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Wind-Tunnel Experimental Investigation on a Fix-Wing Micro Air Vehicle

Jing-xia Zhan,* Wei-jun Wang,† Zhe Wu,‡
and Jin-jun Wang§
Beijing University of Aeronautics and Astronautics,
100083 Beijing, People's Republic of China

Nomenclature

AR	=	aspect ratio, L^2/S
C_{ave}	=	average chord length
C_D	=	drag coefficient
C_L	=	lift coefficient
$C_{L\alpha}$	=	lift-curve slope
C_l	=	roll-moment coefficient
$C_{l\alpha}$	=	two-dimensional slope of lift curve
C_m	=	pitch-moment coefficient
C_n	=	yaw-moment coefficient
C_l^β	=	partial derivative of C_l to β
C_n^β	=	partial derivative of C_n to β
C_{root}	=	length of root chord of wing
C_{tip}	=	length of tip chord of wing
L	=	wing span
S	=	wing area
x, y, z	=	Cartesian coordinate for airplane body, x for chordwise direction, y for normal direction, z for spanwise direction
α	=	incidence angle
β	=	sideslip angle
$\wedge$	=	sweepback angle of wing leading edge
$\wedge_{c/2}$	=	sweep angle at midchord

I. Introduction

MICRO air vehicles (MAVs) could carry payload in the form of sensor and global position system (GPS), etc. to perform many missions. This kind of vehicle attracts much research interest in recent years because of its advantages of low-cost, multi-function, and high flexibility, etc. MAVs, in current concept, are designed to reach the goals as follows: operating range of 10 km, flight endurance of above 30 min, speed range from 20 to 50 km/h, payload capability up to 20 g with maximum dimension of 15 cm, and radio-control or autonomous control. Reynolds number of such MAVs usually ranges between 7×10^3 and 2×10^5, which is the same as low Reynolds number of birds and airplane models.[1] Low aspect ratio (LAR) is below 2.0 because of the dimension requirement and structure strength requirement, which makes MAV have unique aerodynamics. Detailed researches on flow over LAR wings at low Reynolds number are dramatically needed.

In past decades, some attention had been paid on researches into flow at low Reynolds number. In most investigations, aspect ratio (AR) of wings was high.[2–5] Some researches provided promising data of thin wings with LAR at low Reynolds number. Pelletier and Mueller's research indicated that, at low Reynolds number, LAR enhances the linearity between lift coefficient and incidence angle within small incidence angles, delays stall angle, and increases maximum lift coefficient.[6] Furthermore, Torres and Mueller[7] conducted investigation into the effects of wing planform upon aerodynamics of thin wings with LAR (0.5–2.0) at low Reynolds number (7×10^3–2×10^5). They concluded that AR is the most important parameter affecting aerodynamic characteristics of LAR wings at low Reynolds number. Wing-tip vortex has a strong effect on the flow over the wings with AR below 1.5, and lift is provided by vortex flow and attached flow on such low-aspect-ratio wings. Turbulence intensity barely affects the flow over thin wings for the absence of transitional separation bubble, which is usually found on thick wings at high Reynolds number.[1]

Although Laitone[5] pointed out that thin wing is more favorable than thick wing at low Reynolds number when $AR = 6$, research on thick wing with LAR at low Reynolds number is rarely. Mueller and Delaurier[1] implied that flow over thick wing with LAR at low Reynolds number would be strongly affected by turbulence intensity and Reynolds number for the existence of laminar separation bubble, and wing-tip vortex would make the problem more complex.

As a vehicle designed for application, the performance of a MAV is not only related to its wing, but also to other components, such as stabilizers and control surfaces, which also can affect the whole aerodynamics of a MAV. But related data are seldom.

In this paper, we present some results of a force measurement experiment on a MAV with a fixed thick wing at low Reynolds number and give some data about aerodynamics of thick wing with LAR at low Reynolds number. Other than the performance of thick LAR wing, the effects of leading-edge sweep angle $\wedge$ and the position of vertical stabilizer (VS) on the whole aerodynamic performance are discussed to provide technical support for analysis and design of MAVs.

II. Experimental Model and Equipments

A. Experimental Model

The experiment was conducted over a full-scale fixed-wing MAV in a wind tunnel. The MAV ever successfully flied under remote control. As shown in Fig. 1, the wing and fuselage of the MAV are molded as a whole. Its frame is made of light wood and pine wood, and covered with PVC membrane. The cross section of its wing is S5020-84 airfoil (Fig. 2), which is a low-Reynolds-number airfoil with thickness of 8.4%. Compared with the thickness of 2.0% in aforementioned researches,[6,7] the wing is much thicker. The dihedral angle of the wing is zero. A group of batteries provides power for a small electric motor and some controlling actuators. Batteries,

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*Ph.D. Candidate, Fluid Mechanics Institute, School of Aeronautical Science and Technology; jxzhan@ase.buaa.edu.cn.

†Lecturer, Department of Aircraft Design, School of Aeronautical Science and Technology; Kevin_jun@126.com.

‡Professor, Department of Aircraft Design, School of Aeronautical Science and Technology.

§Professor, Fluid Mechanics Institute, School of Aeronautical Science and Technology; jjwang@buaa.edu.cn.

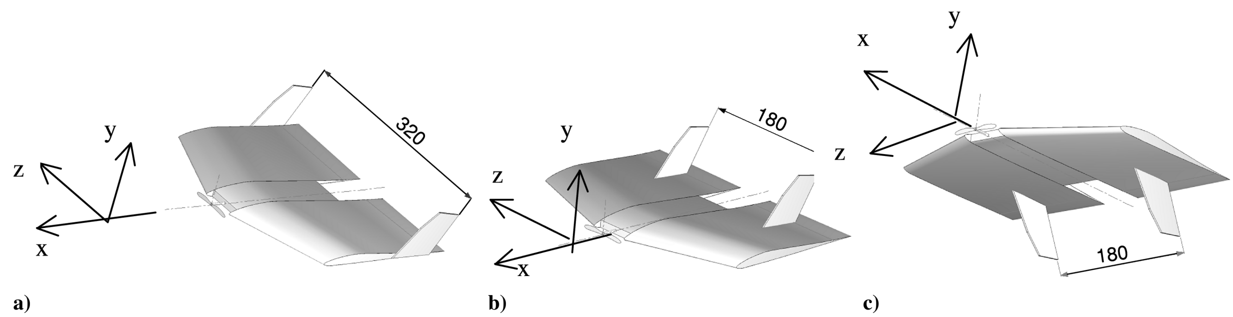

Fig. 1 Body axes and sketch of the MAV with a) tip VS, b) upper VS, and c) bottom VS (unit:mm).

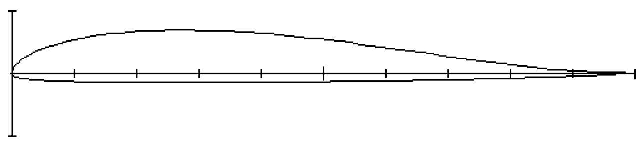

Fig. 2 S5020 airfoil.

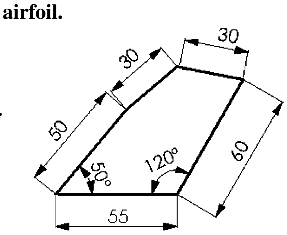

Fig. 3 Sketch of vertical stabilizer (unit:mm).

Table 1 Dimensions of the MAV in present experiment

$\wedge$, deg	L, mm	C_{root}, mm	C_{tip}, mm	C_{ave}, mm	S, m^2	$\mathcal{R}$
15	320	230	180	205	0.0656	1.561
30	320	255	153	204	0.0653	1.569

motor, control facilities, and visible sensor are embedded in the fuselage of the MAV. The total weight of the MAV is 130 g. As a normal air vehicle, ailevator is used to control pitching and rolling, and vertical stabilizer provides direction control. Presently, the MAV could fly for 10 min at the speed of 45 km/h. Because the weight of motor, batteries, and visible sensor we chose is kind of heavy, the size of the MAV is hardly reduced. Given the application of micro and light apparatus, the size could be decreased to 50% of the present size. According to the match of weight and size in nature, the weight of 90 g needs at least a span of 15 cm, which is realizable according to the results of our remote-control flight and wind-tunnel experiment.

In the experiment, sweepback angle $\wedge$ was set to be 15 and 35 deg with VS located at different position. Vertical stabilizer with identical planform (as shown in Fig. 3) was placed at three positions: wing tip, upper, and bottom surface (represented as tip VS, upper VS, and bottom VS, respectively in this paper, as shown in Fig. 1). The chordwise location of tip VS was the same as that of upper and bottom VS. Upper VS was set up symmetrically with the spacing of 180 mm, and so was bottom VS. Other dimensions of the MAV are shown in Table 1. And the MAV was equipped with a propeller, which was allowed to windmill. But the effect of the propeller on aerodynamics is tiny as shown in Fig. 4.

B. Experimental Equipments

The model was supported by a sting to measure forces by a six-component strain force balance. Experimental uncertainty is approximately 0.15% in rolling-moment coefficient and 0.1% in yaw-moment coefficient. Error bars for C_L and C_D are shown in Fig. 4. The experimental wind speed is maintained at 14 m/s. Based on the speed and average chord length C_{ave}, the Reynolds number is equal to 1.95×10^5. Incidence angle α is from -10 to 45 deg, stepped by 2 deg. Sideslip angle β is from -12 to 0 deg. The uncertainties in α and β are 0.1 deg.

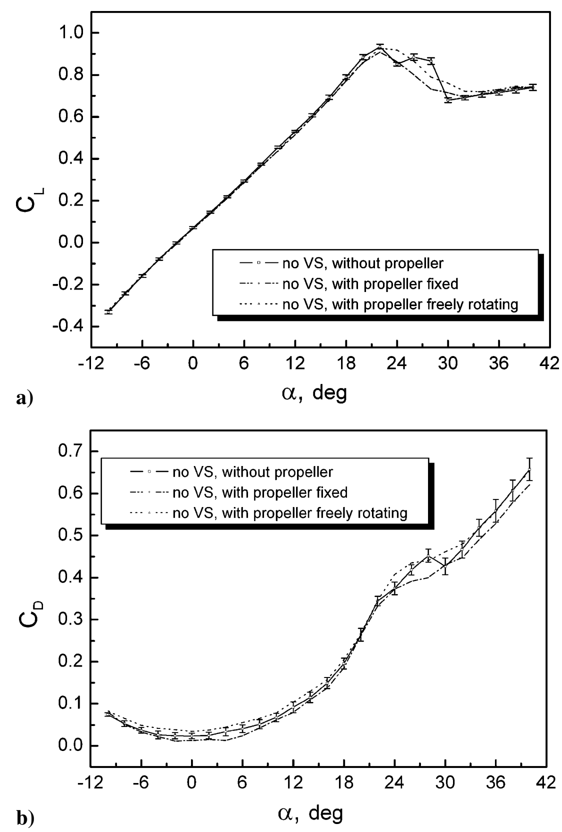

Fig. 4 Uncertainty and the effects of propeller with $\Lambda = 15$ deg: a) C_L and b) C_D.

The wind tunnel in which the experiment was done is an open-circuit low-speed wind tunnel in Beijing University of Aeronautics and Astronautics. The tunnel has a 1.02×0.76 m ellipse-shaped test section with a length of 2 m. The blockage of the MAV at $\alpha = 45$ deg is below 1.9%. Because the value is small, we did not make blockage correction. The turbulent intensity at the speed of 14 m/s is about 0.13%.

III. Results and Discussions

A. Longitudinal Aerodynamics

Generally, wing with thickness below 6% is considered as thin wing, so that the MAV's wing with thickness of 8.4% should be thick. Researches on thin wings with LAR at low Reynolds number indicated that the characteristic of thin wings is different from that of thick wings. The longitudinal aerodynamics of the MAV's wing with LAR at low Reynolds number is shown in Fig. 5. It is found that stall angle and maximal lift coefficient of the thick wing are higher than those of thin wing with $\mathcal{R}$ about 3.0 described by Pelletier and Mueller,[6] as shown in Fig. 5a. When $\mathcal{R} < 1.5$, the mechanism of aerodynamics can dramatically change at low Reynolds number, that is to say, wing-tip vortex contributes much to aerodynamic

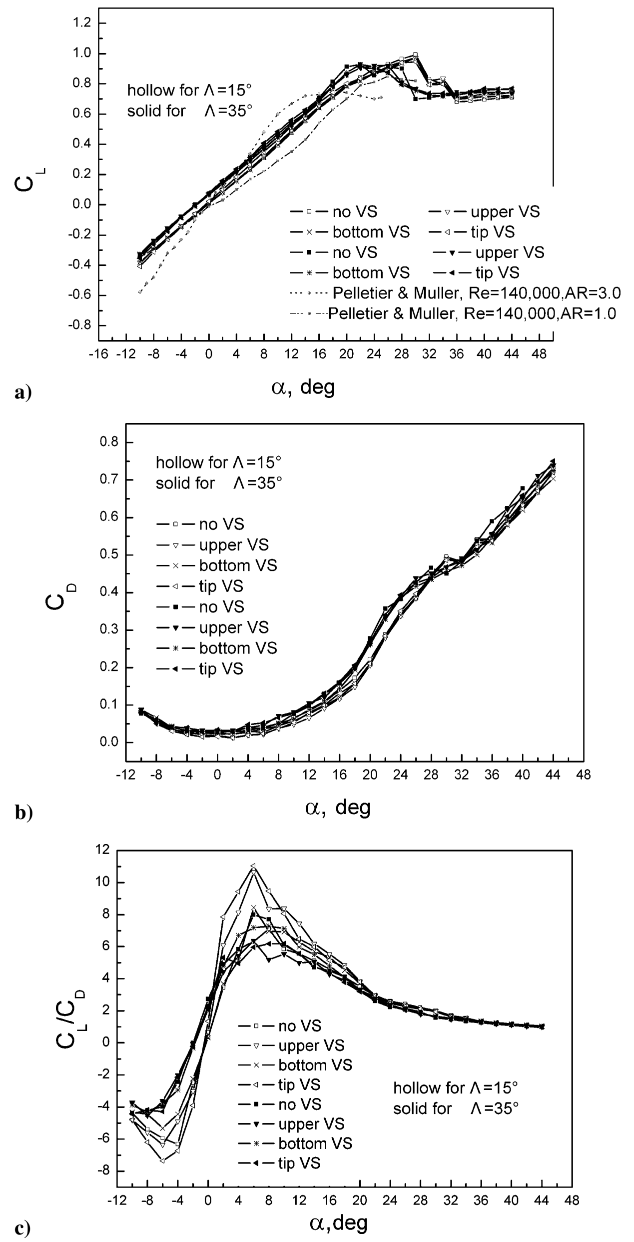

Fig. 5 Longitudinal aerodynamics vs incidence angle α: a) C_L, b) C_D, and c) C_L/C_D.

forces, especially to lift. This mechanism can be used to explain the aforementioned distinction.

Theoretical lift-curve slope of the MAV was calculated according to three theoretical equations. The first one is the classic equation for $C_{L\alpha}$, originating from Prandtl's lifting-line theory:

$$C_{L\alpha} = (1/57.3)\{C_{l\alpha}/[1 + (C_{l\alpha}/\pi A\!\!R)(1+\tau)]\}(1/\,\mathrm{deg}) \qquad (1)$$

where the Glauert parameter τ is equivalent to an efficiency factor. The value of $C_{l\alpha}$ was taken to be 5.1566 (1/rad) based on the lift-curve slope of airfoil S5020-84. With $\tau = 0.26$, theoretical lift-curve slope is 0.0387 while $\wedge = 15$ deg and 0.0388 while $\wedge = 35$ deg. The second equation is proposed by Lowry and Polhamus[8]:

$$C_{L\alpha} = \left(\frac{1}{57.3}\right)\left\{\frac{2\pi A\!\!R}{2 + \sqrt{\left[A\!\!R^2/(C_{l\alpha}/2\pi)^2\right]\left(1 + \tan^2 \Lambda_{c/2}\right) + 4}}\right\} \times \left(\frac{1}{\mathrm{deg}}\right) \qquad (2)$$

The results from Eq. (2) are 0.0358 and 0.0356 when $\wedge = 15$ and 35 deg, respectively. And the third one is suggested by Hoerner and Borst[9] for thin rectangular plates of LAR (less than 2.5):

$$C_{L\alpha} = [36.5/A\!\!R + 2A\!\!R]^{-1} \qquad (3)$$

From this equation, lift-curve slope is 0.0377 while $\wedge = 15$ deg and 0.0379 while $\wedge = 35$ deg. Compared the slopes calculated from these three equations with the experimental lift-curve slope of 0.0387, it can be found that Eqs. (1) and (3) are better than Eq. (2) to calculate lift-curve slope of the thick wing.

The effects of $\wedge$ and the position of VS are shown in Fig. 5. The curves can be divided into two groups obviously, one with hollow symbols for $\wedge = 15$ deg and the other with solid symbols for $\wedge = 35$ deg. It is demonstrated that $\wedge$ has a stronger effect than the position of VS on C_L, C_D, and C_L/C_D. Before stalling, lift coefficients of the MAV with $\wedge = 35$ deg are higher than those with $\wedge = 15$ deg. The slopes of lift coefficient vs incidence angle are similar. But the maximal lift coefficient and stall angle when $\wedge = 15$ deg are greater. The drag of the wing with smaller sweepback angle is lower as shown in Fig. 5b. As a result, lift-to-drag ratios of the MAV with $\wedge = 15$ deg are generally higher than those with $\wedge = 35$ deg, and the maximum ratios appear at $\alpha = 6$ deg, as shown in Fig. 5c.

Vertical stabilizer contributes much to the aircraft's lateral stability, whereas it hardly affects longitudinal aerodynamic characteristics. Whether $\wedge = 15$ or 35 deg, lift-to-drag ratio of the MAV with tip VS is relatively higher, which is resulted from the decrease of induced drag because of tip VS.

B. Lateral Aerodynamics

Sweepback angle $\wedge$ and VS are important parameters that influence lateral aerodynamic characteristics. For the small values of roll-moment, yaw-moment, and side-force coefficient at $\beta = 0$ deg, the effects of $\wedge$ and the position of VS were investigated on the MAV with β from -12 to 0 deg. In this range, β barely affects C_L and C_D at linear range of incidence angle, as shown in Fig. 6.

In the design of a MAV, the characteristics of roll moment and yaw moment are closely related to its flight capability. Sweepback angle $\wedge$ affects roll moment much more than the position of VS does. It could increase lateral stability, similar to the effect of dihedral increase. Figure 7a shows that higher $\wedge$ produces much greater roll-moment coefficients. Correspondingly, absolute value of C_l^β in Fig. 7b is greater while $\wedge = 35$ deg. These results suggest that higher $\wedge$ improves lateral stability of the model tested.

Although $\wedge$ has a dominating effect on C_l and C_l^β, VS also related to C_l^β, especially tip VS. It is shown that the derivatives C_l^β of the configuration with tip VS are much larger in the negative direction than others. It means that the static lateral stability of the MAV with tip VS is strongest, which makes spiral mode easier to control. When side slipping, the effect of VS on the flow over left-half wing is contrary to that over right-half wing,[10] so that the lift increments

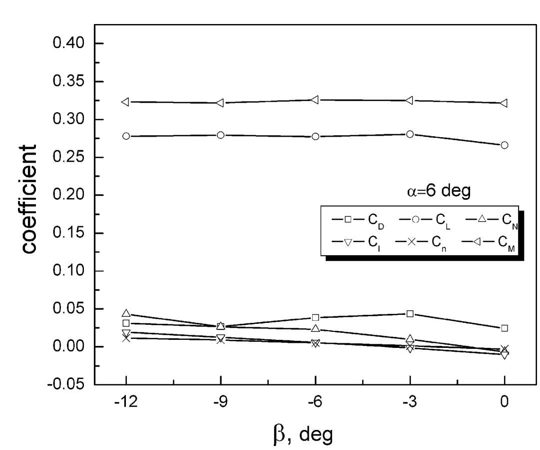

Fig. 6 Aerodynamics vs sideslip angle β (tip VS Λ = 15 deg).

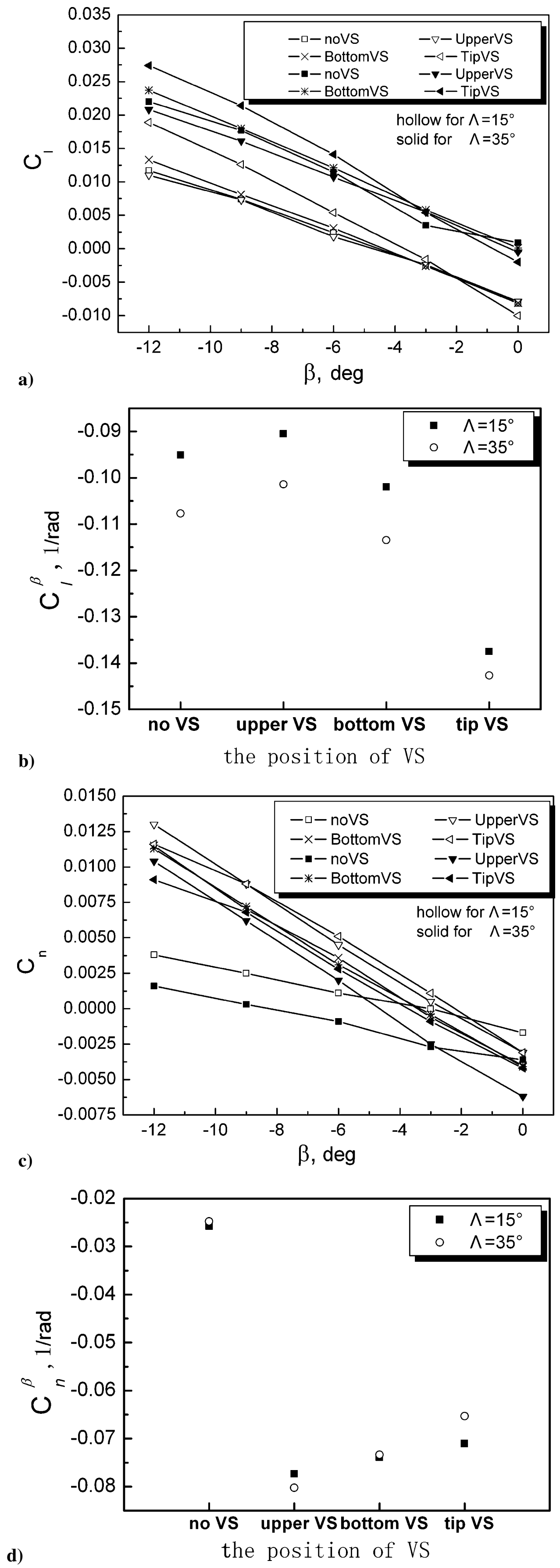

Fig. 7 Lateral aerodynamics vs sideslip angle β ($\alpha = 6$ deg): a) roll-moment coefficient, b) lateral stability derivative C_l^{β}, c) yaw-moment coefficient, and d) directional stability derivative of C_n^{β}.

Table 2 Ratio of C_l^{β}/C_n^{β}($\alpha = 6$ deg)

∧, deg	No VS	Upper VS	Bottom VS	Tip VS
15	3.68889	1.17037	1.37984	1.93548
35	4.34802	1.26429	1.54687	2.18421

on the two sides are different and roll moment is produced. Tip VS produces the effect on a wider wing surface than others and therefore produces greater roll moment. When β increases, the difference between left and right wing as a result of tip VS becomes more distinct, and so the value of C_l becomes much higher as the case shown in Fig. 7a.

However, for C_n^{β} the position of VS is more important than ∧. In Fig. 7c, the curves of C_n vs β at $\alpha = 6$ deg cannot be divided into two groups according to ∧ as the case in Fig. 7a. Although C_n of the MAV with $\wedge = 15$ deg is higher than that with $\wedge = 35$ deg when the positions of VS are same, C_n^{β} is almost equal. The slopes C_n^{β} are quite different when VS locates at different position, as shown in Fig. 7d. So ∧ just affects the value of C_n, and the position of VS has a dominating effect on C_n^{β}, that is, the position of VS is more closely related to directional stability.

The derivatives C_l^{β} and C_n^{β} are closely related to flight quality. Table 2 shows the ratio of C_l^{β} to C_n^{β} at $\alpha = 6$ deg. The ratio is related to dynamic stability, which can reflect spiral mode stability and Dutch roll stability. The acceptability of this ratio is determined by airplane's dimensions and dynamic derivatives. In our experiment, we did not measure dynamic derivatives, and so the acceptable range of C_l^{β}/C_n^{β} is unknown. We evaluate the ratio just based on the feeling of controller in remote flight. Without VS, the ratio is greater than 3.0. That means too much lateral stability and too little directional stability to be controlled comfortably. With VS, the ratio falls down. And the higher the wing's sweepback angle, the greater the ratio. Among three positions, the ratio of the MAV with upper VS is the lowest and highest with tip VS. In remote flight with different configurations of the MAV, the controller was more satisfied with the MAV with bottom VS. Of course, a different controller can have different feeling.

IV. Conclusions

Force measurement was conducted to investigate aerodynamics of the micro air vehicle with a thick fixed-wing at low Reynolds number. In the experiment, the position of vertical stabilizer and leading-edge sweepback angle of wing were variable parameters. Experimental results display that longitudinal aerodynamics of the micro air vehicle with thick wing is favorable. It is found that sweepback angle is an important parameter to static lateral stability, which has strong effects on the value of roll moment and yaw moment. Roll-moment coefficient C_l and derivative C_l^{β} of the micro air vehicle with 35-deg sweepback wing is greater, whereas C_n is smaller while sweepback angle is 35 deg. Smaller sweepback angle increases maximum lift coefficient and delays stalling. The results also show that the position of vertical stabilizer mainly affects directional stability. It is indicated that the vertical stabilizer set up at wing tip has the advantages of increase in lateral aerodynamics and improvement of lateral stability.

The results provide an insight into thick LAR wing at low Reynolds number and supply a good reference for the design of micro air vehicles. Nevertheless, there are many problems about flow structure and interaction to be clarified, and further researches on thick wings with LAR at low Reynolds number are expected.

Acknowledgment

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