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Fabrication of a hummingbird-mimetic flexible flapping wings

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Abstract:
Hummingbirds have been regarded as promising models for future micro aerial robots, because they capable of both sustained hovering and agile maneuvers. Their wings are mainly composed of flexible flight feathers, that allows passive feathering deformation of the wing during its flapping. In this study, we measured the flexural stiffness of the flight feather of a museum specimen of Amazilia hummingbird (*Amazilia amazilia*). It was found that the flexural stiffness can be expressed by the power function of a distance from the feather tip. Then, the artificial wing was designed based on the flexural stiffness of the real feather. The wing was fabricated by the laser cutting and heat pressing with minimum manual process. The mass and the flexural stiffness of the leading-edge shaft of three artificial wings with the same design were measured to evaluate the fabrication accuracy. As a result, the variation in mass and flexural stiffness was small, demonstrating the high accuracy of the fabrication of delicate flexible wings.

1. Introduction

Hummingbirds are well known for their ability of sustained hovering and agile maneuvers. Hence, the hummingbirds are promising design references for small flying robots. The wing of hummingbird consists of multiple flight feathers that allow significant feathering deformation during its flapping. Similarly, wings of previous flapping-wing aerial robots inspired by hummingbirds are flexible to some extent [1]- [4]. The wing typically consists of a polymer film supported by a leading-edge spar and chordwise ribs made of relatively stiff materials such as CFRP (carbon fiber reinforced plastic). Those previous wings were, however, empirically designed through prototyping, and the design principle of the wing flexibility has not been established yet. Moreover, the spars and ribs in the previous wings are typically uniform in the width and thickness, so the flexural stiffness of the whole wing was not delicately controlled. Precision in fabrication is also important since slight error due to manual fabrication such as gluing easily leads to considerable variation in stiffness and mass of the thin and lightweight wing.

In this study, the flexural stiffness of hummingbird feathers was measured by static bending tests and mimicked with UV-laser-cut tapered CFRP spar and ribs. The CFRP spar and ribs were bonded to a polyimide film vis thermosetting adhesive film by heat pressing [5], that eliminated fabrication error due to manual gluing.

2. Materials and Methodss

2.1 Measurement of flexural stiffness of feathers

The flexural stiffness of feathers of a museum specimen of Amazilia hummingbird (*Amazilia amazilia*) collected by Yamashina Institute of Ornithology was measured by cantilever static bending tests (Fig. 1). In this measurement, a feather shaft was clamped and vertical force was applied at

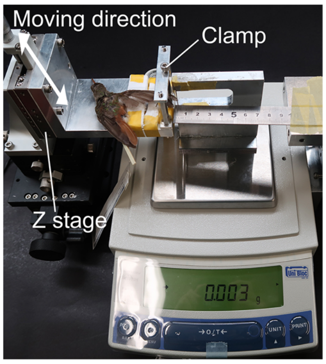

Fig. 1. Setup for static bending tests of feather shadts of a museum specimen of an Amazilia hummingbird.

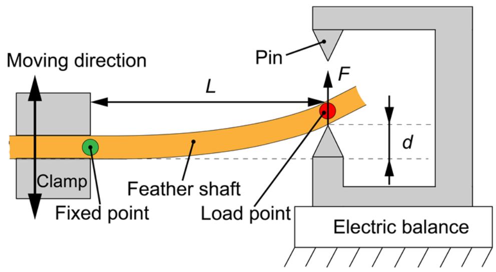

Fig. 2. Side-view schematic of the static bending test

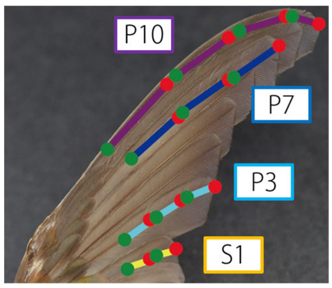

Fig. 3. The measured feathers and measurement points.

another point of the feather shaft.The flexural stiffness, EI, was calculated as $EI = FL^3/3d$ where E is Young's modulus, I is moment of inertia, F is the load, L is distance between the clamping point and the force application point, and d is the displacement by the force (Fig. 2). The measured feathers and sections are shown in Fig 3. Each point was measured twice for bending to the dorsal side and ventral side. The calculation position representing each section was defined as the midpoint between the clamping force application points.

2.2 Fabrication of the artificial wing

The planar shape of the artificial wing and the mechanical properties of the materials are shown in Fig 4 and Table. 1. The artificial feather shafts were named as F1 to F4 from the leading edge to the side edge. F1, F2, F3, and F4 shafts represent 3, 3, 4, and 5 real feathers, respectively. The tapered width of the shafts was determined based on the flexural stiffness of the real feathers, while its minimum width was set to 100 μm to prevent breakage during fabrication. Since the actual wing root of the hummingbird possesses bones and does not deform significantly [6], the root of the artificial wing was reinforced by doubling the thickness with a bone part (Fig. 4). The procedure of fabricating is as follows. Firstly, as shown in Fig 5 (a, b and c), feather shafts, alignment holes and bone part were cut out from a polyimide film, sheet adhesive (DuPont™ Pyralux® FR1500) and a CFRP plate, respectively. The DPSS laser (Nd:YVO4; 355 nm; 7 W) cutting machine, which allows high-speed cutting in arbitrary curved shape with accuracy of 1μm in positional repetition and 20μm in the diameter of laser spot on the surface, was used for cutting out. The laser-cut materials were laminated as shown in Fig 6. The thick polyimide film and rubber layers protect the materials from the heat press machine. Then, the materials were pressed with 400 kPa at 190°C for 1 hour, and then outline was laser-cut (Fig 5, d).

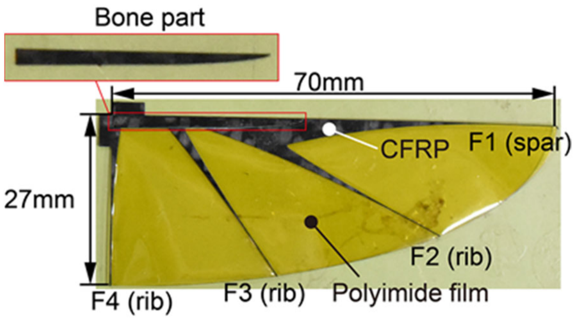

Fig 4. Top view of the fabricated artificial wing.

Fig 5. Laser-cut materials. (a) Polyimide film. (b) Adhesive sheet. (c) CFRP plate. (d) Artificial wing cut out from the laminated materials.

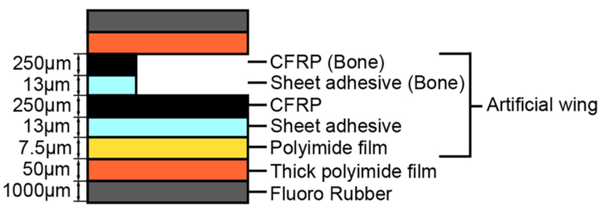

Fig 6. Cross-sectional schematic of the lamination.

Table 1. Mechanical properties of CFRP and polyimide film used for the artificial wing

Material	Thickness [μm]	Young's modulus [GPa]
CFRP	250	23
Polyimide film	7.5	5.3~5.6 [7]

3. Experiments and Results

3.1 Flexural stiffness of real feather shafts

The flexural stiffness of real feather shafts was proportional to the power of the distance from the feather tip (Fig. 8). The filled markers represent the values when the feather was bent to the dorsal side, and the open markers represents the values when the feather was bent to the ventral side, respectively. By fitting a power curve to all the data points, the flexural stiffness was expressed as $EI = 2.0 \times 10^{-9} x^{2.65}$ where x is the distance from the feather tip. The CFRP spars and ribs in Fig. 4 were designed using this equation.

3.2 Evaluation of the artificial wing

Three artificial wings with the same design were fabricated to evaluate the fabrication accuracy. The flexural stiffness of F1 shafts and the total mass were measured for each wing (Fig. 9 and Table 2). Variation in mass was less than 3.5 % owing to exclusion of manual gluing. Measured flexural stiffness well matched the designed values. The tip region, however, was still affected by slight alignment error in the outline cutting, since the shaft was very narrow near the tip and its design value of flexural stiffness was very small as well.

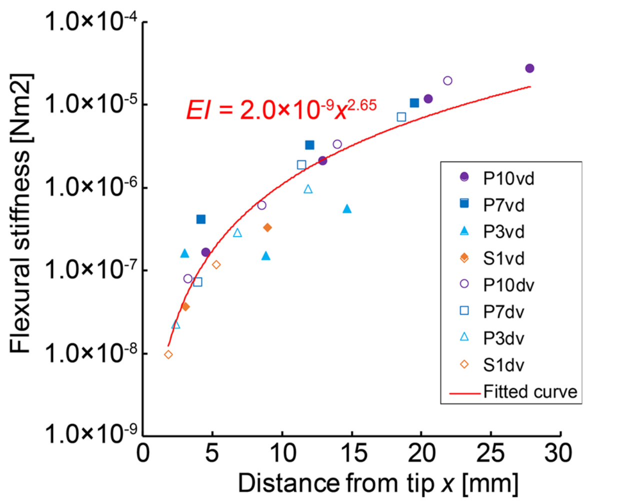

Fig 8. Measurement result of static bending test

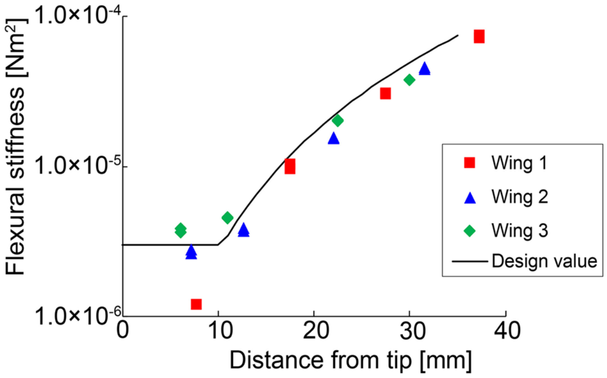

Fig 9. Measurement result of the flexural stiffness of F1

Table 2. Mass of the three artificial wings

Wing 1	Wing 2	Wing 3
118 mg	116 mg	120 mg

4. Conclusion

Flexural stiffness of feather shafts of a museum specimen of Amazilia hummingbird was measured. It was found that the flexural stiffness was proportional to the power of the distance from the tip. Then, the artificial wing was designed based on the result. The wing was fabricated by the laser cutting machine and heat press. As a result, the fabrication error of manual gluing was eliminated and the variation in the flexural stiffness and mass is small.

Acknowledgement

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