FLUTTER INHIBITION IN ANIMAL WINGS

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Animal wings are usually made of elastic materials and thus have different characteristics from conventional airplane wing made of hard stuff. The elasticity of wing provides merits such as a large straight-line stability but causes a serious problem of flutter. This study investigates how animals withstand this problem focusing on the bird wing. The wing of birds is composed of many feathers, the representative of which is a primary feather. Interestingly, flutters are hardly observed in the primary feathers. The reflection in the primary feather was supposed to be the key factor of flutter inhibition. The wind tunnel tests with feather models with and without reflection were conducted and it was confirmed that the feather with reflection more effectively inhibited the flutter generation than the feather without reflection.

Keyword: flutter inhibition, bird wing, primary feather, reflection

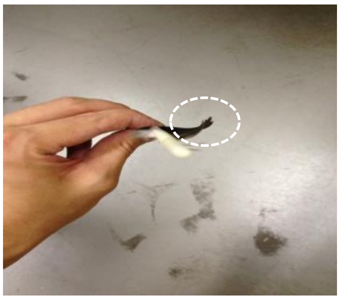
1. INTRODUCTION

Wing of flying animals such as birds or insects is made of elastic materials. Feather of bird wing is made of “keratin” which is a kind of protein known as a main component of human hair. Wing of insect is made of “chitin” which is a kind of saccharide. Both materials have moderate elasticity and thus it raises a question that why birds or insects use elastic materials instead of hard one such as calcium for wings. It may involve both aerodynamic and structural contexts. For the structural one, a wing made of hard material may be easy to crash or hurt subjects and heavy. In contrast, the aerodynamic one was not fully clarified so far.

Investigations to solve this problem were conducted previously focusing on a bird wing. Bird wing is composed of several kinds of feathers. Primary feathers are generally longer than other feathers and located at the wing tip. About 10 pieces of primary feather align anteroposteriorly and generally bend up while flying which is typically observed in the gliding hawk or condor wings[1)]. In the previous researches, the aerodynamic effects of primary feathers were investigated and several benefits were pointed out such as a reduction of induced drag or an increase of lift slope[2-5)]. However, those studies were based on hard wing models made of aluminum or stainless steel and thus the elasticity was not considered.

The study to clarify the function of elasticity in a bird wing was conducted previously in our laboratory[6)] and some benefits were pointed out such as a large resistance force to prevent a side slip or a large restoring moment of rolling both of which were larger than that of the hard wing models, and thus were

(a) plan view



(b) lateral view

Figure 1: Primary feather of a bird wing. The part in the dashed circle shows the reflection

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effective for enhancing a straight-line stability. However, the elasticity in the wing model caused a problem of flutter. The flutter is generally caused by a coupling of the aerodynamic force and the elastic force of the subject[7]. So, the soft and flexible subject is easy to generate flutter. The feather model used in the previous study was made of elastic plate such as vinyl chloride, so the flutter was unavoidable.

In contrast, flutters are hardly observed in the bird wing even though the feather of the wing is flexible. We supposed that the reflection in the primary feather as shown in Fig. 1 was a key factor for this flutter inhibition. The reflection of the wing has the characteristics of pitching stability which stabilize the pitching angle of the wing and inhibit its divergence[1]. The flutter generally starts with the torsion of the wing, so, the pitching stability may inhibit the torsion and thus have the effective role of flutter inhibition. The wind tunnel test was conducted to confirm this role and the results are reported in the following sections.

2. METHOD

The reflection wing model for the wind tunnel test is fabricated using a thin aluminum plate. The plate size is 45[mm]x180[mm]x0.3[mm] and is bent convexly in front and concavely in rear to reproduce the reflection shape as shown in Fig. 2. The height h_1 and the depth h_2 are varied to make several types of the reflection. For instance, the normal reflection type has h_1=2[mm] and h_2=2[mm]. The length of the convex c_1 and the concave c_2 are also varied. For the normal type, c_1=(2⁄3)c and c_2=(1⁄3)c, where c is the wing chord length. The other values are shown in Table 1. The large type has the double size of h_1 and h_2 to the normal type; the even type has the same size of the convex and the concave parts, i.e. the border of the convex and the concave part is the center line of the wing; the camber type has only a convex part; the oblique type has the border which runs obliquely from the root to the tip of the model. Figures 3(a)-(d) show the typical types of the wing model.

