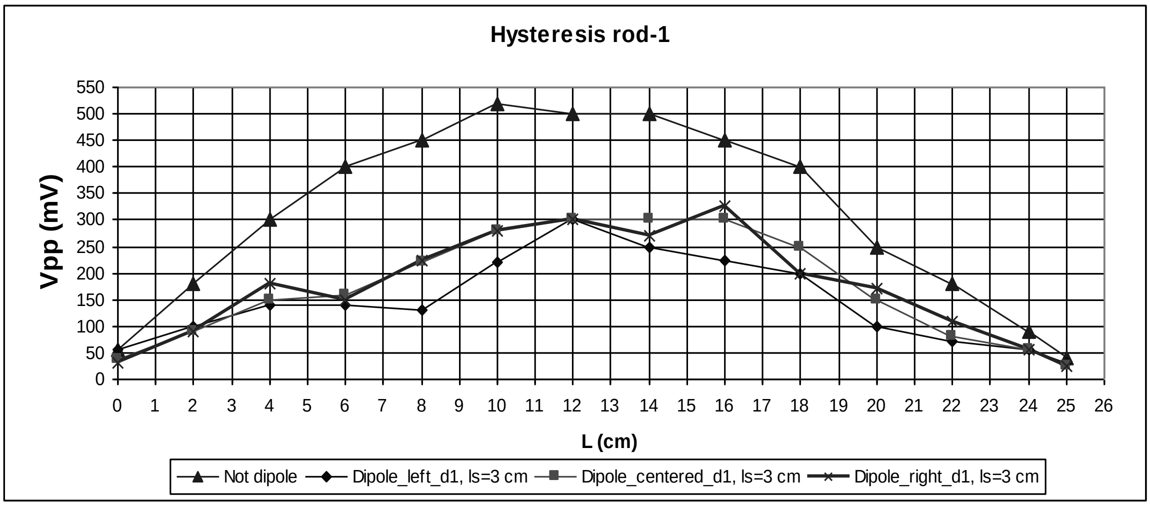

Fig. 23. Permanent dipole located at ls=3 cm in different positions with respect to the rod and coil-2. Results of the measurements for rod-1, when Vcoil=2 V

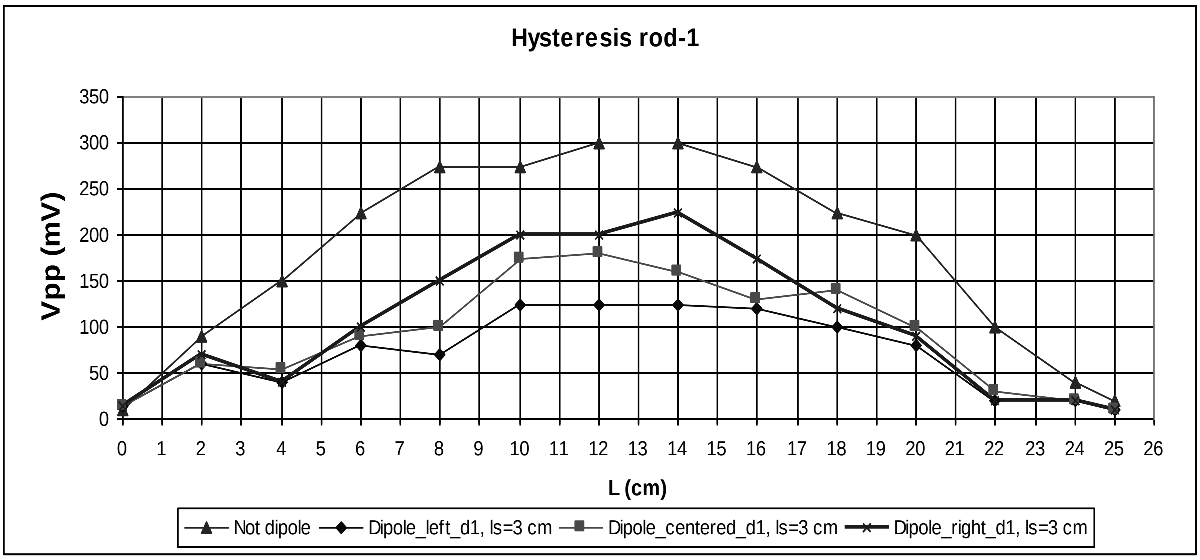

Fig. 24. Permanent dipole located at ls=3 cm in different positions with respect to the rod and coil-2. Results of the measurements for rod-1, Vcoil=1 V

7. EFFECT OF THE FIELD OF A PERMANENT MAGNET ON HYSTERESIS RODS: RESULTS OF THE TESTS ON ROD-2

Measurements have been carried out on the rod-2 following the scheme available in Table 3: changing distance of permanent dipole with respect to the rod-2 for different voltage applied to the coil-1 in different positions of the permanent magnet with respect to the direction of the geomagnetic field and changing location of the dipole with respect to the coil-2. Results obtained for rod-2 show that effect of permanent magnet is smaller then for rod-1: when the distance of the permanent dipole with respect to the rod-2 is about 3 cm effect of field of the magnet can be neglected (Fig. 25).

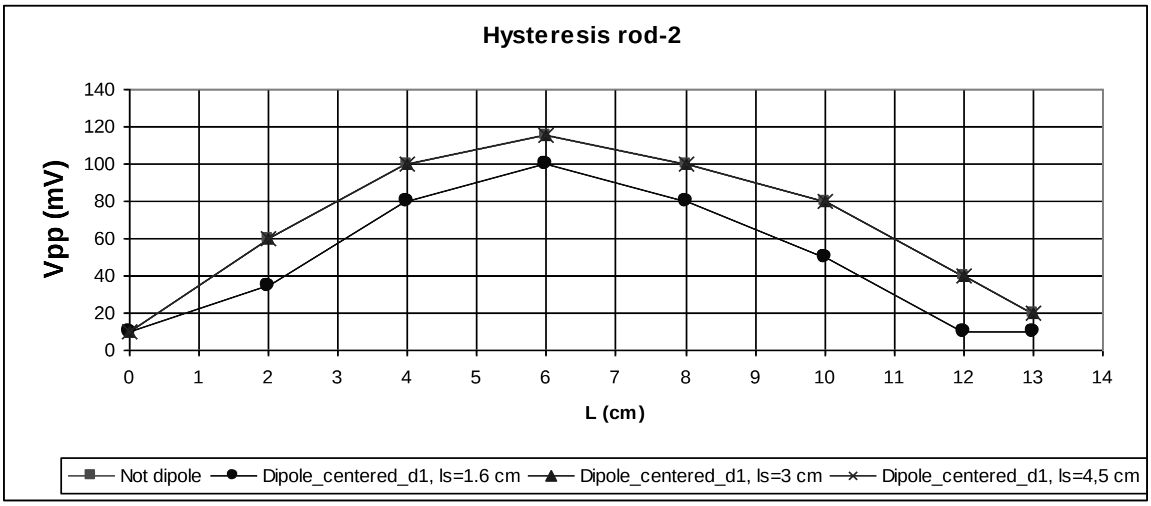

Fig. 25. Permanent dipole located in the middle of coil-2 for different distances between dipole and rod: ls=1,6 cm, ls=3 cm and ls=4.5 cm. Results of the measurements for rod-2, when Vcoil=0.5 V

These results have been confirmed for different voltages applied in different positions of the facility with respect to the geomagnetic field as we see in Fig. 26 where results for $V_{coil} = 1$ V in the perpendicular direction of the facility with respect to the geomagnetic field are shown.

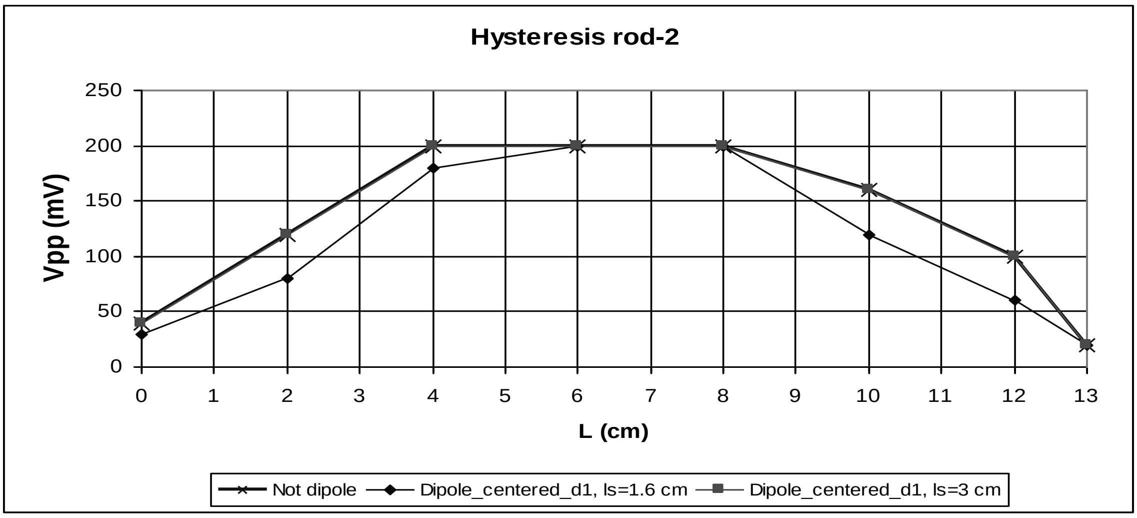

Fig. 26. Permanent dipole located in the middle of coil-2 for different distances between dipole and rod: ls=1,6 cm, ls=3 cm. Results of the measurements for rod-2, Vcoil=1 V

Comparison of the results shown in Fig. 26 for rod-2 with results shown in Fig.16 obtained for rod-1 gives a very different effect of a permanent magnet on two rods used for testing in the laboratory. Same comparison can be done for Fig. 18 and Fig. 27 where results for $V_{coil} = 1$ V in the parallel direction of the facility with respect to the geomagnetic field for rod-1 and rod-2 respectively are shown. In the last also in this case effect of changing of position of the permanent dipole with respect to the coil-2 during the measurements has been evaluated: results for rod-2 when voltage applied to the coil-1 is $V_{coil} = 1$ V with the facility arranged in the perpendicular direction to the geomagnetic field and with the dipole located at 1.6 cm far from the rod are available in Fig. 28. Comparison with diagram of Fig. 22 obtained for rod-1 in the same conditions shows that effect of a changing of the position of the permanent magnet is different and bigger for rod-2.

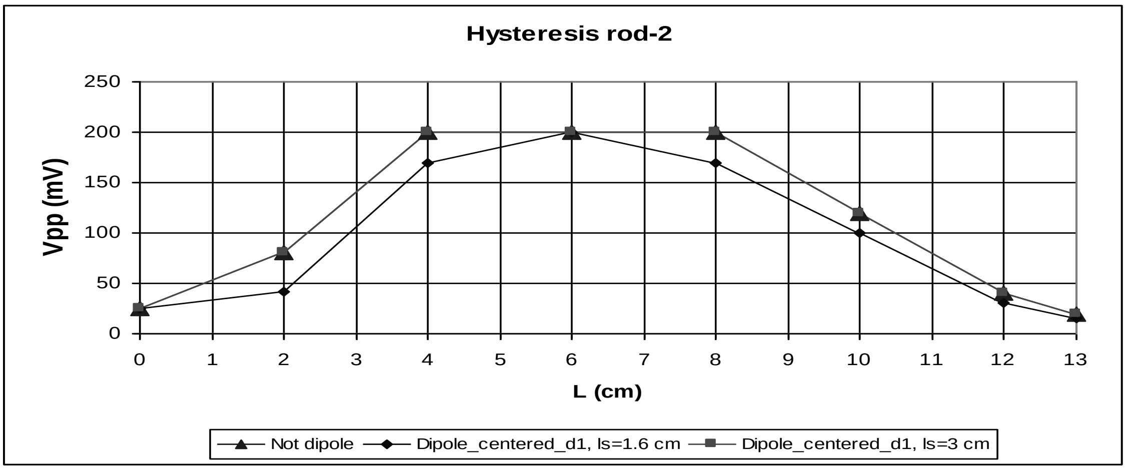

Fig. 27. Permanent dipole located in the middle of coil-2 for different distances between dipole and rod: ls=1,6 cm, ls=3 cm. Results of the measurements for rod-2,Vcoil=1 V

