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A magnetic fluid microdevice using insect wings

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Abstract
A magnetic fluid microdevice using Diptera insect wings is proposed and constructed. The magnetic fluid device is composed of insect wings, a small permanent magnet, coil, and kerosene-based magnetic fluid. First, the structural properties of insect wings are studied through measurements of certain morphological parameters. Secondly, the novel type of microwind energy converter is constructed. Thirdly, the power generation characteristics of the magnetic fluid microdevice using insect wings are examined. It is found that the output power is roughly proportional to the cube of the airflow velocity.

1. Introduction

In the development of micromachining technology and microelectromechanical system (MEMS) technology, the applications of miniaturized and ultraminiaturized components and devices have been rapidly increasing. Moreover, with the critical development in microprocessing technology and the availability of various functional materials and intelligent material systems, the importance of the developments of micromechanisms and micromachines is well recognized. Magnetic field based micro/nanoelectromechanical system devices have been proposed that use 10 nm diameter magnetic particles, with and without a carrier fluid, for a new class of nanoduct flows, nanomotors, nanogenerators, nanopumps, nanoactuators, and other similar nanoscale devices [1]. The authors have also proposed a new type of magnetic fluid microdevice composed of a permanent magnet and magnetic fluid, in the previous paper [2]. The microactuators proposed by the authors are driven by the alternating magnetic field [2].

On the other hand, the authors have been studying the flight functions of flying insects. For example, the wing structure and the aerodynamic characteristics of a dragonfly in flight were examined using a scanning electron microscope and a small low-turbulence wind tunnel [3]. The surface roughness of some insect wings was measured using a three-dimensional, optical shape measuring system [4]. The free flight of the wasp was analyzed using a three-dimensional motion analysis system [5]. The wing motions of some flapping insects were analyzed using a three-dimensional motion analysis system; the displacement and frequency of extrinsic skeleton vibration produced by contraction of the dorsoventral and the dorsal longitudinal muscles were measured, and the surface roughness of insect wings was measured morphologically using a three-dimensional, optical shape measuring system [6]. Through these studies, it became clear that Diptera wings have excellent aerodynamic characteristics.

In this paper, a magnetic fluid microdevice using Diptera insect wings is proposed and constructed. The magnetic fluid microdevice is a kind of energy converter that changes wind energy into electric energy. The power generation characteristics of the magnetic fluid device are examined.

2. Diptera insects

Insects are a remarkable group of species. They are the most numerous and successful creatures on this planet. They belong to a group of invertebrates known as arthropods, which are characterized by their jointed limbs, segmented bodies, and tough outer skeletons. They occur almost everywhere; they play a significant role in the world of Nature and affect us directly or indirectly in many ways. Most of them are small, and some are minute. This means that they can live in small

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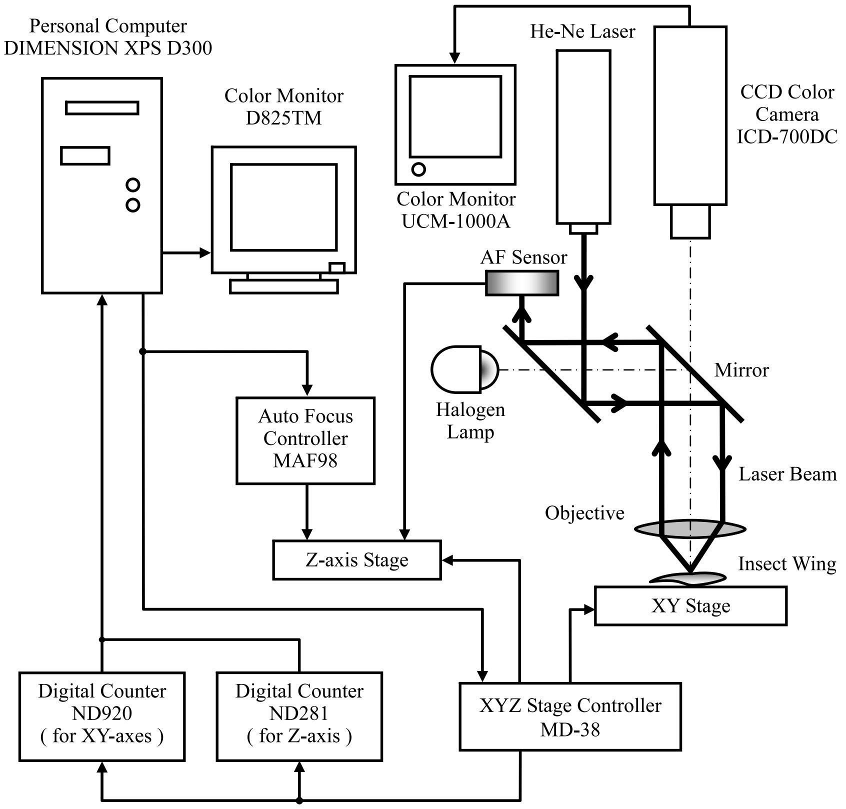