The reflection or the camber type is hard to bend or twist because the structural stiffness becomes larger than the flat plate. This means the wing model is hard to flutter itself. So the plastic plate is attached to the wing root as shown in Fig. 4 and the opposite side of this plate is fixed to a sting in the wind tunnel. The wing model, then, becomes easy to twist or bend and thus can generate the flutter under 4[m/s] air currency.

The wind tunnel is equipped with a closed type test section which is surrounded by walls. The wind tunnel can make the wind speed up to 20[m/s], but we use 4[m/s] because the wind faster than 4[m/s] generates large flutters which makes the wing touch the surrounding walls and thus prevents the correct measurement.

The flutter is recorded by a high speed video camera (NAC MEMRECAM fx-k4). The torsion θ [deg] and the bending d [mm] of the wing are measured by the motion tracking software (DITECT Dipp-MotionPRO). The definition of them are shown in Fig. 5, where a, b, p are the leading edge, the trailing edge, and the central point of the wing section, respectively.

Table 1: Reflection parameter

Type	h_1 [mm]	h_2 [mm]	c_1	c_2
Flat plate	0	0	n/a	n/a
Normal	2	2	(2/3)c	(1/3)c
Large	4	4	(2/3)c	(1/3)c
Even	2	2	(1/2)c	(1/2)c
Camber	2	0	c	0
Oblique	2	5*	root: c tip: (2/3)c	root: 0 tip: (1/3)c

*maximum value at the wing tip

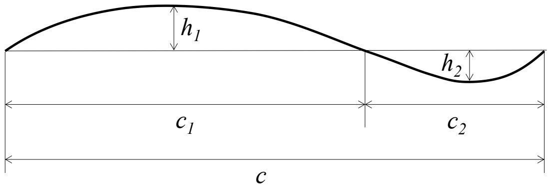
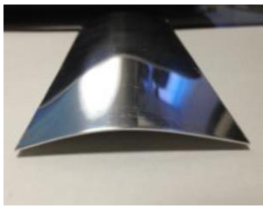


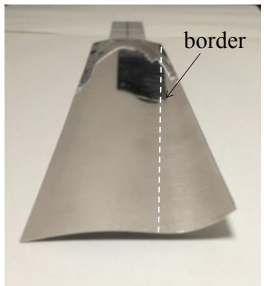
Figure 2: Parameters of reflection wing

(a) Normal

(b) Even



(c) Camber



(d) Oblique

Figure 3: Typical wing models

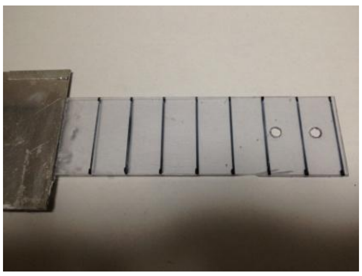
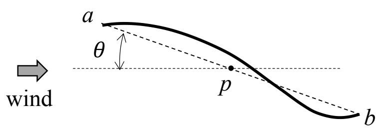
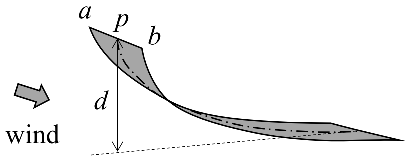


