EFFECTS OF WING STIFFNESS ON LIFT AND THRUST

EXPERIMENTAL STUDY ON TEST APPARATUS WITH PASSIVE WING ROTATION

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Abstract: The effect of flapping wing stiffness on lift and thrust was studied through experiments on a test bench which provided model wings with an active flapping motion and a passive rotational motion about its longitudinal axis. All five wings under test had the same wing planform which was an enlarged version of a hindwing from a dragonfly Aeschna. However, their stiffness varied from wing to wing in both chord and span wise. The experiment was carried out by applying the method of Design of Experiments (DOE). The results showed that there existed an optimum wing flexibility at which the maximum lift was produced, and the minimum thrust occurred when the maximum lift was generated.

Key-Words:  wing stiffness, passive wing rotation, effect on lift and thrust

1. Introduction

From the perspective of an engineer, the objective of studying flapping wing unsteady aerodynamics is to build the Micro-air-vehicles (MAV) suitable for the purposes found in domestic and military, with ease. Although the understanding of unsteady flapping aerodynamics is still in its infancy, it seems there is a trend that the size requirement of MAVs is getting smaller. When the dimensions of MAV become smaller, Reynolds number comes down accordingly. With the Reynolds number lowered, the unsteadiness of the flow around the wing increases. In the unsteady situation, flexible wing shows many advantages over the rigid wing. Therefore, in order to find a way one can easily build the desirable MAV, the understanding of wing flexibility effect need to be expanded.

The importance of wing flexibility in natural flyers or fish has long been noticed [1-3]. But not many researches have been
done in this area, possibly because of its intrinsic difficulties.

Shyy [4] studied a single membrane as an airfoil and found that flexible wing has better lift-to-drag ratio compared to the rigid one, if flexibility is applied properly. Then he studied further on a wing with the upper surface flexible and concluded that “adaptive airfoils can improve the performance of the MAV to sustain flying in a fluctuating environment”.

Heathcote[5] suggested that an optimal wing stiffness exist to produce maximum propulsion after the experiment, in which he tested 3 plunged rectangular wings having different thickness in a water tank. These rectangular plates having different thickness served as the wings with different flexibility. Heathcote[6] furthered his experiment with flexible rectangular wings using the same experiment equipment and found the similar results as before that modest flexibility is beneficial to the thrust. He also noticed that it happened when the Strouhal number is about 0.2~0.4.

By numerical analysis, Pederzani [7] showed that chordwise flexibility increase the efficiency than rigid wing in heaving motion. Also by numerical simulation, Chimakurthi’s [8] computational results matched Heathcote [6] experimental results. Previous wing flexibility researches have been focused on rectangular wing in heaving motion, wing deformed in one direction, and wing rotation were not included.

We ask ourselves what the effect of wing stiffness on aerodynamics would be if we put the wing in the situation where it flaps actively but rotates passively [9]. In addition, use a wing planform found in the nature and being flexible in both span and chord wise. This combination looks more like an insect wing flapping.

Based on this consideration, a mechanical model with the characters mentioned above was designed and manufactured. The experiment was conducted on a batch of 5 wings, whose stiffness were ranged from rigid to flexible, having a same dragonfly wing planform but enlarged about 12 times to its natural original size [10]. In attempting to extract the major aerodynamic effects with minimal times of experimental runs, a Design of Experiments (DOE) method was employed in the current experimental research.

2. Experimental Methods

The experiment to study the flexural stiffness effects of flapping wing on lift and thrust was carried out with the aid of a test bench, which was designed to have the functions that the wing flapping actively but rotated passively. Two sensors were installed on the test bench: one for collecting the force and torque generated by the wing and the other for obtaining the rotational angle inside the rotational angle control housing. The method of DOE was employed to capture the desired effects of wing stiffness on aerodynamic forces, by which a large amount of experimental work was eliminated.
2.1. Experimental Device

The experimental system shown in Figure 1 contains three major subsystems, namely mechanical, electrical and data acquisition system.

