A Split-wing Micro Air Vehicle*

By Shigeru SUNADA, Kazuki TSUJI, Yuji FUKAMI and Shoma AKI

Osaka Prefecture University, Osaka, Japan

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This paper presents a proposal for a split-wing aircraft. The split wing proposed is composed of a number of square plates. The distances between the square plates are varied according to flight conditions. For a flight where high efficiency is required, the distances are 0 and the characteristic of the wing is that of a wing with an aspect ratio equal to the number of square plates. On the other hand, during a flight where wind gusts are experienced, the distance is not 0 and the characteristic of the wing is close to that of a square. The split-wing enhances the flight stability of MAVs. The enhanced stability will increase opportunities where MAVs can be utilized.

Key Words: Micro Air Vehicle, Low Aspect Ratio, Split Wing

Nomenclature

- a : lift slope
- C_L : lift coefficient
- $C_{L\max}$: maximum lift coefficient
- c : chord length
- h : distances between squares
- n : number of square wings in a split wing
- Re : Reynolds number
- S : wing area
- V : forward velocity
- W : weight of an airplane
- w : vertical upward gust
- α : angle of attack
- $\bar{\alpha}$: angle of attack for a given lift coefficient C_L ,
 $\bar{\alpha} = C_L/a$
- $\hat{\alpha}$: angle of attack for a maximum lift coefficient $C_{L\max}$,
 $\hat{\alpha} = C_{L\max}/a$
- ρ : air density

1. Introduction

Many fixed wing-type micro air vehicles (MAVs) have low-aspect ratio wings, presumably for the following two reasons:

(1) A MAV must be compact in order to be carried easily. Therefore, a planform that is close to a square is most suitable.

(2) Wind gusts strongly affect MAVs. This is because the ratio of a wind gust to forward velocity during trimmed flight is high. Thus, a low-aspect-ratio wing that is robust to vertical wind gusts is desirable for MAVs.

Here, the forward velocity V and wing area S are given constants. The lift coefficient of a wing is assumed to be $C_L = a\alpha$ and this value is also given as $C_L = 2W/\rho V^2 S$.

The angle of attack $\bar{\alpha}$ for C_L is $\bar{\alpha} = C_L/a$. The angle of attack $\hat{\alpha}$ for the maximum lift coefficient $C_{L\max}$ is $\hat{\alpha} = C_{L\max}/a$. This $\hat{\alpha}$ represents the stall angle of attack.

(2-I) The increases in an angle of attack and lift coefficient when the wing encounters a vertical upward gust w are w/V and $a(w/V)$, respectively. The variation in lift coefficient $a(w/V)$ decreases as the lift slope a decreases. A low-aspect-ratio wing is then suitable for MAVs because of the small variation in lift. Note that lift slope a is smaller as the aspect ratio decreases. The relation between C_L and α for a rectangular planform at $Re = 10^5$ has been explained by Mueller et al.¹⁾

(2-II) The difference between $\bar{\alpha}$ and $\hat{\alpha}$ is $(C_{L\max} - C_L)/a$. When $C_{L\max}$ and C_L are given, a wing having a smaller lift slope a has a larger difference between $\bar{\alpha}$ and $\hat{\alpha}$. As stated above, a low-aspect-ratio wing has a smaller lift slope. Thus, when a low-aspect-ratio wing has a $C_{L\max}$ which is not smaller than that of a high-aspect-ratio wing, it is robust to vertical wind gusts.

Considering reason (2) stated above, we propose a split wing. Furthermore, the aerodynamic characteristics of the split wing will be demonstrated to confirm its functions and to determine the width of the spaces between the squares. In addition, airplanes developed with the split wing, whose flights have been confirmed to be stable while varying the width of the spaces, will be introduced.

2. Proposal for a Split Wing

Figure 1 shows a split wing composed of n sheets of square wings arranged along the span. This is a slide-type split wing. (Another type of split wing will be explained in the Appendix.) The wing area is constant, independent of the spaces existing between the square wings. Note that the wing area in the present study is not an area determined by the outline of the planform, but an area where the wings exist on the planform. The V and C_L are also

Fig. 1. Split wing ($n = 3$ as an example).

The square wings slide along the span. This type of split wing is called the slide-type.

Fig. 2. Tested wings.