Figure 4: Plastic plate at the root of the wing



(a) Torsion



(b) Bending

Figure 5: Definition of torsion and bending

3. RESULTS AND DISCUSSION

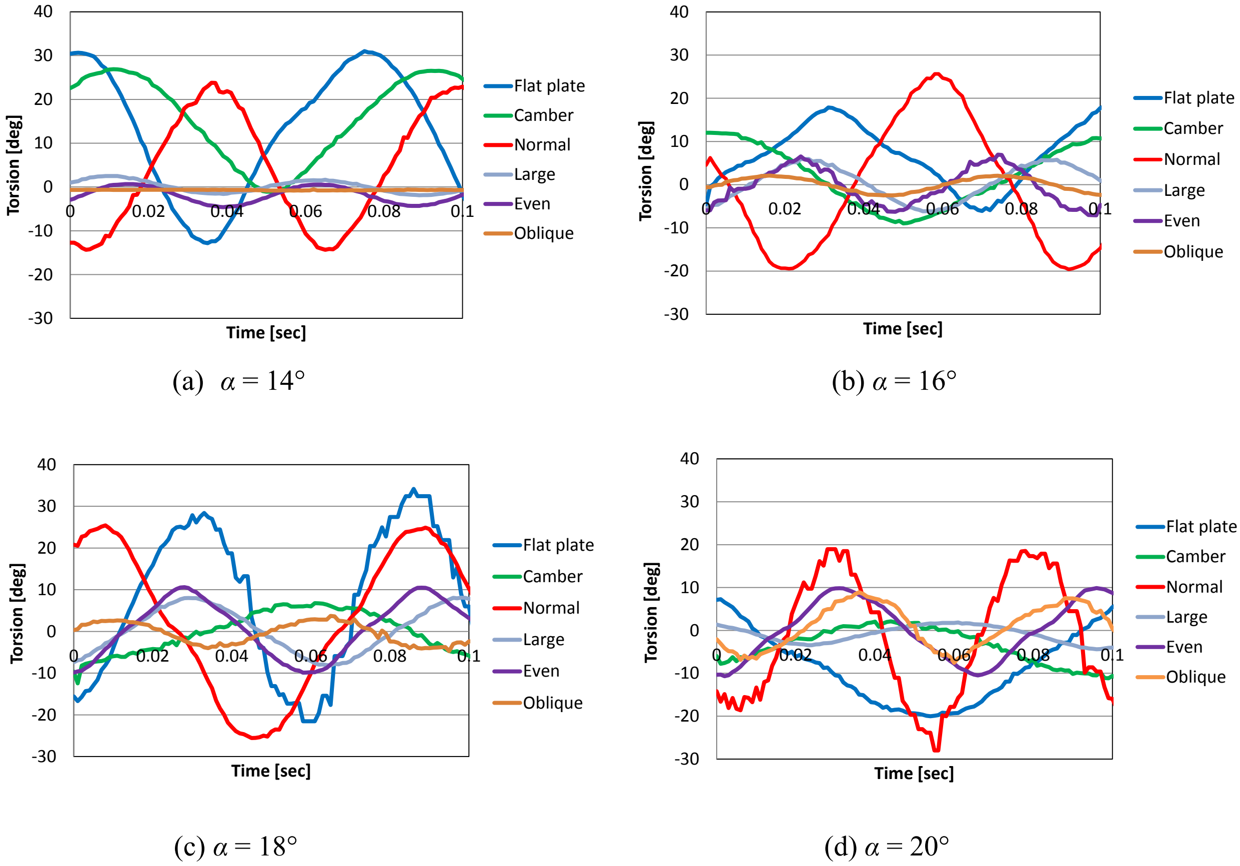
The temporal change of torsion of wing models is shown in Figs. 6(a)-(d) for various angles of attack α. Distinct flutter was not observed when α was small ($\alpha<14°$). So the results are shown for $\alpha\geq14°$. The torsion and the bending of wing became oscillatory when $\alpha\geq14°$ and both the amplitude and the frequency were different for different wing models. When $\alpha=14°$, the amplitude of torsion oscillation was large for the flat plate and the normal type as shown in Fig. 6(a). The camber type was next large. The amplitudes of even and large types were small and the oblique type had the smallest amplitude. When $\alpha=16°$, the normal and the flat plate types had a large amplitude and the camber type followed it as shown in Fig. 6(b). This tendency was same for $\alpha=18°$ and $\alpha=20°$ as shown in Figs. 6(c) and 6(d) and the amplitude did not show the obvious dependency on the angle of attack. Namely, the amplitude was about ±30° for the flat plate and the normal types for all angles of attack, and it was about ±10° or less for other types of the wing