Figure 1. Block diagram of the experimental apparatus for the surface shape measurement. The positioning resolution of the XY-stage is 0.1 μm, and the accuracy of the measurement in the Z-direction is 0.01 μm.

places, and a small but diversified area may contain many kinds.

In this paper attention is given to Diptera insects. These insects have just one pair of wings, that is, the hindwings are reduced to small, club-shaped balancing organs called halters. Horseflies were used in the experiment. The surface shape of the Diptera insects was measured using a three-dimensional, optical shape measuring system. This measuring system is composed of an automatic focus microscope with a laser beam driving the servomechanism and a high accuracy XY-stage. In this experiment, the test insect wings were horsefly wings. The test insect wing was severed from the insect body before the measurement and mounted on the XY-stage. When the laser beam impinges on the surface of the test insect wing, a diffused or scattered reflection occurs. The scattered light reflection is then focused through an objective lens on an unique semiconductor sensor. The output signal from the photodetector gives the position of the measured surface relative to the gage probe. A three-dimensional measurement of the wing was made by scanning the XY-stage. A schematic diagram of the measuring device is shown in figure 1. Figure 2 shows a three-dimensional display of the measurement result for the right wing of the horsefly *Tabanus rufidens*. In general, insect wings are composed of veins and membranes that are identical on the top and bottom surfaces. The 'ups and downs' shown in figure 2 form along the veins, and the difference in elevation between the longitudinal veins is especially remarkable. The corrugated wings of insects perform several functions for the insect flight [3].

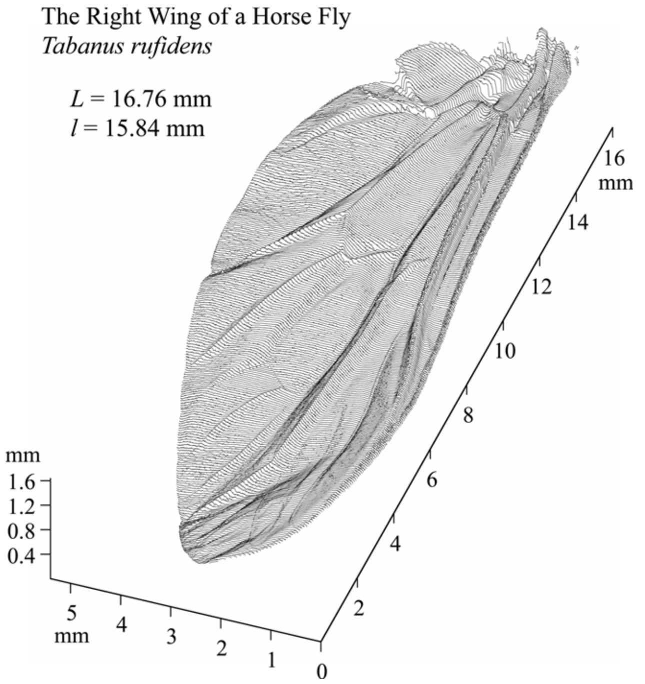


Figure 2. Three-dimensional description of the surface shape measurement of the horsefly wing. The vertical scale in this figure is emphasized.

Generally, winged insects produce aerodynamic force by flapping their wings, causing them to fly in air [7]. The airflow over a wing generates forces of lift and drag which

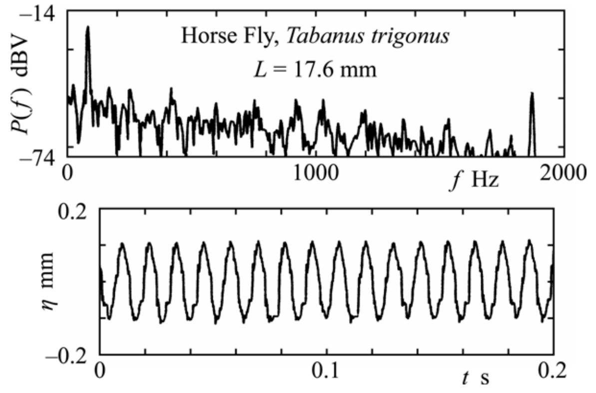


Figure 3. Extrinsic skeleton vibration of the horsefly, *Tabanus trigonus*, and the power spectrum. The lower figure corresponds to the extrinsic skeleton vibration during the flapping motion. The upper figure shows the power spectrum of the skeleton vibration.

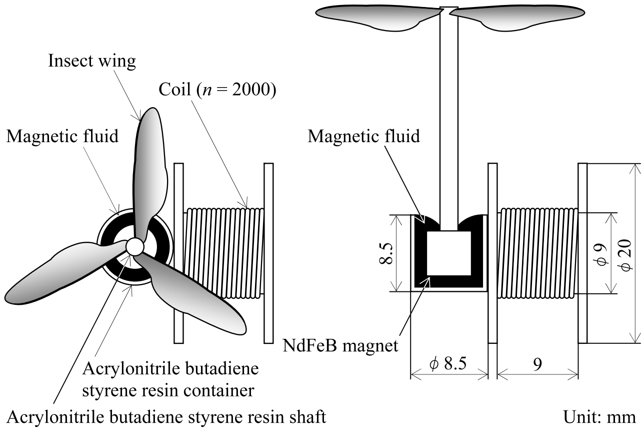


Figure 4. Composition diagram of the magnetic fluid microdevice using horsefly wings.

combine to create a resultant force. Lift is a component normal to the wing, and drag is a component parallel to the wing. The velocity at each place on the wing is different, because the insect flaps around the wing root. This shows that insect wings are appropriate for use as the airfoils of microenergy converters. The airflow velocity over a wing depends on the size and the flapping frequency of the insect wing, and it relates to the characteristics of an energy converter. Therefore, the flapping frequency of the horsefly was measured using an optical displacement detector system. The optical displacement detector system and the experimental procedure were described in our previous paper [6]. Figure 3 shows an example of the output signal from the optical displacement detector. The power spectrum shows a sharp peak. The dominant frequency agrees with the flapping frequency of the horsefly. It was observed that the flapping frequency of horseflies depends on the body size, and $f_i = 80$–100 Hz. Through various such measurements, the following dimensionless numbers were obtained:

Reynolds number:

$$Re = \frac{\text{inertial force}}{\text{viscous force}} = \frac{\rho U^2 L^2}{\mu U L} = \frac{UL}{\nu} = 2.4 \times 10^4; \qquad (1)$$

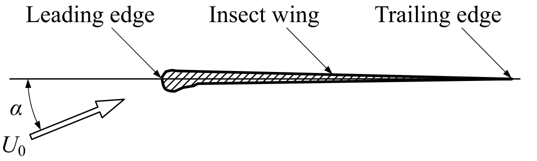


Figure 5. Definition of the angle of attack α for the uniform airflow velocity U_0.

reduced frequency:

$$k = \frac{\text{angular velocity}}{\text{linear velocity}} = \frac{L\omega}{U} = 0.57; \qquad (2)$$

where L is the physical length, U is the linear velocity of the object, ω is the angular velocity, ρ is the fluid density, μ is the fluid viscosity, ν is the kinematic viscosity. The drag coefficient and the maximum lift coefficient are strongly related to the Reynolds number. The reduced frequency is a dimensionless angular velocity parameter. The value in equation (1) indicates the maximum, and the value in equation (2) indicates the minimum. The above dimensionless numbers show that insect wings may correspond to a relatively wide range of airflow velocity.

3. Magnetic fluid device

The magnetic fluid microdevice is composed of insect wings, a permanent magnet immersed in magnetic fluid, and a coil. Figure 4 shows the outline of the magnetic fluid microdevice. Horsefly wings were used as the airfoils of the magnetic fluid device. The installation angle of the insect wing into the shaft influences the lift characteristics of the magnetic fluid device. In this experiment, the insect wing was bound to the shaft for the airflow at the angle of attack α shown in figure 5. In general, the resultant of two forces of lift and drag depends on the angle of attack α. Insect wings have excellent lift characteristics at low Reynolds number. The permanent magnet (NdFeB magnet) is a cylinder (5 mm diameter and 5 mm height). The sample magnetic fluid is kerosene-based ferricolloid HC-50. The permanent magnet is suspended in magnetic fluid. The induced emf is proportional to the number of turns, n, of a coil. In this experiment, a coil with $n = 2000$ was used. Figure 6 shows the permanent magnet suspended in the magnetic fluid. In figure 6, V_m is the volume of magnetic fluid, and g is the gravitational acceleration. The measured free surface of magnetic fluid corresponds to the surface with equal magnetic field. This self-levitating situation of the magnet makes this device effective. When three insect wings as propeller blades are subjected to an airflow, the magnet in the magnetic fluid rotates easily without friction. Faraday's law shows that a current can be produced by a changing magnetic field. The emf induced in a circuit is directly proportional to the time rate of change of magnetic flux through the circuit. It can be written as

$$E = -n\frac{\mathrm{d}\Phi_B}{\mathrm{d}t} \qquad (3)$$

where Φ_B is the magnetic flux associated with the circuit.

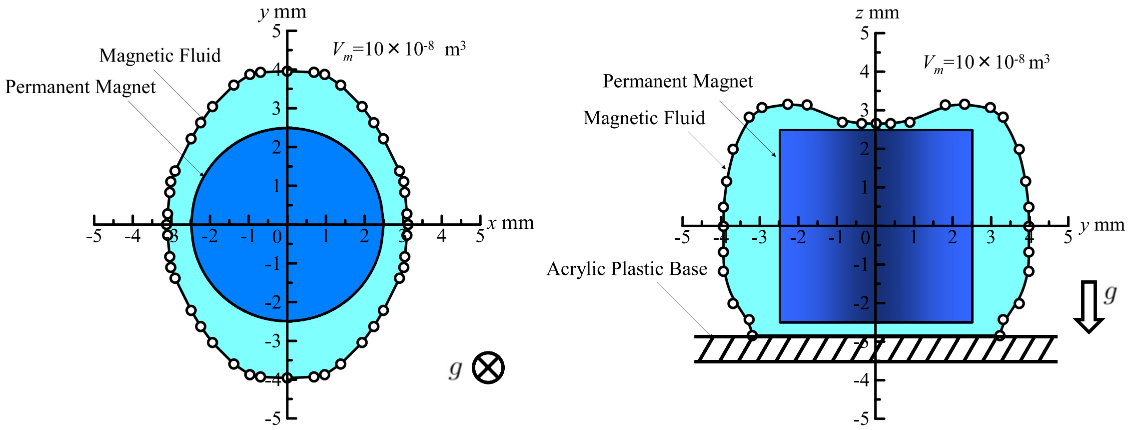
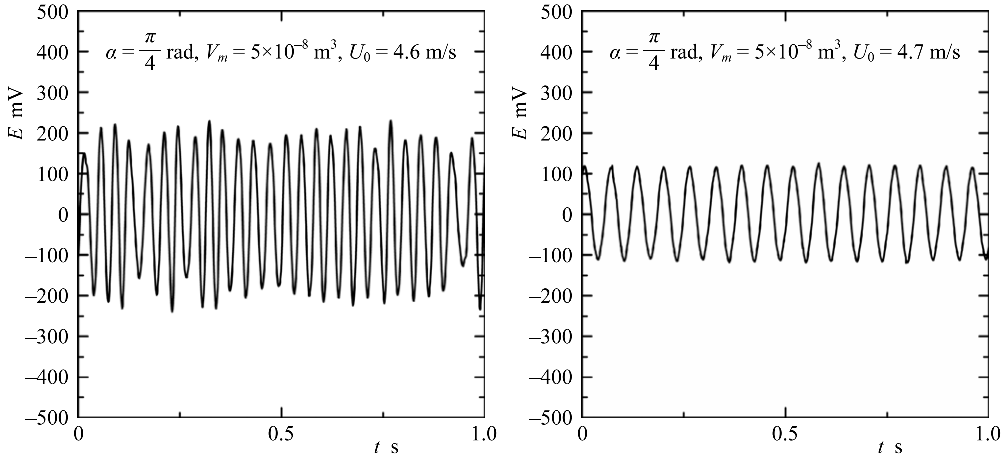