There two major assemblies in mechanical system, which are a wing flapping mechanism represented by wing flapping axis in Figure1, and wing rotating mechanism including wing itself, force/torque sensor and wing rotation housing which contains 2 angle limit springs inside. Wing flapping mechanism generates a swing motion for wing to flap in vertical stroke plane about wing flapping axis. Wing rotation mechanism makes the wing rotating about the wing rotation axis passively. The passive wing rotation is realized in the following way. During up or down stroke, wing experiences aerodynamic force due to the surrounding air, as well as inertial force due to the angular acceleration. The centers of these forces don’t lie in the wing rotational axis. Hence, a net torque about the rotational axis.

Figure 1 Schematics of experimental system designed to test wing stiffness effects on aerodynamic forces generated by an actively flapping but passively rotating wing.
by these forces is produced and consequently it makes the wing rotating. Two springs in the rotation angle control housing limit the degrees that the wing could rotate in either direction independently. The major function for electrical system is to drive the wing and control the flapping speed. Data acquisition system (DAS) employs a 6 degree of freedom (6 DOF) force and torque sensor mounted on the wing root to collect the force and torque generated by the wing in 3 dimensional-spaces. DAS also employs a sensor to collect wing’s rotational angle which is necessary for measuring AOA and converting the force/torque data from sensor reference to ground reference in the pro-test data processing.

2.2. Wing Design and Fabrication

The factors under consideration during wing design were: shape, weight, flexural stiffness and its variation in span and chord directions. The planform of a dragonfly wing was chosen considering dragonfly is popular for its aerial maneuverability. The model wing had the shape of an enlarged version of the real dragonfly Aeschna’s hindwing [10]. It has the span of 499 mm measured from wing root to tip, and the maximum chord of 145 mm.

The light weight wing was desirable so that the flapping inertial effect when can be minimized. Carbon fiber was selected as the material for making wing veins by taking advantage its lightness and strength. Wing membrane was made of cello sheet, with the thickness of 0.03 mm for all wings. The cello sheet was so thin that its stiffness could be ignored compared to the one of carbon veins. Therefore the stiffness of the wing was mainly determined by the vein material.

In the model wing, the vein was arranged as the one shown in Figure 2. A main spar runs in spanwise while 7 minor spars running in chordwise and evenly placed. Since the trivial effect of the cello sheet, the flexural stiffness of the wing in span and chordwise were determined by main spar and minor spars separately by the current

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**Figure 2** Fabricated wing with the shape of dragonfly Aeschna’s hindwing
vein arrangement. The main spar illustrated in Figure 2, is tapered in shape with the end near wing root larger and has the same thickness at any section. The minor spars were made with the shape of rectangular strips. In the same wing, 7 minor spars have the same height, but the widths descents from the chord near the wing root to chord near the tip. Although the height of chords is different from wing to wing, the width and length were kept the same for the chord spar placed at the same corresponding position for all wings.

The membrane was formed by a piece of thin clear cello sheet cut to a shape of dragonfly *Aeschna’s* hindwing but enlarged by about 12 times. The main and minor spars were joined together by super glue to form the wing vein structure. The final wing was completed by bounding the wing vein structure and membrane by double sided sticky tape. The mass properties of the fabricated wings are listed in Figure 3.

<table>
<thead>
<tr>
<th>Wing</th>
<th>Mass [g]</th>
<th>Centre of Mass [mm]</th>
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<td>5</td>
<td>2.8</td>
<td>186</td>
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**Figure 3** Table of wings’ mass property

### 2.2.1. The Measuring of Wing Stiffness

To simplify the stiffness expression without losing the nature of stiffness, the stiffness in the current experiment is defined as the vertical force divided by the deflection at the point where the force is acting upon in either span or chord wise.

