Characteristic evaluation of a bristled wing using mechanical models of a thrips wings with MEMS piezoresistive cantilevers

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Received 7 May 2014

Abstract
This paper discusses similar-scale mechanical models of a thrips wing using microelectromechanical systems (MEMS) piezoresistive cantilevers to quantitatively evaluate bristled wing characteristics. Each cantilever had combs with varying widths and neighboring gaps that were adjusted so that a constant surface area was maintained. The cantilever body was $1,324 \times 256 \times 5 \mu m^3$ in size. An aerodynamic drag force from the airflow applied to the cantilever surface was measured using the fractional resistance change of the piezoresistor due to the cantilever’s deformation. The aerodynamic characteristics of each model were evaluated in a wind tunnel with airflow velocities between 1.2 and 5.6 m/s. The experimental results suggest that at a lower comb-width-based Reynolds number that was approximately equal to that of a bristled wing of a thrips, the comb areas of the cantilever act as an airflow suppression due to boundary layer effects, which results in an increased aerodynamic force.

Key words: Bristled wing, Thrips, Piezoresistive cantilever

1. Introduction

Conventional methods for evaluating insect wing aerodynamics have primarily utilized large-scale robotic wing models. This study discusses similar-scale mechanical models of a thrips wing using microelectromechanical systems (MEMS) piezoresistive cantilevers with comb structures, which can cover both steady and unsteady motions in principle.

The wing shapes of flight birds and insects in nature vary depending on the creature’s size. This curious fact leads one to believe that an optimal wing size and, in particular, an optimal Reynolds number may exist for a given size (Azuma, 2006, Thomas, 2002, Shyy et al., 2011). For example, a large bird has streamline wings. A butterfly or dragonfly flies by flapping membrane wings. The thrips family of insects, whose size is on the order of 1 mm, has bristled wings rather than membrane wings (Ellington, 1980). A thrips flaps its wings at several hundred hertz, and the Reynolds number around its wings is less than 100. Recently, these unique wings have received attention for the development of artificial, micro-sized flying robots that will be able to fly in a similar manner as insects.

A number of studies have been performed to estimate the aerodynamic forces acting on bristled wings of a thrips to understand the aerodynamic mechanism behind a thrips’ flight. These studies have mainly been performed using theoretical analyses (Weihs and Barta, 2008, Davidi and Weihs, 2012, Shawn et al., 2013, Barta and Weihs, 2006) and large-scale robotic wings (Sunada et al., 2002, Sunada et al., 2003). In computational studies, the aerodynamic forces were calculated by theoretical models based on simple arrayed rods. In robotic-wing experiments, a large artificial bristled wing was tested in oil to mimic the Reynolds number of a thrips. The aerodynamic force was measured using a load cell that was attached to a wing root. Both methods have estimated that a bristled wing can produce a force similar to that of a continuous membrane wing because of the effects of viscosity, which results in the air next to the bristles being dragged with the bristle due to boundary layer effects at low Reynolds numbers. Thus, the fluid-dynamic force...
coefficient of the bristled wing is larger than that of the solid wing because of the difference between the wing surface areas.

This larger force coefficient is thought to be advantageous for a thrips because it induces a smaller inertial force during flapping. Thus, its wing performance is also considered suitable for application to micro-sized flying robots. The evaluation of the enhancement of the force coefficient in a bristled structure is required to design an optimal wing with an emphasis on the quantitative size effect of the enhancement. A similar-scale model of a thrips is also desirable for this evaluation in anticipation of actual use. Additionally, a similar-scale model is suitable for evaluating the aerodynamics in detail because it is possible that simulations based on continuum equations (Navier-Stokes equations) may not accurately describe airflow conditions at such ultra-low Reynolds numbers due to rarefied effects, and dynamically-scaled robotic-wings may not result in the correct answer for the same reason (Liu, H. & Aono, H., 2009).

In this study, an artificial model of a bristled wing is formulated to evaluate wing aerodynamic characteristics. The model is based on a MEMS Si (density: 2330 kg/m³) cantilever that has a similar size and flexural stiffness to a thrips wing. In principle, the cantilever can be used in both steady and unsteady motions, such as a flapping motion, because the ratio between the aerodynamic and inertial forces is approximately equal to that exhibited by actual thrips; i.e., the forces exhibited by the cantilever and thrips are of the same order of magnitude.

