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50. Internationales Wissenschaftliches Kolloquium
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K. Zimmermann / I. Zeidis / V. Naletova / V. Turkov / G. Stepanov

Behavior of a Magnetizable Worm in a Magnetic Field

ABSTRACT

The motion of a magnetizable elastic body in an alternate magnetic field is experimentally studied. The body of a cylindrical form (worm) is located in a cylindrical channel. By an electromagnetic system a traveling magnetic field is generated. The agreement experimental data with theoretical results is obtained.

INTRODACTION

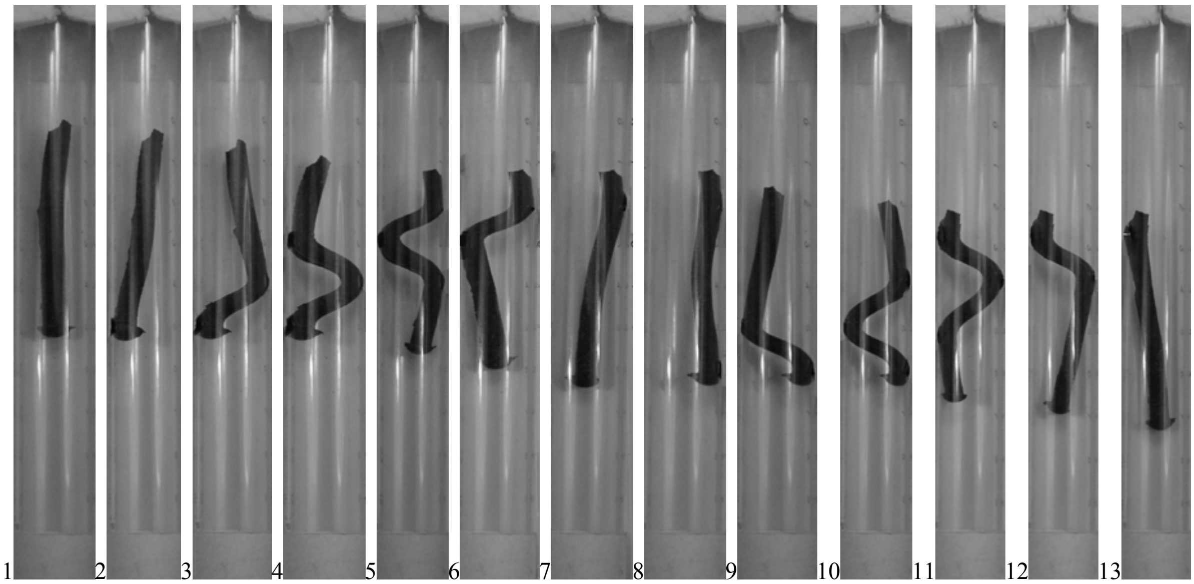
The realization of locomotion systems using deformation of magnetizable materials (a magnetic fluid in a elastic capsule or a magnetizable polymer) in an applied magnetic field is a new interesting problem. The deformation of a surface of a magnetic fluid in a traveling magnetic field is used in pumps with magnetic fluids.

In [1-3], the theory of a flow of layers of magnetizable fluids in a traveling magnetic field is discussed. It is shown, that the traveling magnetic field can create the rate of flow in the fluid layers. The initiator of the motion is an alternate magnetic field, which forms to exterior sources (electromagnetic system or motion permanent magnets [4]). Such devices have some characteristics, which allow to use them in medicine and biology. For example, it does not contain solid details contacting with a surrounding medium. In [5], the theory of the behavior of a locomotion system using periodic deformation of a magnetizable polymer, when an alternate uniform magnetic field operates, is discussed. The average velocity of such locomotion systems is proportional to the difference of the friction coefficients between the system and the substrate, which depends on directions of motion.

In the present paper a deformation and a motion of a body made by a magnetizable composite (an elastic polymer and solid magnetizable particles [6-7]) in an alternate magnetic field are experimentally studied. The cylindrical body (worm) which is located in a cylindrical tube is considered. The estimation of the deformation of the worm in applied magnetic field and velocity of travel of the worm is done.

EXPEPIMENTAL RESULTS

In our experiments we use the worm of a cylindrical form which is located in a cylindrical channel. The channel diameter is more in 2.5 times then the worm diameter. An electromagnetic system forms a magnetic field $\boldsymbol{H}$, which is a function of x (x is the coordinate along the channel) and a function of t, so that the traveling magnetic field $\boldsymbol{H} = \boldsymbol{H}\,(x - c_H\, t)$ of special structure is formed. The maximum value of the magnetic field is about 250 Oe. The velocity $c_H = nL$, here L is a spatial period of the electromagnetic system, n is the frequency of the electromagnetic system. The form of the worm changes, because the magnetic forces act on the worm when traveling magnetic fields covers the worm. Under activity of magnetic forces the deformation of parts of the worm along its axis is various because the gradient of the magnetic field is non uniform one. Some phases of the deformation of the worm can be selected. This deformation and the worm movement along the channel are demonstrated.



- Fig. 1. The magnetizable worm in the traveling magnetic field at the different moments.

The phases of the motion and the deformation of the magnetizable elastic worm are shown in Fig. 1 (photos N 1-13). There are two cycles of interaction of the magnetic field and the worm.

The direction of the worm movement is opposite to the direction of the motion of the traveling magnetic field. In Fig. 1 (the photo N 1) we can see that when the magnetic field is absent the orientation of the worm is along the axes of the channel. In the photo N 2, the beginning of interaction of the magnetic field with the worm is shown. Here a fixation of the left endpoint of the worm is realized due to the magnetic field. In the next phase (the photo N 3), the magnetic field starts to deform the worm and an undulation of the worm surface is created. In result the right endpoint of the worm moves. Further (photos N 4-7) the undulation moves along the worm to the right, and the worm moves to the left (in the opposite direction). In the second cycle of interaction of the traveling magnetic field with the worm all phases repeat and the worm makes a new motion cycle (see, Fig. 1, photos N 7-13).

In experiment a frequency of the magnetic field changes from $n = 2\ s^{-1}$ to $n = 50\ s^{-1}$, herewith the worm velocity changes from 0.3 cm/s to 6.5 cm/s.

THEORETICAL ESTIMATIONS AND DISCUSSION

Let $l = 48$ mm be length of the magnetizable elastic worm, $d = 11$ mm be the channel width, $d_w = 4$ mm be the worm diameter. Consider the case when a magnetic field is a traveling magnetic field $H = H(x - c_H t)$, $c_H = L n$ here $2L = 20$ mm is a spatial period of magnetic field, $2n$ is the frequency of a magnetic field. We can estimate the worm velocity of the worm using some assumption.

Sinusoidal form. Let us assume that the form of the segment of the worm between two boundaries of the channel in the magnetic field is a sinusoidal form. The equation of the central line of the segment $y_S = y_S(x)$ in this case is:

$$y_S = \left(\frac{d}{2} - \frac{d_w}{2}\right)\sin\left(\frac{\pi x}{L}\right)$$

The length of the segment is $l_s = 12.6$ mm. There are about four such segments in the worm length. The displacement of the end of the worm w_s during time $t = 7/n$ (here we assume that there are no pauses between two cycles of an influence of the traveling magnetic field on the worm) equals $w_s = 4\,(l_s - L)$ and the velocity of the worm is $v_s = w_s/t = 1.5\ n$.

Worm form is determined from model of elastic beam. Let us assume that the form of the segment of the worm between two boundaries of the channel in the magnetic field is determined from the model of an elastic beam without extension (a bending moment is due to the magnetic forces, we assume that magnetic forces act on the ends of the worm). The equation of the central line of the segment $y_E = y_E(x)$ in this case is:

$$y_E = ax^3 + bx^2 + d_w/2,$$
$$a = -2(d - d_w)/L^3, \quad b = 3(d - d_w)/L^2$$

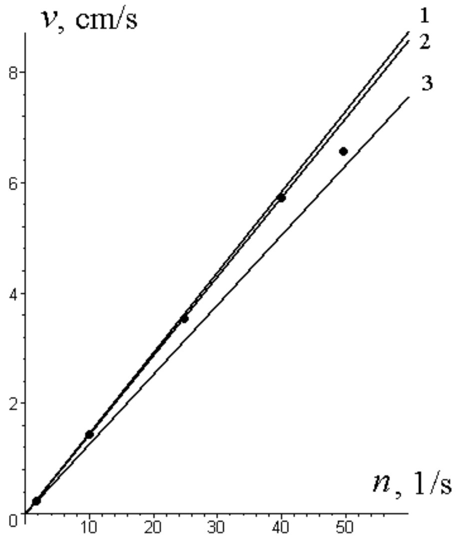
The length of the segment is l_E = 12.50 mm. There are about four such segments in the worm length. The displacement of the end of the worm w_E during time $t = 7/n$ equals $w_E = 4\ (l_E - L)$ and the velocity of the worm is $v_E = w_E/t = 1.4\ n$.

Worm form is broken line. Let us assume that form of the segment of the worm between two boundaries of the channel in the magnetic field is a straight line. The equation of the central line of the segment $y_R = y_R(x)$ is:

$$y_R = (d - d_w)x/L = 7x/10$$

The length of this segment is l_R = 12.2 mm. There are about four such segments in the worm length. The displacement of the end of the worm w_R during time $t = 7/n$ equals $w_R = 4\ (l_R - L)$ and velocity of the worm is $v_R = w_R/t = 1.3\ n$.

The theoretical dependences of the velocity of the worm from n for these case and experimental points are shown on Fig. 2.



- Fig. 2. Worm velocity $v = v(n)$. Theoretical results: line 1 – a sinusoidal form, line 2 – a form of the segment is determined from model of elastic beam, line 3 – a form is broken line, and experimental points.

From Fig. 2 we can see that for $n \leq 50\ s^{-1}$ the theoretical results agree with the experiments. It is obviously that for enough large frequency ($n > 50\ s^{-1}$) inertia force begins to influence on the worm velocity and the worm velocity begins to decrease when n increases.

The worm velocity depends on many parameters: the elastic properties, and magnetic properties of the material of the worm, the value of the magnetic field, the geometrical parameters of the worm and the channel. Also these parameters determine the value of frequency of change of the magnetic field n, for which inertial forces are appreciable.

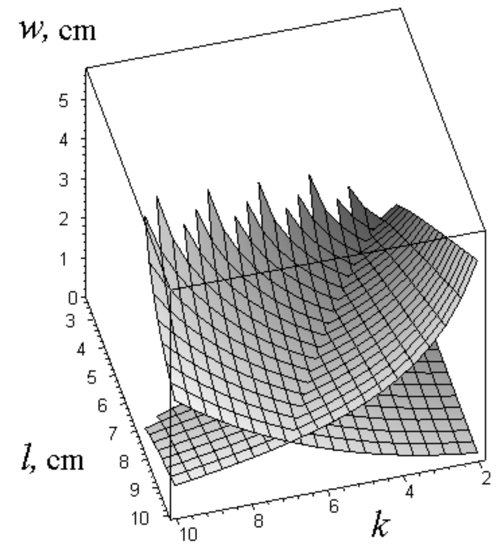
The maximum speed of the worm can be received if an optimum relation between space periodicity of an electromagnetic system and the geometrical sizes of the worm and the channel is retrieved. The optimum length of the cylindrical worm l and length L can be obtained by the equation

$$L = \sqrt{l^2/k^2 - (d - d_w)^2},$$

here $k = 1,2\ldots$ is an integer number (here we consider that a the form of the deformed worm is a broken line). On the other hand the displacement of the worm due to one cycle is

$$w\,(l,k) = l - k\,L$$

If $w\,(l,k) = L\,(l,k)$ the process of the worm moving become a periodical process and this equation ($w = L$) together with the formula for L and w allow us to find optimal value of L, k and l.



- Fig 3. Dependency between the length of the worm, its displacement and the spatial periodicity of the magnetic field.

In Fig. 3 the best relation between l and k is shown as a line of cross of two surfaces: $w\,(l,k) = l - k\,L(l,k)$ and $w=L(l,k)$. Here the axes of coordinates are: l – length of the worm; w – displacement of the worm for one complete cycle of interaction; k – number of the segments of the deformed worm between the boundaries of the canal.

The shown interrelation (see, Fig. 3) allows correctly to select the spatial periodicity of the electromagnetic system L for known geometrical parameters of the worm and channel. In our experiment $k = 4$, $L = 10$ mm and $l = 48$ mm, and the condition $w = L$ is approximately valid.

CONCLUSIONS

It is found that there is an undulation of the magnetizable elastic worm in a periodic traveling magnetic field of special structure and the worm moves along the channel. It is proved, that the direction of its motion is opposite to the direction of the traveling magnetic field. It is shown that for $n \leq 50$ s^{-1} the theoretical results agree with the experiments. The optimum relation of the geometrical sizes of the worm and the channel, the parameters of spatial periodicity of a magnetic field is explored. In experiments maximal worm velocity has been 6.45 cm/s.

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