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A deformable magnetizable worm in a magnetic field—A prototype of a mobile crawling robot

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Abstract

The paper deals with the deformation and worm-like motion of a magnetizable elastic body in an alternate magnetic field from an experimental and a theoretically point of view. Theoretically (analytically and numerically) calculated results of the body velocity are compared with the experimental data.

Keywords: Magnetic field; Magnetizable media; Locomotion systems; Movement

Biologically inspired robots are the best examples of design in collaboration with nature. The ability to operate in unpredictable environments is an advantage of worm- or snake-like robots. But one of the most important problems in realization of autonomous robots is the power supply. Therefore, using ferrofluids the transfer of energy and information for locomotion can be achieved contact- and wireless by a controlled magnetic field. So, the realization of locomotion using the deformation of magnetizable materials (a magnetic fluid or a magnetizable polymer) in the magnetic field is an actual problem.

The deformation of a surface of a magnetic fluid in a travelling magnetic field is used in pumps. In Refs. [1–3], the theory of a flow of layers of magnetizable fluids in a travelling magnetic field is considered.

It is shown that the travelling magnetic field can create a flux in the fluid layers. This effect can be applied for the realization of locomotion. Compact locomotion devices using the deformation of magnetizable materials in the applied magnetic field is a new interesting problem.

The initiator of a motion is an alternate magnetic field formed by exterior sources (electromagnetic system or motion permanent magnets [4]). In [5], the theoretical study of the behavior of a locomotion system using periodic deformation of a magnetizable polymer is done, when an alternate uniform magnetic field operates. The average velocity of such locomotion system is proportional to the difference of the friction coefficients between the system and the substrate, which depend on the directions of motion. In Ref. [6], we studied experimentally the worm-like motions of the magnetizable elastic body in an alternate magnetic field for small frequency of an electromagnetic system which creates a magnetic field.

In the present paper, the worm-like motions of the two magnetizable elastic bodies (magnetizable worms) with different properties are studied experimentally for large diapason of the electromagnetic system frequency. The prolate bodies from the magnetizable composites (an elastic polymer and solid magnetizable particles) are used. The analytical estimation and numerical calculation of the deformation of the elastic body in an applied magnetic field and the velocity of the body are carried out. The deformable magnetizable worm in a magnetic field is a prototype of mobile crawling robots. Such devices have

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some characteristics, that allow for their use in medicine and biology. For example, it does not contain solid details contacting with a surrounding medium and it moves autonomously.

In our experiments, we used cylindrically-shaped (with circler cross-section) bodies located in a cylindrical (with circuler cross-section) channel. The channel diameter d exceeds that d_w of the body. We denote the length body as l_w. The bodies consist of magnetizable polymers. We studied two examples with different Young's modulus E and different geometrical parameters.

The magnetic field is created by coils. The axes of coils are in the horizontal plane, L is the distance between the axes of the coils and I is the current in the coils (see Fig. 1). The coils are placed at the left- and right-hand sides of the channel. Magnetic field is created by three coils simultaneously (for example, coils number 6–8 in Fig. 1), the axis of the middle coil is the symmetry axis of the magnetic field. Periodically, the left coil (for example, the coil number 6) is switched off and the next coil (the coil number 9) is switched on, n is the number of switches per second (further we name n as the frequency), so $T = 1/n$is the time period between change-over of the coils. Currents flowing through the coils are unidirectional. Such electromagnetic systems form a "travelling" magnetic field **H**, which is a complex function of x, y, z, t (x is the coordinate along the channel, z is parallel to axis of the coils, y is orthogonal to x and z). It is shown experimentally that in such periodic magnetic field the cylindrical magnetizable elastic body moves along the channel. The direction of the body motion is opposite to the direction of the travelling magnetic field. A cycle of body deformation by the travelling magnetic field is the process when the travelling magnetic field covers the body (see Fig. 2). At the end and beginning of this process the body is not deformed.

The body velocity depends on the geometrical shape of the deformed body and that of the channel. If n is small enough and the body inertia does not affect the body velocity, the following formula is valid:

$$v = w/t_c, \quad t_c = (k_s + 3)T, \quad w_s = k_s(l_s - L). \tag{1}$$

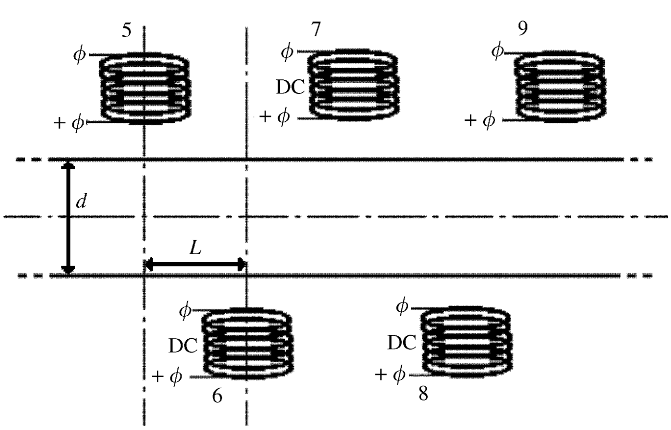

Fig. 1. Arrangement of coils of the electromagnetic system.