The temporal change of bending of wing models is shown in Figs. 7(a)-(d) for various angles of attack α. Period of oscillation for bending tended to differ among wing models and the oscillation was recorded for one or several cycles. So, the lines of oscillation with small periods ended earlier than that of the longer one in the graphs. As shown in Fig. 7(a), the amplitude of bending oscillation was large for the flat plate when $\alpha=14°$. The amplitude for other types was significantly smaller than that of the flat plate. When $\alpha=16°$, the bending oscillation of flat plate showed a conspicuously large amplitude and slow oscillation as shown in Fig. 7(b). This means the quality of bending oscillation changed from a local one at the wing tip to the global one which made the whole wing oscillate up and down largely. When $\alpha=18°$, the camber type also showed a large and slow oscillation as shown in Fig. 7(c), and when $\alpha=20°$, the normal type also showed a large and slow oscillation as shown in Fig. 7(d). Meanwhile, the oblique, the large, and the even types showed conspicuously small oscillations. In particular, the oblique type hardly oscillated when $\alpha=20°$.

In summary, the wings with reflection showed flutter inhibition characteristics except the normal type. They showed a small oscillation of torsion and bending for all values of angle of attack. Meanwhile, the flat plate, the normal, and the camber types showed a large oscillation for all angles of attack and did not show the flutter inhibition. The reason for this difference might be the pitching stability of the reflection wing. From the thin wing theory [1, 8], the reflection wing has the stability of pitching rotation. When the angle of attack increases or decreases from the equilibrium angle, the center of pressure tends to move backward or foreword, respectively, to generate a restoring moment and the wing recovers its original angle. This pitching stability inhibits the torsion of the wing and thus inhibits the rapid increase or decrease of the angle of attack of the wing. The lift of the wing may then relatively stay stable and thus the bending oscillation may also be inhibited.

The flat plate and the camber types did not have this characteristics, thus the significant flutter was generated both in torsion and bending. The normal type showed a large flutter although it had the reflection. This means small size reflection is not enough to inhibit the flutter. The values of h_1 and h_2 of the normal type were both 2[mm] which was 4.4% of the chord length, whereas h_1 and h_2 of the large type were both 4[mm] which was 8.9% of the chord length. This result indicates that the necessary values of height and depth of reflection exist for the flutter inhibition. The even type showed the flutter inhibition although h_1 and h_2 were both 2[mm]. The even type had larger space of concave than the normal type. Therefore, the effect of reflection may be augmented both/either by making the height (h_1) and the depth (h_2) larger and/or the space of concave larger.