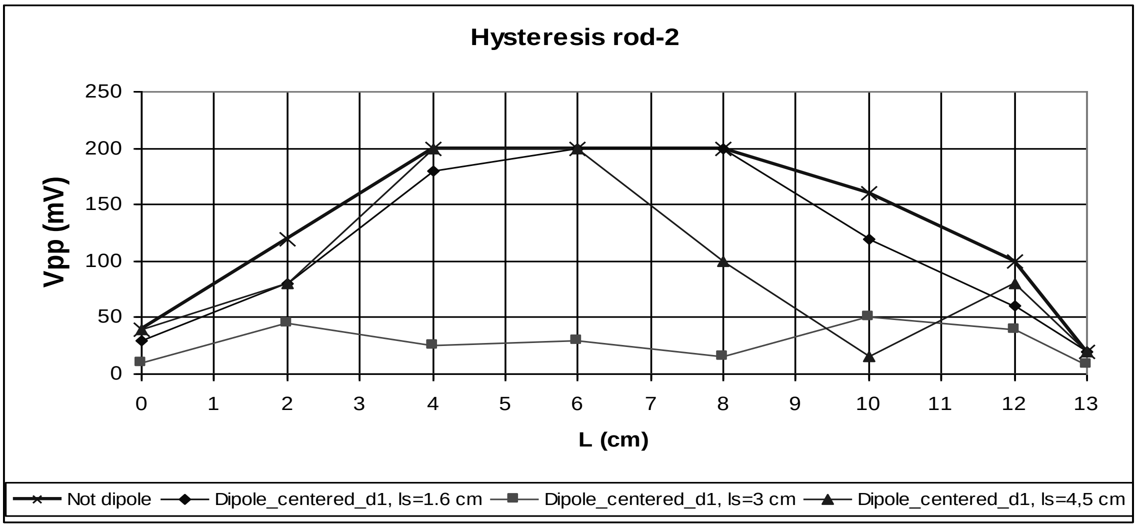

Fig. 28. Permanent dipole located at ls=1.6 cm in different positions with respect to the rod and coil-2. Results of the measurements for rod-2, Vcoil=1 V

These results have been confirmed for different voltages applied to the coil-1 and in different positions of the facility with respect to the direction of geomagnetic field: in Fig. 29 and Fig. 30 some results of the measurements for rod-2 are sketched to allow easy comparison with results of the measurements obtained for the rod-1 available in Fig. 23 and Fig. 24. These results show that effect of a magnet dipole can be very different depending from rod and from its properties. In any case these preliminary tests demonstrated that with this simple facility it is possible to establish the minimum distance necessary to arrange a permanent dipole and a set of rods on board of a small satellite to avoid mutual interferences. This is a very useful result when designers need to choice the arrangement of the dipole and of the rods on board of the satellite in the preliminary phase of design and integration of all subsystems.

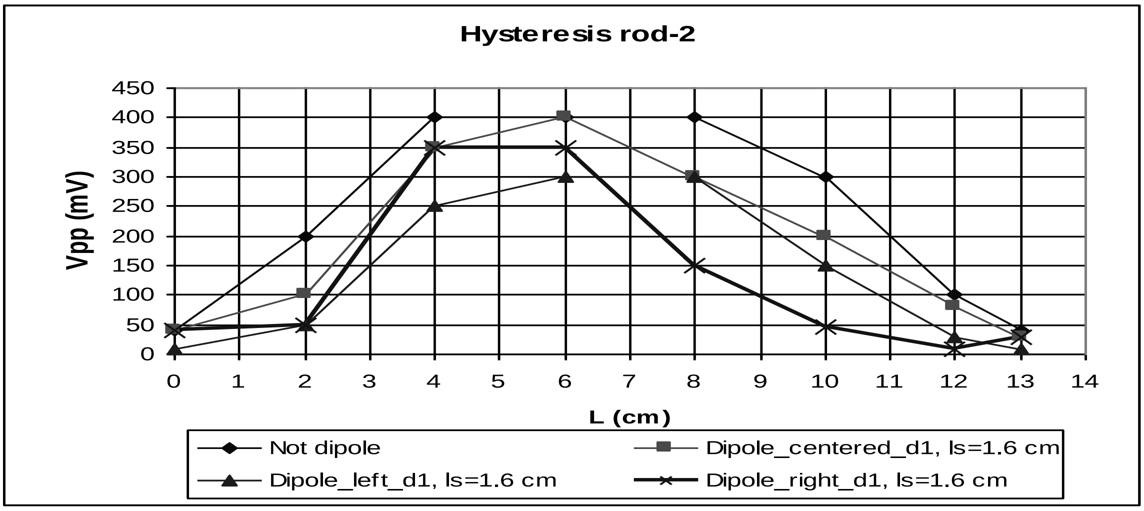

Fig. 29. Permanent dipole located at ls=1.6 cm in different positions with respect to the rod and coil-2. Results of the measurements for rod-1, Vcoil=2 V

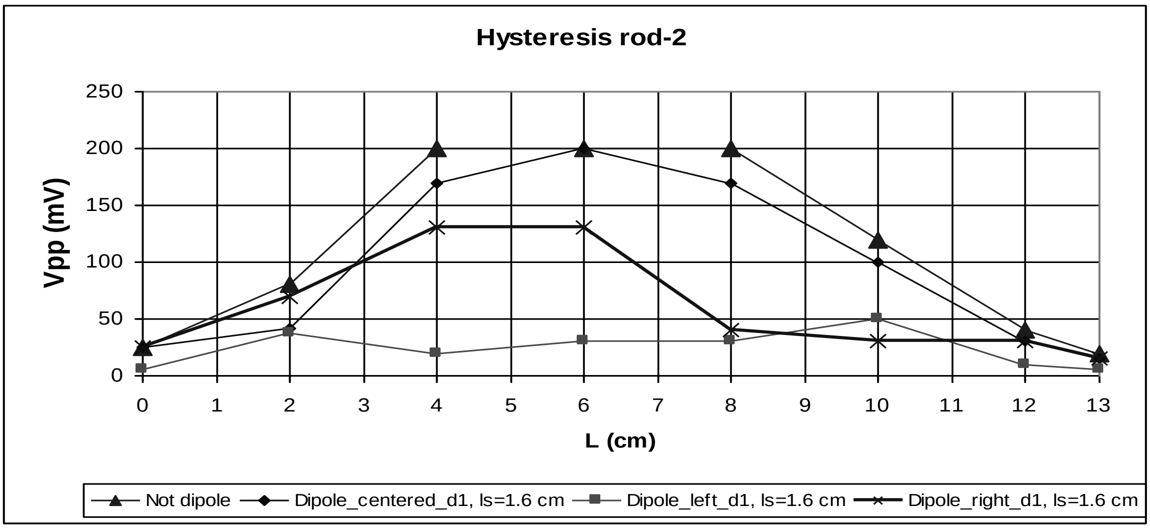

Fig. 30. Permanent dipole located at ls=1.6 cm in different positions with respect to the rod and coil-2. Results of the measurements for rod-2, Vcoil=1 V

8. CONCLUSIONS AND NEXT DEVELOPMENT

The paper presents results of the continuation of the experimental activity described in [1]. In [1] the results of preliminary tests carried out on two different hysteresis rods using a facility opportunely sized and developed have been presented. In particular, tests have been performed to evaluate effect of a permanent magnet on the hysteresis rods when they are arranged in a plane different by equatorial plane of the permanent magnet. Preliminary results showed that this effect depend strongly by the rod and they confirmed that it is possible to employ the developed facility to evaluate in a simple and fast way the minimum necessary distance between permanent dipole and rods to avoid interferences which reduce the rod efficiency on board of a satellite. Next steps are necessary in this experimental activity. It is important to repeat tests on other hysteresis rods for a better and more accurate analysis of the signal obtained in the oscilloscope when voltage applied to the solenoid changes and to confirm behaviour of this signal along the rod. To evaluate effect of a permanent dipole on the hysteresis rods it is necessary to repeat tests in different configurations especially in different planes with respect to the equatorial plane of the permanent magnet because in this preliminary work the position of the rod was fixed. It would be also useful to confirm experimentally that effect of magnet can be neglected when rod is arranged in the equatorial plane of the permanent dipole as it can be demonstrated theoretically. It is useful to use this facility to investigate mutual demagnetizing effect which appears when more parallel rods are arranged on board of the satellite, in order to confirm important experimental result available in [3] which fixes at 0.3 l the minimum necessary distance between two rods to neglect the mutual demagnetization effect using different kind of rods. Another basic goal of the research is to analyze all experimental results in order to try to develop a general modelling of the magnetic permeability of the rod depending by its length. In this direction a first step has been performed describing analytically the magnetic permeability curve when the applied magnetizing field changes.

9. AKNOWLEDGEMENTS

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APPENDIX 1:LIST OF SYMBOLS

V	voltage
V_p	voltage peak (maximum amplitude)
V_{pp}	voltage peak to peak
i	current
p	elongation of rod
m	magnetic dipole intensity
$\mathbf{B}$	magnetic field induction vector
B	magnetic field induction
$\mathbf{H}$	magnetic field intensity vector
H	magnetic field intensity
$\mathbf{M}$	magnetization vector
Φ	magnetic flux
I_c	currant in coil
V_{coil}	voltage in coil
B_{coil}	coil magnetic field induction
H_{coil}	coil magnetic field intensity
B_s	magnetic field induction of saturation
B_r	retentivity
B_E	geomagnetic field induction
H_s	intensity of saturation
H_c	coercitive force
H_E	geomagnetic field intensity
μ_0	magnetic permeability of vacuum
μ_{in}	initial magnetic permeability
$\mu_{\max}$	maximum magnetic permeability
μ_r	relative permeability of material
μ_{r_in}	initial magnetic permeability of rod
$\mu_{r\_\max}$	maximum magnetic permeability of rod
α_R	Ryaleigh constant