The model is composed of a cantilever with a comb structure. The piezoresistors are located on the surfaces of the cantilever legs so that minute differential pressures can be detected. The micro-scale cantilever structure and sensing element for the aerodynamic force are compatible in the MEMS process (Su et al., 2002, Wang et al., 2007, Gotszalk et al., 2000). Our group has previously developed MEMS piezoresistive cantilevers (Takahashi et al., 2013, Takahashi et al., 2012, Gel and Shimoyama, 2004). This cantilever-type model is highly sensitive; therefore, the model is highly advantageous for evaluating forces. In this study, the mechanical models of a thrips wing were designed and fabricated using comb cantilevers. The drag force and drag coefficient of the comb were evaluated using several parameters for the comb size and airflow velocity based on wind tunnel experiments.

2. Materials

2.1 Device design

Figure 1(a) and Table 1 present the design of the mechanical model of a thrips wing with a comb-type piezoresistive cantilever. The cantilever is composed of a comb area and a leg area. The comb area is composed of a straight beam with comb structures that are distributed symmetrically. A piezoresistor is formed on the surface of the two legs of the cantilever. The cantilever deforms and changes the resistance of the piezoresistor when airflow is applied to its surface.
The resistance change of the cantilever is proportional to the deformation of the cantilever. This type of cantilever was developed in our previous work (Takahashi et al., 2012, Gel and Shimoyama, 2004), and the details of the mechanism as an airflow sensor were described in a previous publication (Takahashi et al., 2013).

The sizes of the cantilever and comb structure were designed to be similar to those of a thrips wing. Previous studies have reported the parameters of a thrips (Ellington, 1980, Sunada et al., 2002). The wing is between 0.5 and 1.0 mm in length. The bristles of a thrips wing are approximately 2 μm in diameter. The distance between neighboring bristles is approximately 20 μm. The flexural stiffness of the thrips wing in the spanwise direction is calculated using an equation derived from several species of flying insects (Combes and Daniel, 2003). Assuming that the wing length is 1.0 mm, the calculated value of flexural stiffness is approximately $1 \times 10^{-9} \text{Nm}^2$.

The length, width, and thickness of the proposed cantilever part were 1,324, 256, and 5 μm, respectively. We used five types of cantilevers; one was a rectangle-shaped cantilever, and the other four types were comb cantilevers. The combs had different widths, and the number was different from each cantilever. The comb cantilevers were defined as type-1, type-2, type-3, and type-4. The widths and numbers of the combs of the type-1 through type-4 cantilevers were 64, 32, 16, and 8 μm, respectively. The distances between the neighboring combs in the four cantilever types were 896, 299, 128, and 60 μm, respectively. The ratios of the comb width to the distance \((l_1+l_2)/l_1\) were approximately 10, which is equal to that of a thrips wing (Sunada et al., 2002). The length of the combs of the single side \(s\), from the base to the end, was 352 μm. The surface area \(S\) of each comb part, which corresponds to the areas of the model platform, was equal to 0.1 mm$^2$. The type-4 cantilever was the most similar to a thrips wing out of all of the cantilevers. For comparison, a continuous cantilever that had filled gaps between the neighboring combs was also designed and fabricated. The surface area of the continuous cantilever was 0.8 mm$^2$.

The spring constant of each cantilever structure was calculated using finite element modeling (FEM) software (COMSOL Multiphysics, COMSOL), as shown in Table 2. Young’s modulus of silicon was taken to be 169 GPa in the calculations (Hopcroft et al., 2010). The comb-less cantilever and comb cantilevers had approximately equal spring constants of 0.56 N/m. The spring constant of the continuous cantilever was 0.71 N/m. The flexural stiffnesses of the cantilevers, \(EI\), were also calculated as follows:

$$EI = \frac{1}{12}kL^3. \quad (1)$$

The calculated flexural stiffness of each cantilever is shown in Table 2. The values ranged from $4.3 \times 10^{-10} \text{Nm}^2$ to $5.5 \times 10^{-10} \text{Nm}^2$, which were approximately equal to that of a calculated thrips wing.