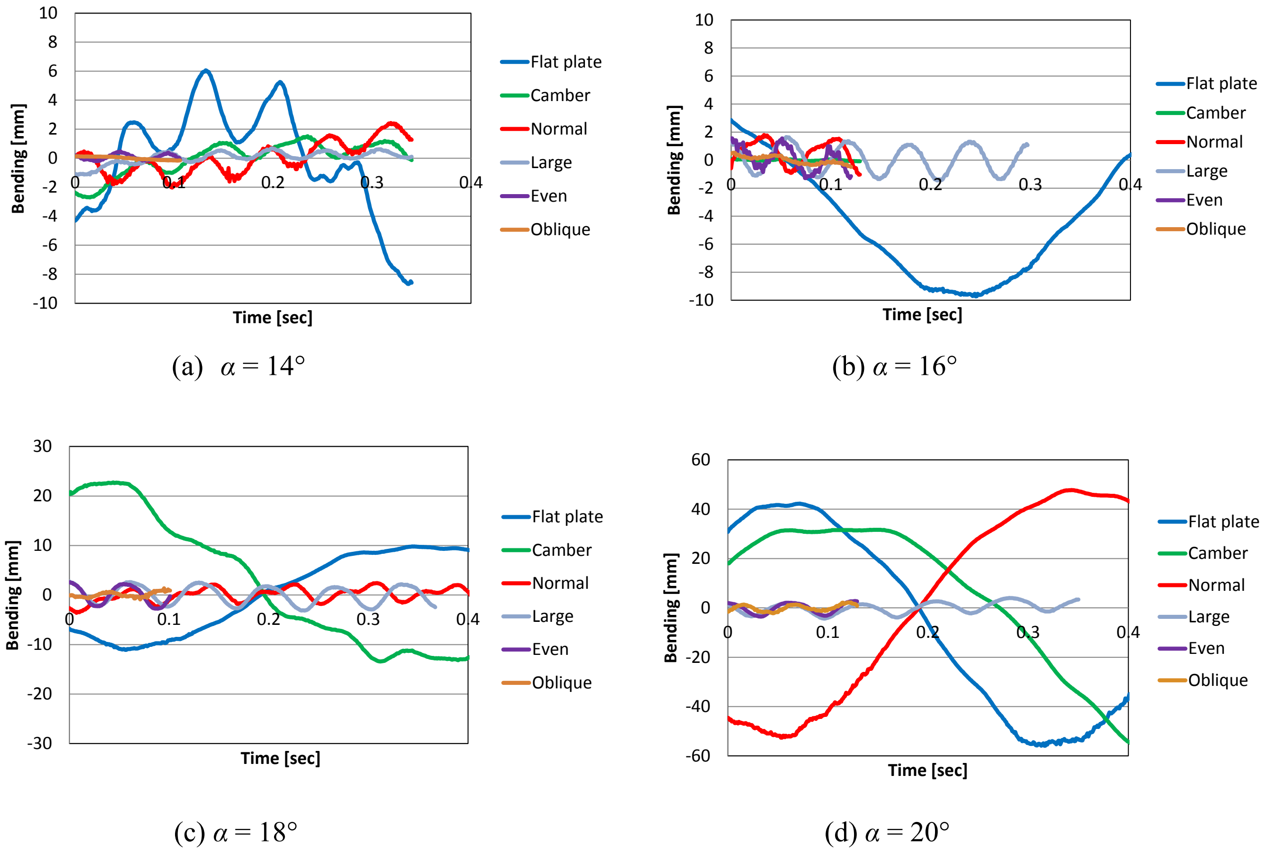
The primary feather of bird wing generally has a large and oblique reflection. The oblique type in this study mimicked it and showed a conspicuous flutter inhibition effect. This may be because the continuous change of wing section shape from the root to the tip of the wing realizes the flutter inhibition over the wide range of angle of attack. The conspicuous flutter inhibition of oblique type reflection in a bird wing may realize the stable lift generation and stability in the flight, thus significantly advantageous for the long duration and long range flight.



(a) $\alpha = 14°$ (b) $\alpha = 16°$

(c) $\alpha = 18°$ (d) $\alpha = 20°$

Figure 6: Torsion for various angles of attack



(a) $\alpha = 14°$ (b) $\alpha = 16°$

(c) $\alpha = 18°$ (d) $\alpha = 20°$

Figure 7: Bending for various angles of attack

REFERENCES

1) A. Azuma, The Biokinetics of Flying and Swimming, Second Edition, AIAA Education Series, AIAA, Virginia, USA, 2006.

2) V. A. Tucker, Gliding Birds: Reduction of Induced Drag by Wing Tip Slots between the Primary Feathers, *J. exp. Biol.*, vol 180, pp. 285-310, 1993 .

3) V. A. Tucker, Drag Reduction by Wing Tip Slots in a Gliding Harris' Hawk, *Parabuteo Unicinctus*, *J. exp. Biol.*, vol 198, pp. 775-781, 1995.

4) D. S. Miklosovic, Analytic and Experimental Investigation of Dihedral Configuration s of Three-Winglet Planforms, *J. Fluid. Eng*., vol. 130, pp.07113-1-07113-10 , 2008.

5) J. E. Guerrero, D. Maestro, A. Bottaro, Biomimetic Spiroid Winglets for Lift and Drag Control, *C. R. Mecanique*, vol 340, pp. 67-80, 2012

6) M. Motomatsu, Y. Inada, Effect of Elasticity in the Bird-like Primary Feather Wing on the Flight Stability, Proceeding of the 29th Congress of the International Council of the Aeronautical Sciences (ICAS 2014), 2014.

7) R. L. Bisplinghoff, H. Ashley, R. L. Halfman, Aeroelasticity, Dover Publications, Inc. Minesota, New York, 1996.

8) J. J. Bertin, Aerodynamics for Engineers, Fourth Edition, Prentice-Hall, New York, 2002.