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Engineering Notes

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Experimental Study on Lift Characteristics for Flow over Flexible Cropped Delta Wings

J. J. Wang* and Y. Liu†
Beijing University of Aeronautics and Astronautics, 100191 Beijing, People's Republic of China

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Nomenclature

α	=	angle of attack of the cropped delta wing, deg
α_{stall}	=	stall angle of the cropped delta wing, deg
C	=	heterogeneous flexible wing
C_L	=	lift coefficient of the cropped delta wing
$C_{L\max}$	=	maximum value of C_L
c	=	root chord length of the cropped delta wing, mm
Re	=	Reynolds number
t	=	wing thickness, mm
t/c	=	relative thickness of the cropped delta wing
U_∞	=	freestream velocity, m/s
Λ	=	sweep angle of the cropped delta wing, deg

Introduction

MICRO air vehicles (MAVs), which are characterized by their dimensions of less than 15 cm, have attracted more and more attention since the 1990s. Compared to regular vehicles, MAVs not only have lighter mass, smaller dimension, and lower cost, but are also more convenient for manipulation, have less noise, better stealth, and more agile maneuverability. Furthermore, accompanied with video cameras, chemical sensors, electronics, and communication devices, MAVs have wide practical applications in both the military fields, such as reconnaissance, weapon delivery, and objective predator, and the civil fields, such as environment monitor, nuclear-biochemistry sampler, aerophotograghy, pasture patrol, and so on.

The wing of a MAV, as the main lift surface, has important influence on MAV aerodynamics. In previous studies, Waszak et al. [1], Smith and Shyy [2], and Ifju et al. [3] pointed out that flexible wings would be more suitable than rigid ones for MAVs because of their favorable aerodynamic performance in unsteady environments. The flexible wing could change its local angle of attack and camber, and deform its platform in flight so as to accommodate to the given condition. This capability is critical to MAVs because, for flight speed, dimension, and weight of MAVs, the Reynolds number can be changed by more than 30% as a result of wind speed. In addition, the roll and sideslip of a MAV could be controlled by its deformation without aileron and rudder, which would reduce the vehicle's mass. Therefore, it is believed that flexible wings will play a significant role in the development of pragmatic MAVs in the future.

For flow over flexible, nonslender delta wings ($\Lambda \leq 55$ deg), some detailed investigations [4,5] have indicated that the wing flexibility has a great influence on lift enhancement and stall delay. These investigations revealed that the differences between flexible and rigid wings lie in two aspects: 1) spanwise camber deformation caused by flow, and 2) vibration of the wings. Similar results were obtained by Wang and Wu [6] for different elastic cropped delta wings with $\Lambda = 40$ deg; they also found that the angle of attack, at which the maximum deformation of the wing apex appeared for the elastic wing, is in accordance with the angle of attack where the leading-edge vortex broke down at the wing apex for the rigid wing. Thus, it can be seen that the aerodynamic performance and the flow structure for flow over flexible, nonslender delta wings are very complicated, and very little has been known so far. The purpose of this Note is to discuss the flexibility and Reynolds number effects on lift coefficient and hysteresis for flow over cropped 40 deg delta wings, and it is expected that some insights into this issue can be provided.

Experimental Facilities and Setup

The models tested in the present experiment are cropped 40 deg sweep delta wings (Fig. 1) with a chord length c of 181.84 mm and a trailing-edge spanwise length of 350 mm. The model flexibilities are changed with different materials and thicknesses. One type is a homogeneous wing made of aluminum alloy LY12CZ. The model of 0.8 mm thickness ($t/c = 0.44\%$) is designed as an elastic wing, and the model of 3 mm thickness ($t/c = 1.65\%$) is used as a rigid wing with leading and side edges symmetrically beveled at 60 deg. The other type is a heterogeneous wing, which consists of an airframe made from five-layer unidirectional carbon fiber (each layer is 0.12 mm thick) using extensible film to adhere to the frame, and this manufacturing method is popular in making MAVs [3]. Here, this heterogeneous wing is defined as a flexible wing, and both its lateral and longitudinal cambers can be changed at certain angles of attack under the action of aerodynamic load in this experiment.

The force measurement was implemented in a closed circuit wind tunnel at Beijing University of Aeronautics and Astronautics, which has an oval work section of 1.02×0.76 m inlet and 1.07×0.82 m outlet. Models are supported with a sting at the middle of the trailing edge, the experimental wind speed U_∞ ranges from 10 to 29 m/s with turbulent intensity less than 0.3%. The experimental Reynolds number based on the root chord length of the model is from 1.27×10^5 to 3.68×10^5, and the maximum blockage is about 4% at $\alpha = 40$ deg, thus the blockage correction is not made. To analyze the hysteresis of the lift coefficient, the angle of attack of the model is increased from 0 to 40 deg, then backward from 40 to 0 deg, with a step of 1 deg. The force is measured with a six-component strain balance with an uncertainty of 3%.