The fabrication process of the device is shown in Fig. 1(b). The details of the fabrication process were provided in our previous studies (Gel and Shimoyama, 2004, Takahashi et al., 2012, Takahashi et al., 2013). A 5/2/300 μm-thick
silicon-on-insulator (SOI) wafer was used for the device material. An N-type resistor was formed on the device Si layer, as shown in Fig. 1(b)(i). Next, we deposited an Au layer and etched the Au/Si layers to form the cantilever and comb structures, as shown in Fig. 1(b)(ii). The Au layer was patterned again to form the piezoresistor parts, as shown in Fig. 1(b)(iii). Finally, the handle Si/SiO\textsubscript{2} layers were etched to release the cantilevers, as shown in Fig. 1(b)(iv).

2.2 Fabrication

A photograph of the fabricated device is provided in Fig. 2(a). The fabricated device chip was composed of the comb cantilever, comb-less cantilever, and temperature-compensating cantilever. Photographs of (b) the comb-less cantilever, (c) the type-1 cantilever, (d) the type-2 cantilever, (e) the type-3 cantilever, (f) the type-4 cantilever, and (g) the continuous cantilever.

2.3 Force calibration

The displacement sensitivity of the fabricated device was measured. The cantilever tip was touched to a glass tube that was fixed on a piezoelectric actuator. Figure 3 illustrates the relationship between the fractional resistance change of the type-4 cantilever and the displacement of the cantilever tip. The resistance change was proportional to the average strain of the legs, where the piezoresistor was formed, due to the displacement of the cantilever tip. The fitted line

\[ \frac{\Delta R}{R} = -1.2 \times 10^{-4} \Delta x \quad (2) \]
was obtained using a least-squares fit. Thus, the displacement sensitivity $S_d$ was $-1.2 \times 10^{-4}$ $\mu$m$^{-1}$. All of the displacement sensitivities of the devices used in this experiment were between $-1.2 \times 10^{-4}$ and $-1.0 \times 10^{-4}$ $\mu$m$^{-1}$.

Considering a cantilever, when the cantilever tip was pushed, the relationship between the displacement and applied concentrated force could be expressed as

$$F = k\Delta x.$$  \hspace{1cm} (3)

The concentrated force could be determined from the resistance change in Equations (2) and (3).

When an aerodynamic drag force caused by the airflow velocity was applied to the cantilever surface horizontally, the force was assumed to be a distributed load on the cantilever surface. By subtracting the response of the cantilever used for temperature compensation from that of the other cantilevers, we were able to obtain the responses from a distributed load on the surface of the comb area. The moment of the cantilever generated from a distributed load is equal to that of a concentrated load applied at the central point of the distributed load. We assumed that the central point of the distributed load was that of the uniformed distributed load. The center of the distributed load was assumed to be constantly at the center of comb area, even if the extra aerodynamic drag force was generated around the comb, because of the symmetry of the structures. Thus, the ratio between the average moment of the legs from the concentrated force at the cantilever tip and that of the distributed force on the comb area is expressed as

$$r = \frac{2l_1 l_2 + 2t}{l_1 + l_2 + 2t} = 1.75$$ \hspace{1cm} (4)

assuming that the amplitudes of the forces are equal. The ratios for the comb-less and continuous cantilevers were the same as in Equation (4). The resistance changes were proportional to the average moment. Thus, the measured aerodynamic drag force of the cantilever can be roughly expressed as

$$F = r \times k \times S_d \times \Delta x.$$ \hspace{1cm} (5)

The displace sensitivities of all of the devices were also calibrated using the same method used to calculate the applied drag force from the fractional resistance change.

3. Experiments and results

3.1 Experimental setup

To evaluate the characteristic of a bristled wing using the fabricated mechanical models, we applied a constant airflow to the models and measured the drag forces as the first step of our proposed method. A thrips flaps its wing at several hundred hertz. The airflow velocity around the wing can be up to several meters per second at the wing tip. The average airflow velocity on the whole surface of the wing is approximately on the order of less than one meter per second. In this experiment, the applied airflow velocity was of an order of magnitude ranging from one to several meters per second. Assuming that the combs length, $s$, and the applied airflow velocities are the characteristic linear dimension and flow velocity, respectively, as is found in previous studies, the Reynolds number becomes approximately several tens.

Figure 4 presents photographs and the concept of the experimental setup to apply a steady airflow to the device. A wind tunnel was designed and fabricated for the airflow test. The wind tunnel was composed of honeycomb structures to align the airflow, a squeezing nozzle, an acrylic pipe, and a DC fan motor with a nozzle to draw in air. The squeezing
nozzles were fabricated using UV-cured acrylic. The total length of the wind tunnel was approximately 0.4 m. The airflow velocity could be controlled by adjusting the power of the fan. The wind tunnel provided a laminar airflow. The airflow velocity at the test section was calibrated using an airflow sensor (Model 6332D, KANOMAX). As the test section, the device chip was affixed perpendicular to the airflow direction at the middle of a wind tunnel where the end of the nozzle parts. The cantilever was placed on the center of the pipe. The responses of the cantilevers were connected to the bridge circuit, as shown in Fig. 4(a). The outputs of the three cantilevers were measured simultaneously. Airflows between 1.2 and 5.6 m/s at 0.4 m/s intervals were applied.

3.2 Experimental results

The real-time response of the fractional resistance changes of the type-4 cantilever and comb-less cantilever for an airflow velocity of 4 m/s is shown in Fig. 5(a). The airflow was applied to the device during the time period between 6 and 18 s. Corrections were made for the resistance change caused by the airflow temperature in each resistance change using the cantilever designed for temperature compensation. The responses were defined as the averages of the resistance changes excluding the rising and falling responses that occurred during the airflow application and removal, respectively. The calculated drag forces generated on the surface of the type-4 and paralleled comb-less cantilevers as a function of the airflow velocity $V$ are shown in Fig. 5(b). The drag forces increased with increasing applied airflow velocity. It was observed that the drag forces at 4.0 m/s were a little large compared with the trend of the curves.
was thought to be because of the airflow velocity calibration error.

We evaluated the drag force of the combs by subtracting the drag force of the comb-less cantilever from that of the comb cantilever. The relationship between the drag force of each comb $F$ and the airflow velocity $V$ is shown in Fig. 6(a). The drag force of the continuous cantilever $F_C$ was also calculated and plotted using the same method. The drag forces on the continuous cantilever were larger than those of the comb cantilevers at all velocities.

The ratio of the drag force to the continuous cantilever increased with decreasing the airflow velocity, as shown in Fig. 6(b). Among the comb cantilevers, the drag forces of the type-4 cantilever were the largest, whereas those of the type-1 cantilever were the smallest at all velocities. The drag forces increased in the following order: type-4, type-3, type-2, and type-1. At an airflow velocity of 1.2 m/s, the drag force on the type-4 cantilever was approximately 60% of the drag force on the continuous cantilever. Thus, the bristled model of the type-4 cantilever experienced 60% of the force with a surface area equal to 12.5% of the continuous cantilever at this airflow velocity. This result indicates that the comb areas provided an airflow suppression due to boundary layer effects that increased the aerodynamic force at that moment, which corresponds to those of a previous simulation (Weihs and Barta, 2008, Shawn et al., 2013, Barta and Weihs, 2006). Assuming that the mass ratio between the comb and the continuous cantilevers was equal to the ratio of the surface area because of their identical thicknesses, the ratio of the inertial force was proportional to the ratio of the surface area ($1:8$). Thus, a flapping bristled wing would achieve energy-efficient aerodynamic forces efficiently due to its smaller inertial force.

### 3.3 Evaluation of drag coefficient

The aerodynamic characteristic of the combs was evaluated on the basis of the drag coefficient. The drag coefficient was calculated from the measured drag force as

$$C_d = \frac{F}{\frac{1}{2} \rho \cdot V^2 \cdot S}$$  \hspace{1cm} (6)

where $\rho$ is the density of air (1.2 kg/m³). Each calculated coefficient is shown in Fig. 7(a) as a function of the airflow velocity. The coefficient of the continuous cantilever did not change in the range between 1.2 and 5.6 m/s and was approximately two. The approximate Reynolds number was between 100 and 500, assuming that the cantilever length $L_1$ was defined as the characteristic linear dimension and that the kinematic viscosity $v$ was $1.5 \times 10^{-5}$. Thus, the
calculated coefficient of the continuous cantilever was approximately equal to that of square plates for these Reynolds numbers (Hoerner, 1965). In contrast, the coefficients of the comb cantilevers increased with decreasing airflow velocity. The coefficients also increased in order of type-4, type-3, type-2, and type-1 in an identical manner as the drag force. At an airflow velocity of 5.6 m/s, the coefficient of the type-1 cantilever was the smallest in the experiment. The bristled model of the type-1 cantilever could not simulate the aerodynamic effect of the comb structure at this airflow velocity.

Figure 7(b) presents the relation between the calculated drag coefficient and Reynolds number of each comb cantilever. In the calculation for the comb cantilevers, the comb’s width $l_1$ and the applied airflow velocities were defined as the characteristic linear dimension and the flow velocity, respectively. The drag coefficient of the continuous cantilever is also plotted. The width of the comb was varied from 8 to 64 μm, whereas the ratio $(l_1+l_2)/l_1$ only varied within a factor of two. Thus, the difference in the characteristic linear dimension (Reynolds number) was thought to be a dominant factor in the difference between the coefficients for each cantilever, comparing with that of the ratio. The drag coefficients of the comb cantilevers increased with decreases in the Reynolds number. The coefficient also approached that of the continuous cantilever. The discontinuity of each plot results from the difference of the ratio $(l_1+l_2)/l_1$ and comb number, ignoring the device fabrication error; however, the graph shape was similar to the drag coefficient of a square plate in a normal flow as a function of the Reynolds number (Hoerner, 1965), whereas the experimental coefficient was approximately twice larger at each low Reynolds number (5-100). The drag coefficient of the robotic-wing with comb structure was approximately 9 at an angle of attack (AoA) of 45 degrees for a Reynolds number of 12 (Sunada et al., 2002), which was predicted to be slightly larger at an AoA of 90 degrees. This value was similar the experimental result using the same Reynolds number. Thus, the comb structures are dominant dimensional factors in the aerodynamics around the cantilever and produce in an increased drag coefficient, whereas the size of the cantilever remained the same. At low Reynolds numbers, the comb areas of the cantilever acted as an airflow suppression due to boundary layer effects that resulted in an increased aerodynamic force. These results suggest that a thrips utilizes the aerodynamic effect of the comb structure, which would disappear if the bristled wing size increased considerably.

The size of the fabricated device was not entirely the same as that of real thrips anatomy. However, in principle, the MEMS fabrication process can produce a wing with combs approximately one micrometer in width, which is the width
of a thrips wing, for example, using electron-beam lithography as the patterning structure. Additionally, a direct calibration method applying differential pressure to the cantilever with surround structure will provide accurate calibration values (Takahashi et al., 2012).

The device was affixed perpendicular to the airflow direction, which means that we focused on the drag at an angle of attack (AoA) of 90 degree. A thrips flap generates an aerodynamic force by using not only drag but also lift with a variable AoA (Liu & Aono, 2009). In future studies, the device should be designed to measure not only vertical but also horizontal forces on the cantilever, for example, using a sidewall doping method (Kan et al., 2013, Takahashi et al., 2014). Then, both lift and drag forces can be evaluated with varying AoAs to more fully understand bristled wings.

In this study, we evaluated the aerodynamic characteristics of the comb structure using a steady airflow. The minimum airflow velocity was approximately one meter per second; however, the aerodynamic effect of the comb structure would increase at a sub meter per second applied airflow velocity, which is thought to be the average airflow velocity on the entire surface of a thrips wing. Our proposed cantilever can be utilized to evaluate these characteristics with unsteady airflow generated by flapping motions. A more detailed characteristic measurement would facilitate an understanding of the biomechanics of small flying insects as well the aerodynamic properties of their wings.

4. Conclusion

We designed and fabricated mechanical models of a thrips wing with piezoresistive cantilevers. The comb structure was attached to the side surface of each cantilever. Four types of comb cantilevers were tested in the wind tunnel. Aerodynamic drag forces were measured by the fractional resistance change of the cantilevers. Lower comb-width-based Reynolds numbers, which better approximate a bristled wing of a thrips, result in a larger aerodynamic drag force. The comb areas of the cantilever with 8 μm–wide combs experienced 60% of the force experienced by the continuous cantilever in an airflow of 1.2 m/s while possessing a surface area equal to 12.5% of the continuous cantilever. The experimental results suggest that a thrips utilizes an aerodynamic effect of the comb structure that would disappear if the bristled wing size became too large. The fluid-dynamic force coefficient of flying robots will also be enhanced by designing micro-sized wings with a several-micron-long comb structure. Our method will facilitate the evaluation of bristled wings and the development of artificial micro-sized flying robots.

Acknowledgments

This work was partially supported by JSPS KAKENHI (Grant No. 25000010). The photolithography masks were fabricated using the EB lithography apparatus of the VLSI Design and Education Center (VDEC) of the University of Tokyo. The authors thank Professor Shigeru Sunada for his advice on the aerodynamics.

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