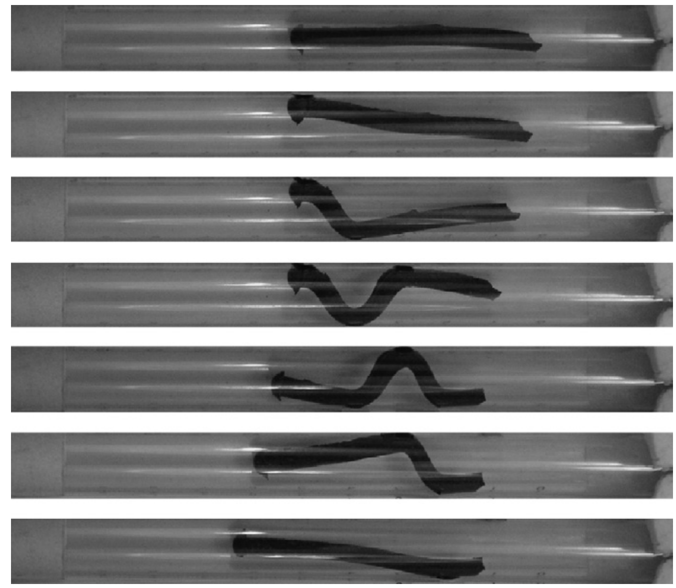

Fig. 2. Magnetizable elastic body (sample 1) in the travelling magnetic field.

Here l_s is the segment length (a segment is a part of the deformed body between two neighboring coils), k_s is the number of segments (k_s is equal to the integral part of the ratio l_w/l_c) and t_c is the time of a cycle. The length of the segment may be determined under assumption about its form. A segment form is determined by the elastic and magnetic properties of the body material, and the value of the magnetic field. The problem of determination of the body form is very complex.

In the first experiment, $I = 3$ A, $L = 10$ mm, $d = 11$ mm, and we study the sample 1: the polymer with Young's modulus $E = 5 \times 10^4$ Pa, $l_w = 48$ mm, $d_w = 4$ mm. The frequency n changes from 2 to 50 s^{-1} in this experiment. Here, we consider three assumptions about the segment form.

Let us assume that the segment of the body between the two coils has a *sinusoidal form*. In this case, the equation of the central line of the segment is as follows:

$$y_S = 0.5(d - d_w)\sin(\pi x/L). \tag{2}$$

For parameters $L = 10$ mm, $d = 11$ mm, $l_w = 48$ mm, $d_w = 4$ mm the length of the sinusoidal segment is calculated as $l_s = 12.6$ mm, $k_s = 4$. The analytical estimation of the body velocity is determined as $v = 1.46n$ mm/s (see Fig. 3, line 1).

Let us assume that the form of the segment of the body between the two coils is determined by the model of the *elastic beam* without extension (the bending moment is due to the magnetic forces, assuming that magnetic forces act on the ends of the segment). In this case, the equation of the central line of the segment is as follows:

$$y_E = ax^3 + bx^2 + d_w/2. \tag{3}$$

Here $a = -2(d - d_w)/L^3$, $b = 3(d - d_w)/L^2$.

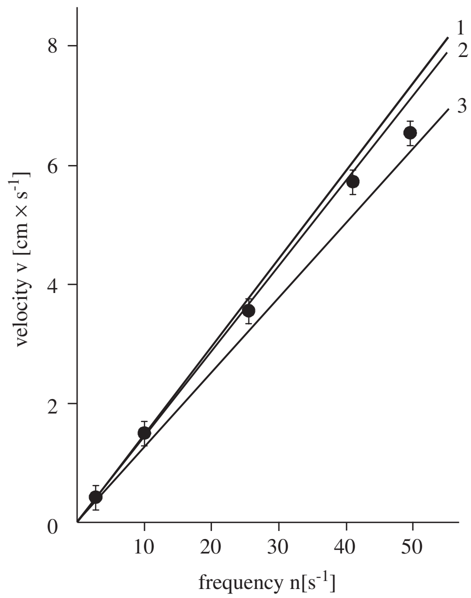

Fig. 3. Body velocity $v = v(n)$ (the first experiment, sample 1).

For this assumption and for parameters as above, the length of the segment is equal to 12.5 mm, $k_s = 4$ and the analytical estimation of the body velocity is $v = 1.43n$ mm/s (see Fig. 3, line 2).

Let us assume that the form of the body segment between two coils is a *straight line*. The equation of the central line of the segment is as follows:

$$y_R = (d - d_w)x/L. \tag{4}$$

In this case for parameters as above, the length of the segment is 12.2 mm, $k_s = 4$ and the analytical estimation of the body velocity is $v = 1.26n$ mm/s (see Fig. 3, line 3).

The theoretical dependencies of the body velocity on n in these cases and experimental data are shown in Fig. 3. From Fig. 3 we can see that for $n < 50\,\mathrm{s}^{-1}$, the theoretical result (line 2: the body form is determined by the model of elastic beam) matches with the experimental results for sample 1. The maximal obtained body velocity is 6.45 cm/s.

In the second experiment, $I = 4.6$ A, $L = 10$ mm, $d = 11$ mm and we study sample 1. The frequency n changes from 5 to $10^3\,\mathrm{s}^{-1}$in this experiment. Here, for the theoretical estimation, we use the model of the elastic beam and obtain that $v = 0.108\,n$ mm/s. The experimental dependency of the body velocity on n is shown in Fig. 4. From Fig. 4 we can see that for $n < 100\,\mathrm{s}^{-1}$, the theoretical result (the body form is determined by the model of elastic beam) matches the experimental data for sample 1. The maximal obtained body velocity is 7.89 cm/s for $n = 100\,\mathrm{s}^{-1}$. For $n > 950\,\mathrm{s}^{-1}$, sample 1 does not move.

In the third experiment, $I = 4.6$ A, $L = 10$ mm, $d = 10$ mm, and we study the sample 2: the polymer with Young's modulus $E = 2.2 \times 10^4$ Pa, $l_w = 75$ mm, $d_w = 4.5$ mm. The frequency n changes from 5 to $10^3\,\mathrm{s}^{-1}$. Here for theoretical estimation, we use the model of elastic beam and obtain that $v = 0.105n$ mm/s. From Fig. 4 we can see that for $n < 100\,\mathrm{s}^{-1}$, the theoretical result matches the experimental data also for sample 2. The maximal obtained body velocity is 10 cm/s for $n = 250\,\mathrm{s}^{-1}$. For $n > 750\,\mathrm{s}^{-1}$, sample 2 does not move.

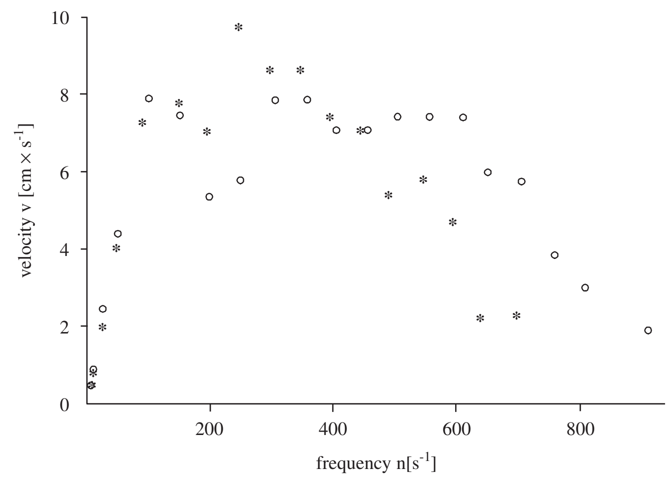

Fig. 4. Body velocity $v = v(n)$ (the second experiment, "circles" = sample 1, the third experiment, "stars" = sample 2).

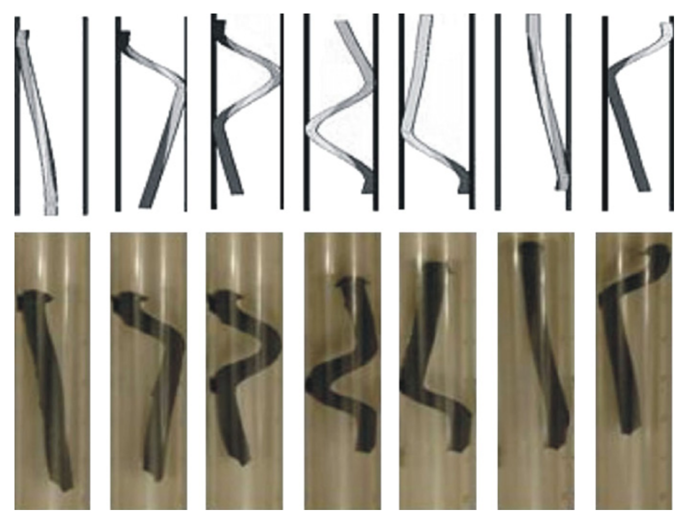

Fig. 5. Analysis of the locomotion using the finite-element-method.

The evaluation of the results, mentioned above, approved their correctness by using the finite-element-method (see Fig. 5).

It is shown experimentally that in the specially structured periodic travelling magnetic field, the cylindrical magnetizable elastic body moves along the channel. The direction of the body motion is opposite to the direction of the travelling magnetic field. The maximal obtained body velocity is 10 cm/s for $n = 250\,\mathrm{s}^{-1}$ (the sample 2). For the frequency $n < 100\,\mathrm{s}^{-1}$, the theoretical (analytical and numerical) estimations of the velocity of the body agree with the experimental data. The creation of active biologically inspired locomotion systems and new principle for a passive motion is thus possible using the deformation of deformable magnetizable media in controlled magnetic fields.

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