Spanwise stiffness was measured by clamping horizontal wing at its root, applying force vertically at desired point, measuring the deflection at the force acting point in the force direction, and dividing the force by the deflection. Chordwise stiffness was measured by clamping horizontal wing at its rotation axis, placing a bar across the wing surface which is horizontal and parallel to the wing rotation axis, applying force vertically on the bar, measuring the deflection at the force acting point in the force direction, and dividing the force by the deflection.
Figure 4  Wings’ spanwise stiffness

Figure 5  Wings’ chordwise stiffness
2.3. Design of Experiments (DOE)

<table>
<thead>
<tr>
<th>Run</th>
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<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
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Figure 6 Taguchi’ DOE L9 Table

According to L9 table, 9 runs are required for each experiment. Four factors and each with 3 levels are involved. In the current experiment, the 4 factors were assigned as follows: factor 1 being flapping frequency; factor 2 stiffness of spring 1; factor 3 stiffness of spring 2; and factor 4 wing stiffness. Three levels (1,2,3) in factor 1 represented flapping frequency “low”, “medium” and “high” respectively. Three levels (1,2,3) in factor 2,3 and 4 represented stiffness in spring1,2 and wing for “stiff”, “medium” and “soft” respectively.

3. Experimental Results and Discussion

Following the procedure in L9 table, experiments were carried out and two types of raw data were collected. One is the force and torque in sensor reference and the other is the wing rotation angle. As an example, figure 4 shows a phase-averaged lift and thrust of the 7th run in sensor reference frame.
The forces recorded above in fact were not the pure aerodynamic forces generated by the air but contaminated with the inertial force of the wing. It can be shown that the wing flapping inertial force is a dominant component compared to the one caused by the wing rotational motion. This implies that inertia caused by wing flapping motion can be considered as the entire wing inertia regardless of the one caused by wing rotational motion. Therefore, in order to remove the inertia of the wing, one practical and simple method is to run the Table L9 again involving the wings with no membranes and record the force and torque as before. Then the pure aerodynamic forces can be resulted in subtracting the inertial force/torque from the one measured previously when the membrane was on the wing. Figure 8 shows the inertia of 7th run in sensor reference frame and Figure 9, 10 shows the pure aerodynamic forces in sensor and ground reference respectively.

Figure 7  Phase-averaged lift and thrust of 7th run with inertia in sensor reference frame.

Figure 8  Phase averaged time history of inertia of 7th run in sensor reference frame.

Figure 9  Phase averaged time history of non-inertia aerodynamic forces of 7th run in sensor reference.

Figure 10  Phase averaged time history of non-inertia aerodynamic forces of 7th run in Ground reference.
During force conversion from sensor reference to ground reference frame, two angles were used: one was the wing rotation angle and the other was the wing flapping angle. Wing rotation angle was measured directly through sensor. Wing flapping angle varied in the current test bench following a sinusoidal function. The actual measurement showed that R-squared value was 0.998 when compared against the ideal sinusoidal function.

Once raw data are acquired following the procedure in Table L9, the effect of each level of any factor can be calculated by averaging the values of the same level of the same factor. Figure 11 shows the effect of wing stiffness on average vertical force and horizontal force in ground reference frames respectively.

![Figure 11](image1.png)

**Figure 11** The effect of wing stiffness on average lift and thrust in ground reference. In this experiment, wing 1, 3 and 5 were used.

It shows that the rigid and very soft wings are not in favor of generating strong lift but thrust. It also showed that there existed an optimum state of wing stiffness at which maximum lift was generated but at the cost of receiving minimum thrust.

To confirm the results in the first experiment, the experiment was carried out once more with a different batch of wings but keeping the moderate stiffness wing in the new batch. In fact, in the first experiment, wing 1, 3 and 5 were used and second time wing 2, 3 and 4 were used. Figure 12 shows the results of the wing stiffness effect from wing 2, 3 and 4. The similar result form the second experiment consolidated the findings from the previous one.

![Figure 12](image2.png)

**Figure 12** Stiffness effect on lift and thrust in ground reference frame. In this experiment, wing 2, 3 and 4 were used.

4. **Conclusion**

A series of 5 wings fabricated from rigid to soft were utilized in an experiment seeking the effect of wing stiffness on aerodynamic forces generated by active flapping but passive rotating wing. With certain flexibility, flapping wing generated maximum lift but at the cost of producing minimum thrust, provided the other flight parameters unchanged.
Reference:


