Locomotion based on the control of the shape of magnetic fluid surfaces and of magnetizable media

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The realization of locomotion based on the deformation of a free surface of a magnetic fluid layer in a traveling magnetic field is studied. A plane flow of an incompressible viscous magnetic fluid layer on a horizontal surface in a nonuniform magnetic field and a plane two-layers flow of incompressible viscous magnetic fluids between two parallel solid planes in a magnetic field was considered. Also the flow of an incompressible viscous magnetic fluid layer on a cylinder in a nonuniform magnetic field was an object of investigation. The deformation and the motion of a body made by a magnetizable polymer in an alternating magnetic field are experimentally studied. The cylindrical body (worm) which is located in a cylindrical tube is analyzed. These effects can be used in designing autonomous mobile robots without a hard cover. Such robots can be employed in clinical practice and biological investigations.

1 Introduction

Biologically inspired locomotion systems are dominated by walking machines, i.e. pedal locomotion. Non-pedal forms of locomotion show their advantages in inspection techniques or in applications to medical technology. The realization of locomotion systems using the deformation of magnetizable materials (a magnetic fluid or a magnetizable polymer) in a magnetic field is an actual problem. In [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 layer. This effect can be applied for realization of a locomotion. In the present paper we investigate theoretical and experimental possibilities of using deformable magnetizable media as actuators for mobile robots.

2 Travelling wave on a free surface of a magnetic fluid layer

We consider a plane flow of an incompressible viscous magnetic fluid layer on a horizontal surface in a nonuniform magnetic field. The magnetic susceptibility of the fluid χ is assumed to be constant. The environment is unmagnetizable and the pressure on the free fluid surface is constant. In this case the body magnetic force is absent and the magnetic field manifests itself in a surface force acting on the free surface. The gravity is not taken into account. In this case, the system of equations consists of the continuity and Navier-Stokes equations:

$$\text{div}\ \boldsymbol{v} = 0\,, \quad \frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v}\cdot\boldsymbol{\nabla})\boldsymbol{v} - \frac{1}{\rho}\ \text{grad}\ p + \nu\Delta\boldsymbol{v} \tag{1}$$

Here $\boldsymbol{v} = (u, w)$ and p are the velocity vector and the fluid pressure $\nu = \eta/\rho$, ν and η are the kinematic and dynamic fluid viscosity coefficients, and ρ is the fluid density. The boundary conditions in the non-inductive approximation takes the form ($\chi \ll 1$, $\chi = M/H$, $[A] = A_f - A_a$):

$$z = 0\ :\quad \boldsymbol{v} = 0\,, \qquad z = h\ :\quad \frac{dh}{dt} = w\,, \quad [-p\boldsymbol{n} + \tau_{ij}n^j\boldsymbol{e}^i] - \mu_0\chi\frac{H^2}{2}\boldsymbol{n} + \frac{\gamma}{R}\boldsymbol{n} = 0 \tag{2}$$

Here τ_{ij} are the viscous stress tensor components, R is the radius of curvature of the free fluid surface, $\boldsymbol{e}^j$ are the basis vectors, γ is the surface tension coefficient, $\mu_0 = 4\pi\cdot 10^{-7}$ H/m is magnetic permeability of the vacuum, $\boldsymbol{H}$ is the magnetic field strength vector, $\boldsymbol{M}$ is the fluid magnetization, indexes f and a denote parameters in the fluid and the environment. We will assume that the magnetic field creates the periodic travelling wave on the surface of a sufficiently thin layer, $h(x,t) = d + a\cos(\omega t - kx)$, $\varepsilon = d\cdot k \ll 1$. If the flow is $T = 2\pi/\omega$ – periodic, we can introduce the dimensionless average flow rate $\overline{Q} = \frac{1}{T}\int_0^T Q(x,t)dt$. The dependence of the dimensionless average volume flow rate $\overline{Q}$ on the surface oscillation amplitude $\delta = a/d$ for $h(\xi) = 1 + \delta\cos(\xi)$ is shown in Figure 1.

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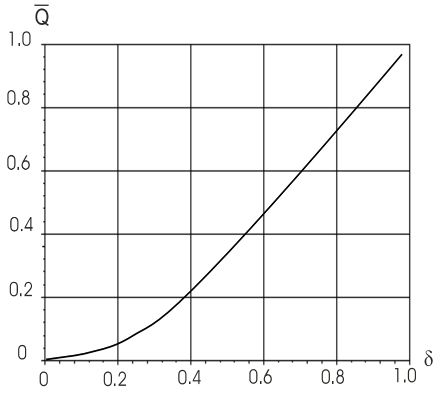

Fig. 1 Average volume flow rate $\overline{Q}$ vs. δ.

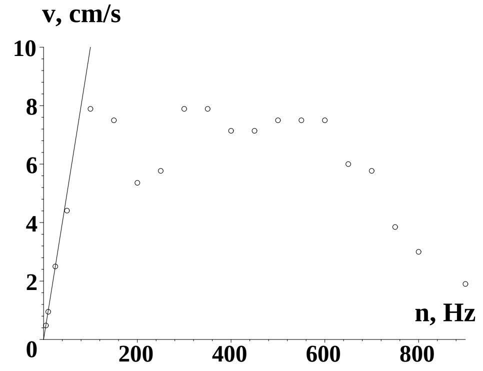

Fig. 2 Body velocity v vs. n.

3 Magnetizable bodies in alternate magnetic field

In the experiments we use cylindrically-shaped bodies located in a cylindrical channel (Figure 3). The coils are placed at the left and right sides of the channel. Periodically the one (left) coil is switched off and the next (right) coil is switched on, n is the number of the coil switches per second (frequency), so $T = 1/n$ is the period between the change-over of the coils. Such an electromagnetic system forms a travelling magnetic field. The maximal obtained body velocity is $v = 7.89\,\mathrm{cm\,s^{-1}}$ for $n = 100\,\mathrm{s}^{-1}$. For $n > 950\,\mathrm{s}^{-1}$ the sample does not move (Figure 2).

Fig. 3 Magnetizable elastic body at different moments in the travelling magnetic field.

4 Conclusion

In our experiments the worm moves along the channel in a travelling magnetic field. The direction of the worm motion is opposite to the direction of the travelling magnetic field. For $n < 100\,\mathrm{s}^{-1}$ the theoretical (numerical and analytical) results for the worm velocity agree with the experimental data. The optimum geometrical sizes of the worm and the channel are found.

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