Figure 6. NdFeB permanent magnet suspended in kerosene-based magnetic fluid. (This figure is in colour only in the electronic version)



(a) Insect wing blades

(b) ABS resin wing blades

Figure 7. Output signals from two kinds of magnetic fluid microdevices. The variation of the amplitude in (a) occurs due to small variations in the size of the insect wings.

The micromagnetic fluid device with artificial wings made of ABS (acrylonitrile–butadiene–styrene) resin was also produced. In the experiment, two kinds of devices were examined.

4. Output from the magnetic fluid microdevice

Some kinds of micromagnetic fluid devices have been proposed by the authors [2]. In this paper, our magnetic fluid microdevice can change the wind power energy into electrical energy. The magnetic fluid microdevice is a microenergy convertor.

Figure 7 shows the output signal from two micromagnetic fluid devices, that is, (a) is for insect wing blades and (b) is for artificial (ABS resin) blades. It can be seen from figure 7(a) that the output voltage E from the micromagnetic fluid device with insect wings exceeds ±200 mV at the uniform airflow velocity $U_0 = 4.6\ \mathrm{m\,s^{-1}}$. However, the output voltage from the device with artificial wings shows ±110 mV at the airflow velocity $U_0 = 4.7\ \mathrm{m\,s^{-1}}$. The change of the signal to positive and negative corresponds to the rotation of the permanent magnet. Comparison of (a) and (b) in figure 7 reveals that the lift generation function of a Diptera insect wing is excellent. Figure 8 shows the output electric power from two micromagnetic fluid devices. It is clear from figure 8 that the micromagnetic fluid device with insect wings has excellent characteristics for power generation compared with artificial wings. In general, the output power from a wind power generator is given by

$$P = \tfrac{1}{2} C_{\mathrm{p}} \rho A U_0^3 \tag{4}$$

where C_{p} is the power coefficient, and A is the wind area. The power coefficient in insect wing is about three times that of the artificial wing.

5. Conclusions

The flapping motions and frequencies of Diptera insects were analyzed, and the structural properties of Diptera wings

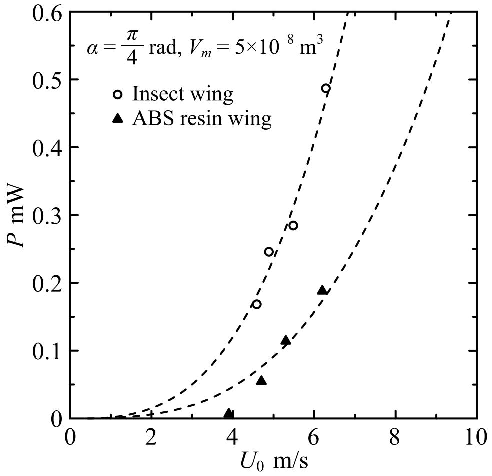


Figure 8. Output electric power P versus uniform airflow velocity U_0.

were examined. On the basis of the analysis of the insect wing, a magnetic fluid microdevice using horsefly wings was constructed, and its power generation characteristics were examined. The results obtained are summarized as follows.

(1) The magnetic fluid microdevice can convert the wind power energy into electrical energy.
(2) The power coefficient of the magnetic fluid microdevice using insect wings is about three times that for the case of artificial wings.

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