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Note: Design of a novel rotating magnetic field device

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A novel device to produce a rotating magnetic field was designed, constructed, and tested. The system consists of a Helmholtz coil pair which is mechanically coupled to a dc electric motor whose angular velocity is controlled. The coil pair generates a uniform magnetic field; the whole system is rotated maintaining the coils energized using brushes. The magnetic field strength is uniform (≈5.8 mT) for a workspace of about 100 mm along the rotation axis. The system remains free of undesirable high amplitude mechanical vibrations for rotation frequencies below 10 Hz. We verified the performance of the apparatus by conducting experiments with magnetic swimmers. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4731262]

Rotating magnetic fields are interesting for many practical applications and natural phenomena. By imposing a magnetic field whose direction rotates, single crystals growth is possible in metallurgy.[1] Some authors have studied the effect of rotating magnetic fields in the physiology of rats.[2] The aggregation of paramagnetic particles[3] and in paramagnetic fluids[4] is affected by rotating magnetic fields. These are just a few examples of applications in which having a rotating magnetic field of well controlled properties is important.

Of particular interest to us, is the development of microscopic magnetic swimmers. Various kinds of miniaturized robot-swimmers have been recently proposed for biomedical applications such as targeted drug delivery, cell manipulation, minimally invasive surgery, and screening for diseases at their very early stages.[5–7] Nevertheless, the first magnetic swimmers actuated by alternating fields and used for medical purposes were developed four and a half decades ago by Frei *et al.*[8] (for some earlier related works, see Ref. 9). Honda *et al.*[10] pioneered the study of locomotion of magnetic micro-machines at low Reynolds numbers taking advantage of the magnetic moment as the basic actuation principle. They built a magnetic swimmer composed of a rigid spiral tail fixed to a magnetic head. The millimeter-sized robot was remotely driven by a rotational magnetic field. Nowadays, this method of actuation still being preferable since the swimmer can be actuated wirelessly.

Usually, orthogonal electromagnetic coil pairs are used (Helmholtz coils) to achieve rotating magnetic fields. Zhang *et al.*[11] used three orthogonal electromagnetic coil pairs and attained a uniform rotating magnetic field; similarly, Zhe *et al.*[12] designed a rotating magnetic generator composed of three pairs of Helmholtz coils which are pair-wise orthogonal. It is worthy to note that the above devices can achieve a rotational field with arbitrary rotation axis, which offers great flexibility in controlling orientation of the applied field. But particularly, the setup by Zhe *et al.*[12] uses a non trivial power supply. They use a tri-phase sinusoidal current input whose implementation requires the use of electronic devices to convert frequency and regulate magnitude of voltage supplied. Furthermore, the size of the region in which the rotating magnetic field is uniform is rather small, so its use is limited to small samples.

To overcome these difficulties, we propose an electromagnetic-mechanical apparatus composed of a single Helmholtz coil pair which is mechanically rotated by an electric dc motor. This system achieves a rotating magnetic field whose angular frequency and strength are modulated by setting the angular speed of the dc motor and changing current density in the coils, respectively. The proposed device is inexpensive and easy to manufacture which make it attractive for several applications, especially in those where a rotating magnetic field of low intensity (≤20 mT) and low frequency (≤20 Hz) is required.

The electromagnetic-mechanical device consists of three subsystems: (1) Helmholtz coil pair[13] (to generate magnetic field); (2) system to rotate the coils (speed-controlled dc motor, pulley-belt arrangement, ball bearings); (3) power supply system (brushes and dc current source). A sketch of the device is shown in Fig. 1.

A Helmholtz coil is a parallel pair of two similar circular coils wounded in series such that electric current passes in same direction in each coil. The coils are spaced one radius apart. When a dc power is supplied to the coil geometry, a uniform magnetic field at the center is produced. The magnetic field in the central region of the coil pair can be shown to be[13]

$$B_z(z) = \frac{8\mu_0 N I}{R\sqrt{125}}\left(1 - \frac{54}{125}\frac{z^4}{R^4} + \cdots\right), \tag{1}$$

where N is the number of turns in each coil, I is the electric current flowing through the coils, μ_0 is the permeability of free space (1.26×10^{-6} T m/A), R is the separation distance between the coils (note that R is also the radius of the coils), and z is the rotation axis. The coordinate system considered here is shown in Fig. 1. In the midpoint between the coils (0,0,0) the magnetic field is

$$B_x(0) = \frac{8\mu_0 N I}{R\sqrt{125}}. \tag{2}$$

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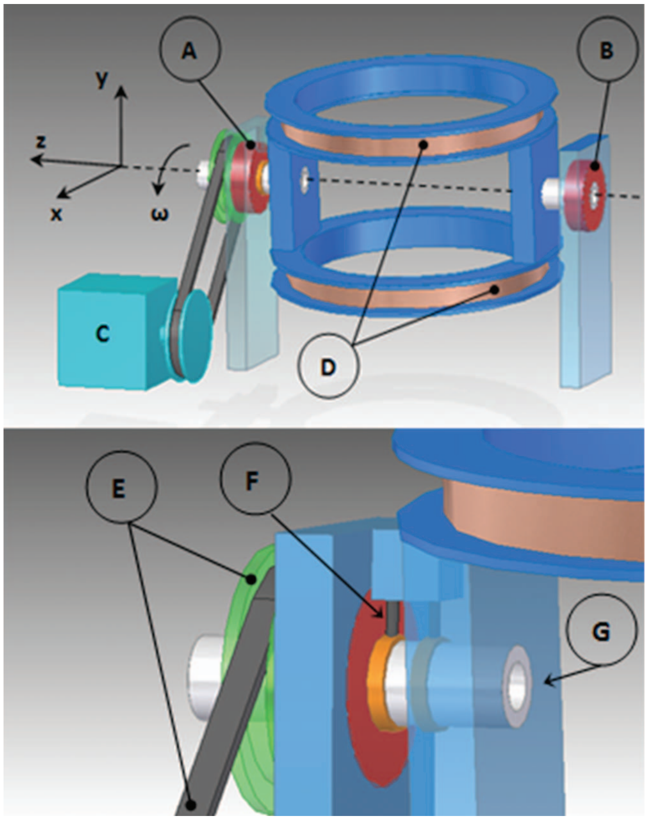

FIG. 1. Electromagnetic-mechanical device. (A) and (B) ball bearings, (C) dc motor, (D) coil pair, (E) pulley-belt arrangement, (F) carbon brush, (G) hollow shaft.

To obtain a magnetic field of about 6 mT, we chose the design parameters shown in Table I. To restrict the maximum current and temperature of the device, we used copper wire of gauge 19 AWG. The structure was constructed using low density polyethylene. The rings were machined from a plate of 31.75 mm of thickness. Steel screws were used to fix the structure. Copper wire, was wounded manually in both the coils and connected in series. Each coil has a diameter of 280 mm with 230 turns of wire. The coil pair was mounted to a pair of aluminum hollow shafts supported by rolling bearings at A and B in the z axis of rotation, see Fig. 1. The coil was constructed using mostly non-metallic parts to ensure the homogeneity of magnetic fields within the test volume. The array was energized using a dc power supply (Agilent E3632A, dc Power Supply) with a maximum current and voltage of 4 A and 30 V, respectively. Taking the design parameters shown in Table I and considering the Joule heating effect ($P = I^2R_c$), we can estimate the temperature rise as a function of time expected for this setup:

$$\Delta T = \frac{I^2 R_c t}{mC}, \tag{3}$$

where m is the mass of wire and C is the heat capacity of the copper wire. Considering $m = 1.181$ kg and $C = 386$ J/°C·kg we estimate a value of 11.253 °C/min. This estimation does not consider cooling by natural convection; therefore, it represents a maximum bound of this effect. In fact, the measured value of temperature increase was about 8 °C/min. Hence, the maximum operating time of the coils without thermal degradation is about 10 min. The intensity of the magnetic field generated by this device was measured using a teslameter (F. W. Bell, 5100 System). This hand held device can measure magnetic field intensity in the range ±30 mT with 0.01 mT accuracy. The probe was used to measure the magnitude of the magnetic field along the z axis of the coil. The results are shown in Fig. 2. The values of the magnetic field are quite constant; in a region of ± 50 mm, the field intensity changes only 1.7%. Along with the results, Fig. 2 also shows the prediction of Eq. (1), which was evaluated numerically considering the parameters shown in Table I. Clearly, the agreement between the measurements and predictions is remarkable.

To assess the intensity of vibrations induced in the test area by the rotating coil, a three axes linear accelerometer (LIS302DL) was placed there and the vibration was recorded in time for different rotating speeds. It is found that the amplitude of vibrations remains within 0.2% g for all cases. Only for rotating frequencies larger than 10 Hz, the vibrations begin to increase slightly. Hence, despite the fact that no special measures were considered to minimize this effect, the proposed arrangement produces a very small vibration environment. Now, as shown in Fig. 1, the coils were mounted on a shaft that was supported on two structures with ball bearings. The shaft was connected with a belt and pulleys to a dc motor. By controlling the power of the motor, the rotating speed was varied; the coil pair was rotated by the mechanical action of the motor.

TABLE I. Characteristics of Helmholtz coil.

Radius, R	140 mm
Number of turns per coil, Nrange	230
Diameter of the wire, d	0.91 mm
Resistance of each coil, R_c	5.34 Ω
Operating temperaturerange	0–80 °C
Coil pair inductance, L	73 mH

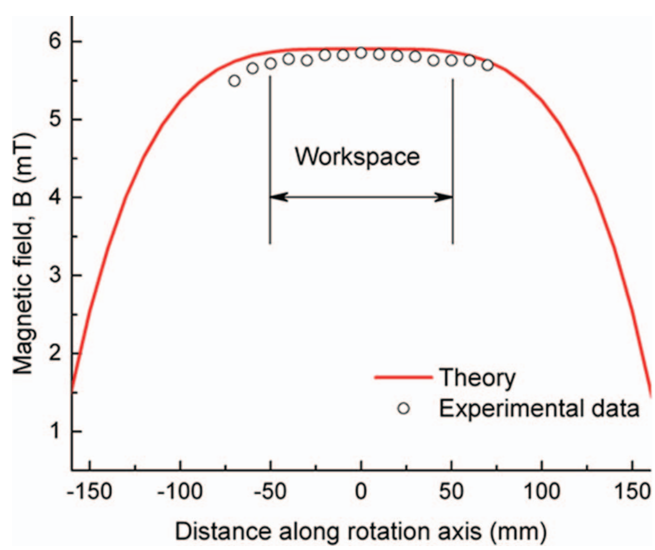

FIG. 2. Magnetic field along the rotation axis, z, of the coils.

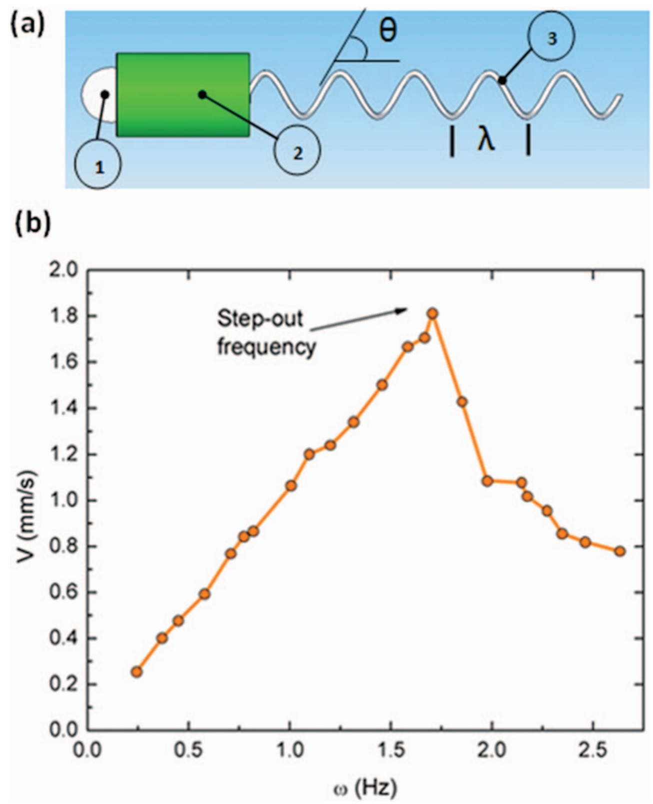

FIG. 3. (a) Construction of the biomimetic swimmer: (1) permanent magnet, (2) polyurethane head, (3) rigid spiral made of a steel wire; $\lambda =$ linear wavelength and $\theta =$ pitch angle between the helix and the z-axis. (b) Dependence of swimming velocity of robot on magnetic field rotation frequency, this experiment was performed in silicone oil ($\eta \approx 5.7$ Pa s) at 25 °C, with $\lambda \approx 8.5$ mm, $\theta \approx 53^\circ$ and Reynolds number Re ≈ 0.01.

To keep the coil energized and the induced magnetic field active during the rotation of the device, a pair of brushes was implemented on one support of the coil. In this manner, the direction of the magnetic field rotated in the central region of the arrangement while keeping the power feeding of coils constant. Furthermore, by making the rotating shaft hollow (as shown in Fig. 1), it was possible to keep a sample fixed in the middle, with a pass-through shaft, exposed to the rotating magnetic field.

Our main interest to generate a rotating magnetic field arises from the study of locomotion of microorganisms. A microswimmer manufactured in our laboratory consists of a permanent magnetic head and a rigid helical tail, which is made of steel wire; see Figs. 3(a) and 3(b). When the permanent magnet is inside the external magnetic field, it tends to align with it. If the external field is rotating, the magnet will rotate accordingly. In this manner, it is possible to rotate the magnet-tail arrangement.

The sum of applied nonfluidic forces f (which are zero here, since there is no spacial gradients in the applied field and gravity is counterbalanced by buoyancy) and torques τ_m that act on the helical microrobot are linearly related to its forward velocity V and rotational velocity ω by a propulsion symetric matrix[14]

$$\begin{bmatrix} f \\ \tau_m \end{bmatrix} = \begin{bmatrix} a & b \\ b & c \end{bmatrix} \begin{bmatrix} \mathrm{V} \\ \omega \end{bmatrix}, \tag{4}$$

the parameters a, b, and c include information about the geometric and environmental properties of the helical swimmer. The applied magnetic torque is given by[10]

$$\tau_m = m\, B_z \sin\theta, \tag{5}$$

where m is the magnetic moment of magnet and θ is the angle between m and B_z. By changing the rotating speed or the geometry of the helix, the swimming performance can be studied. By filming the motion of the robot, its swimming speed can be measured. These results are shown in Fig. 3(b). As expected[10] the swimming speed is linearly proportional to the rotational frequency. We also reproduced the existence of a step-out frequency,[14] beyond which the robot cannot follow the externally rotating magnetic field and its motion is intermittent.

The proposed device is capable of producing a rotating magnetic field of about 6 mT for frequencies up to 10 Hz. The volume in which the magnetic field is uniform is about 400 cm^3. We successfully tested the device to drive magnetic robots which swim at low Reynolds number in a high viscosity silicone oil. We expect that this device can be useful for several other applications where a rotating magnetic field is used, as discussed above.

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