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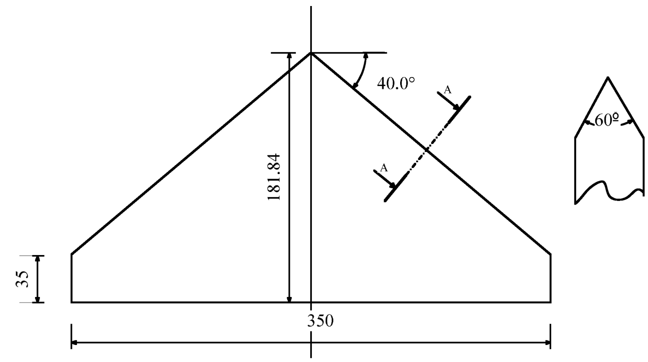
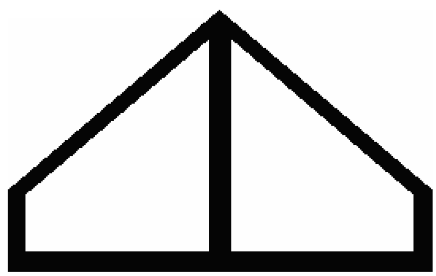
*Professor, Fluid Mechanics Institute; jjwang@buaa.edu.cn.
†Master Student, Fluid Mechanics Institute.



a) Homogeneous aluminum alloy wings



b) Heterogeneous flexible wing

Fig. 1 Schematic of model dimension of wings.

Results and Discussions

Effect of Reynolds Number on Lift Characteristics of Elastic Wing

For the rigid wing ($t/c = 1.65\%$), Fig. 2 shows the variation of the lift coefficient C_L with respect to α at different Reynolds numbers. In general, the C_L curves are the same, regardless of whether the angle of attack increases or decreases. Therefore, the effect of Reynolds number on the rigid wing can be neglected, and no hysteresis is observed.

For the elastic wing with $t = 0.8$ mm ($t/c = 0.44\%$), on the contrary, the lift coefficient is very sensitive to Reynolds number. It can be seen from Fig. 3 that, for $Re = 1.91 \times 10^5$, C_L curves are still nearly the same for both increasing and decreasing α, as in the case of the rigid one, and they are also smooth in the poststall region ($\alpha_{\text{stall}} = 18$ deg). As Re goes up to 2.30×10^5, something unusual occurs. First, the lift coefficient increases dramatically at $\alpha = 18$ deg and continues to increase until $\alpha = 22$ deg where $C_{L\,\max}$ is followed by an abrupt drop. Second, it is shown that the stall angle and maximum lift coefficient are strongly dependent on the way of changing angle of attack when a static hysteresis loop occurs in the lift-enhancement region. As Re continuously goes up to 2.55×10^5, the lift-enhancement still exists but without the hysteresis loop. Finally, when $Re = 3.06 \times 10^5$, both lift-enhancement and hysteresis surprisingly disappear and smooth C_L curves are obtained.

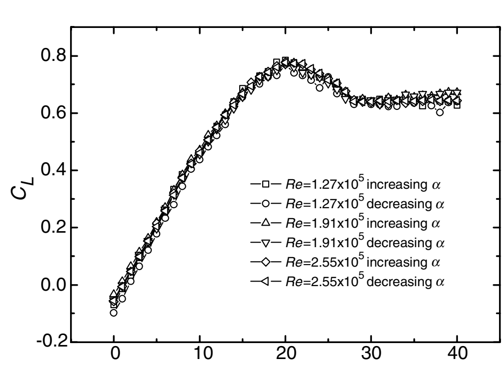
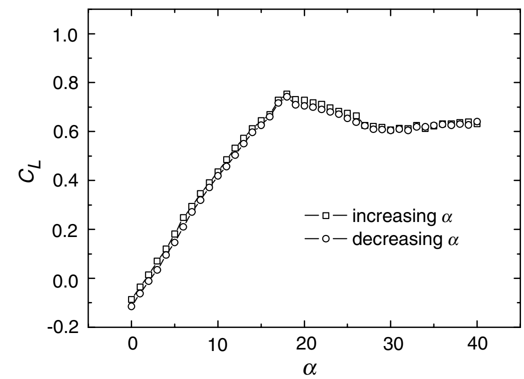
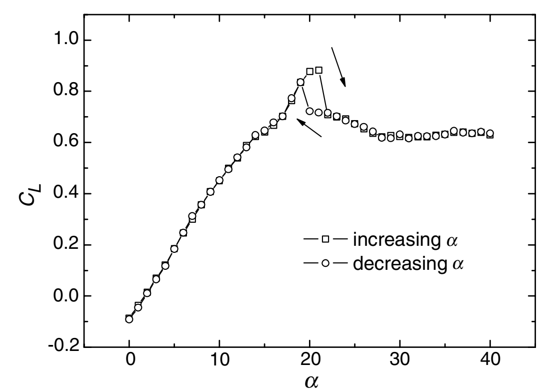


Fig. 2 Variations of lift coefficient with α for rigid wing ($t = 3.0$ mm).

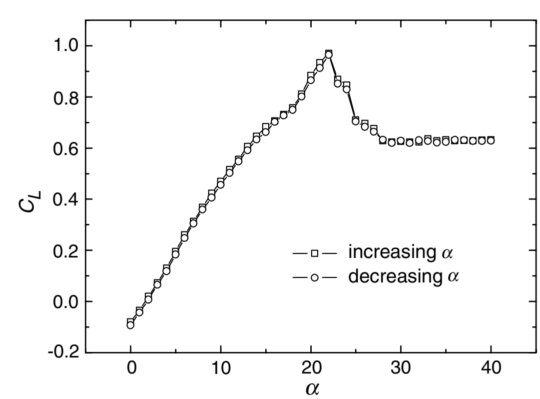
All in all, there is a remarkable effect of Reynolds number on elastic wings compared with that on rigid ones. The wing deformation and vibration will account for the four-stage phenomenon we measured for the homogeneous elastic wings.



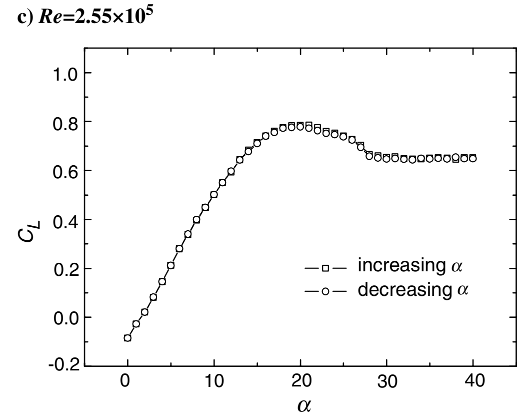
a) Re=1.91×10^5



b) Re=2.30×10^5



c) Re=2.55×10^5



d) Re=3.06×10^5

Fig. 3 Variations of lift coefficient with α for elastic wing ($t = 0.8$ mm) at different Reynolds numbers.

When Reynolds number is low, the wing deformation is unapparent and no lift enhancement can be measured. As Reynolds number goes up, the wing deformation and vibration are amplified, and so the lift enhancement appears with hysteresis. With the further increase of Reynolds number, the wing flexibility is not able to recover the deformation, therefore only lift increment occurs. Finally, the wing deformation brings nearly no lift enhancement, but the lift coefficient changes gradually near the stall angle of attack. Thus, the lift coefficient curve of the wing strongly depends on the interaction of aerodynamic load acting on the wing and wing elasticity. In particular, for a given elastic wing with fixed vibration modes, Reynolds number plays an important role in the variation of the lift coefficient curve.

Figure 4 shows some details for the effect of Reynolds number on the lift coefficient in the region near the stall angle of attack; it can be seen where the lift coefficient strongly depends on Re from 1.53×10^5 to 3.05×10^5, and it experiences a variation from smooth to abrupt, then back to smooth for the 0.8-mm-thick wing ($t/c = 0.44\%$). The maximum lift coefficient reaches as high as 0.9709 at $\alpha_{\mathrm{stall}} = 22$ deg for $Re = 2.42 \times 10^5$. Moreover, at $Re = 3.06 \times 10^5$, the lift coefficient curve appears smooth again with its value slightly higher than those at $Re = 1.53 \times 10^5$ and $Re = 1.91 \times 10^5$ for the same angles of attack, but with 1–3 deg delay in stall angle.

Effect of Reynolds Number on Lift Characteristics of Flexible Wing

Apart from the aforementioned homogeneous aluminum alloy wings, we find that there exists some difference for the lift coefficient of the heterogeneous flexible wing. As shown in Fig. 5, although the lift enhancement exists at relatively high Re, no hysteresis phenomenon is seen under the Reynolds numbers tested in this experiment. Figure 6 shows the effect of Re on the lift enhancement for the heterogeneous flexible wing; it is seen that Re also plays an important role in flexible wing lift enhancement. A maximum lift enhancement of 30.2% is obtained at $Re = 2.55 \times 10^5$, as compared with the case without lift enhancement at $Re = 1.53 \times 10^5$. Moreover, compared with the rigid wing, a maximum lift enhancement of 41.5% is achieved, and the large lift enhancement should be attributed to the increase of wing camber. Thus, it is strongly confirmed that the flexible wing is superior to the rigid one in generating higher lift.

Effect of Wing Flexibility on Lift Characteristics

Figure 7 shows the variations of C_L with α for the homogeneous elastic and rigid wings with thicknesses of 0.8 and 3.0 mm (corresponding relative thickness $t/c = 0.44$ and 1.65%, respectively) at $Re = 2.55 \times 10^5$. The maximum lift coefficient achieves 0.77 at $\alpha = 20$ deg for the rigid wing with $t = 3.0$ mm, whereas the lift enhancement appears at $a_{\mathrm{stall}} = 22$ deg for the elastic wing with $t = 0.8$ mm, where $C_{L\,\max} = 0.97$ with the increment of 26% compared with the rigid wing. Therefore, in this case, the deformation and vibration of the wing plays a significant role in determining aerodynamics as we discussed earlier, and this is also in accordance with previous works [5,6].

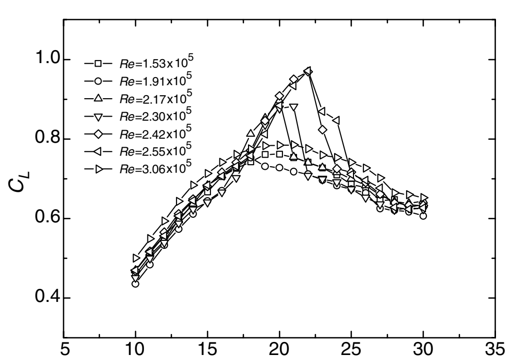
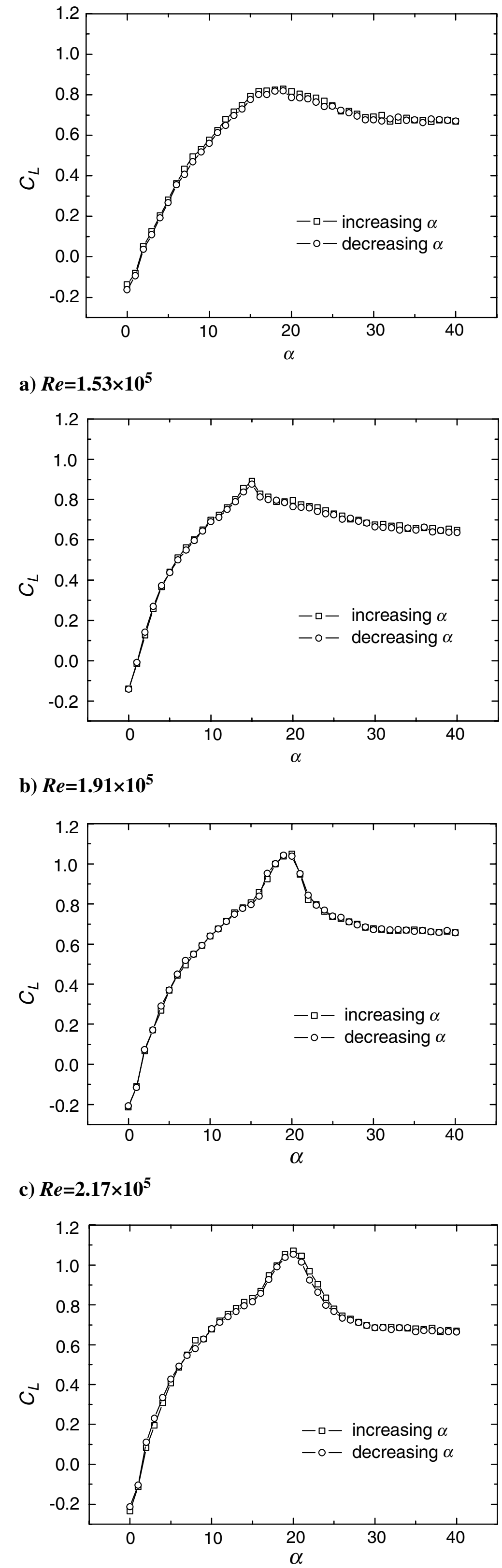


Fig. 4 Variations of lift coefficient with α in the lift-enhancement region for the elastic wing ($t = 0.8$ mm) at different Reynolds numbers.

Figure 8 exhibits the variation of C_L with α for the three wings tested in this experiment at $Re = 2.17 \times 10^5$. It can be seen that only the rigid wing ($t = 3.0$ mm) has no lift enhancement. Moreover, the



a) Re=1.53×10^5

b) Re=1.91×10^5

c) Re=2.17×10^5

d) Re=2.30×10^5

Fig. 5 Variations of lift coefficient with α for heterogeneous flexible wing at different Reynolds numbers.

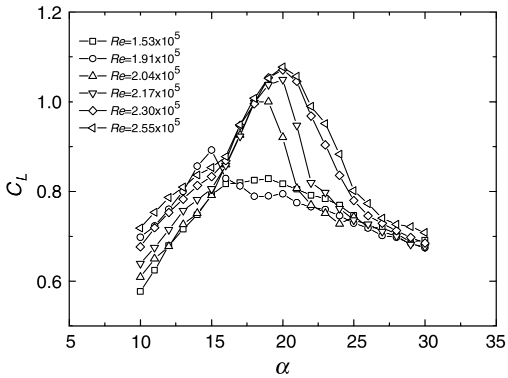


Fig. 6 Variations of lift coefficient with α in the lift-enhancement region for the heterogeneous flexible wing at different Reynolds numbers.

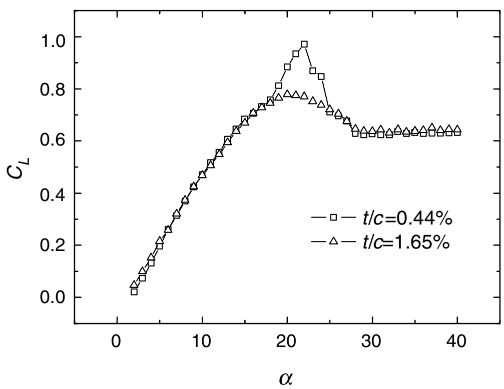


Fig. 7 Comparison of lift coefficient for elastic and rigid wings at $Re = 2.55 \times 10^5$.

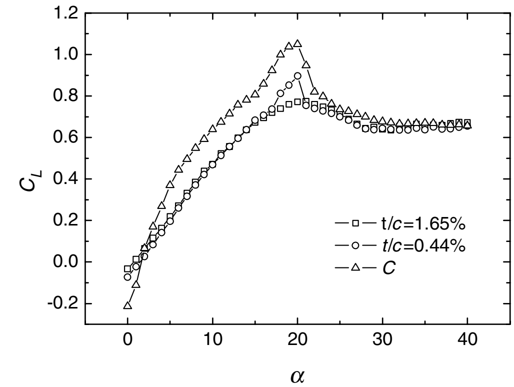


Fig. 8 Comparison of lift coefficient for wings with different flexibility at $Re = 2.17 \times 10^5$.

lift coefficient of the heterogeneous flexible wing is higher than those of homogeneous wings by about 15% from $\alpha = 5$ deg to stall angle, and the maximum lift coefficient increment is about 35.4% compared with the rigid wing. As we discussed before, the lift enhancement of the flexible wing can be attributed to the increase of wing camber under the aerodynamic load. Thus, it may be deduced that the flexible wing can generate much higher lift than the elastic wing does, and as their mechanisms are totally different, more detailed investigations are needed for full understanding of the effect of wing flexibility on lift, especially the lift enhancement phenomenon.

Conclusions

A preliminary experimental investigation on the lift characteristics over a series of cropped 40 deg delta wings is performed in a wind tunnel, and the conclusions are drawn as follows:

1) For the homogeneous elastic wing, the lift coefficient experiences four-stage variations as the Reynolds number increases, which are classified as no lift enhancement, lift enhancement with hysteresis, lift enhancement without hysteresis, and no lift-enhancement regions, respectively.

2) For the flexible wing, only the lift-enhancement phenomenon is observed, and no hysteresis is found. Moreover, the flexible wing can generate much higher lift than the elastic wing does.

3) The mechanisms of lift enhancement are totally different for elastic wings and flexible wings. For elastic wings, the deformation and vibration of the wing's apex and tips play an important role. However, for the flexible wing, the increase of the wing camber may be the main cause. For full understanding of the wing flexibility and Re on lift, especially on the lift-enhancement phenomenon, more detailed investigations are needed.

Acknowledgment

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