(a) Planform with a dihedral angle of 0° . (b) Frontal view with a dihedral Γ of 20° .

constants independent of the spaces existing between the square wings. Under no wind gust, the distances between the square wings is made to be 0 by sliding the squares and the aerodynamic characteristics are similar to a wing with an aspect ratio of n . The flight efficiency, that is lift to drag ratio, is higher than that when the wing is split into n square wings.

On the other hand, when there are wind gusts, the distances between the square wings are not 0. The aerodynamic characteristics of the split wing become closer to that of the square wing owing to the existence of spaces. The variation of lift coefficient $a(w/V)$ when the split wing encounters a vertical gust w is expected to be small and the difference between $\tilde{\alpha}$ and $\hat{\alpha}$, that is $(C_{L_{\max}} - C_L)/a$, is expected to be large. A split wing with spaces is therefore more robust to vertical wind gusts than that without spaces because of the smaller $a(w/V)$ and larger $(C_{L_{\max}} - C_L)/a$.

3. Experiments

We demonstrate the aerodynamic characteristics of the split wing (i.e., slide-type) as a parameter of distances between squares h using a wind tunnel test. The dihedral angles of the split wings are 0 and 20° .

3.1. Tested wings

Figure 2(a) shows the planform of a split wing with a dihedral angle of 0° deg used for the wind tunnel test. The

Fig. 3. Experimental results²⁾ when $Re = 5 \times 10^4$ and $\Gamma = 0^\circ$.

(a) Lift coefficient, (b) Drag coefficient, (c) Lift-to-drag ratio.

wing consists of three square plates arranged along the span. The chord length c of one square plate is 100 mm, and the airfoil shape is a rectangle with a thickness of 1%. Figure 2(b) shows a frontal view when the dihedral angle is 20° . The planform of this split wing shown in Fig. 2(b) is different from that shown in Fig. 2(a). The span length in Fig. 2(b) is $c + 2(c + h) \cos 20^\circ$.

The distances between the neighboring plates h were varied as $h/c = 0, 0.2, 0.5, 0.7, 0.9, \infty$ in the wind tunnel test when the dihedral angle was 0° . The h was varied as $h/c = 0, 0.2, 0.5, \infty$ in the wind tunnel test when the dihedral angle was 20° . Note that a wing where $h/c = \infty$ means three square plates without any interaction. The aspect ratio of the wing with $h/c = 0$ is 3. The wind velocity was 7 m/s for both the dihedral angles and the Reynolds numbers were 5×10^4 . When the dihedral angle was 0° , the measurements under $V = 14$ m/s were also made in order to confirm the functions of the split wing

Fig. 4. Experimental results²⁾ when $Re = 10^5$ and $\Gamma = 0^\circ$.
(a) Lift coefficient, (b) Drag coefficient, (c) Lift-to-drag ratio.

for a larger Reynolds number. The Reynolds number at $V = 14$ m/s is 10^5 .

4. Experiment Results

Figures 3 and 4 show the experimental results for the dihedral of 0° , as well as the results at $Re = 5 \times 10^4$ and 10^5 , respectively. Note that the wing area used for calculating the lift and drag coefficients is half of the wetted surface area. Figure 5 shows the experimental results for the dihedral of 20° and $Re = 5 \times 10^4$.

The characteristics of the split wing realized from the experimental results, are summarized as follows:

1) The stall angle (i.e., angle of attack for maximum lift coefficient) and the maximum lift coefficient increase as h/c increases. The differences between $h/c = 0.2, 0.5, 0.7$, and 0.9 are fairly small.

Fig. 5. Experimental results³⁾ when $Re = 5 \times 10^4$ and $\Gamma = 20^\circ$.
(a) Lift coefficient, (b) Drag coefficient, (c) Lift-to-drag ratio.

2) The lift slope when the angle of attack is less than the stall angle is independent of h/c ($=0-0.9$). The lift slope for $h/c = \infty$ is smaller than that for $h/c = 0-0.9$.

Assuming 2), the variation in lift coefficient $a(w/V)$ when the wing encounters a vertical gust w is independent of h/c ($=0-0.9$), and assuming 1), the difference between $\bar{\alpha}$ and $\hat{\alpha}$ is larger as h/c increases. The difference is especially large when $h/c = 0$ and $h/c = 0.2$. Therefore, the function of a split wing, which is to enable variation of the stall margin, can be accomplished by varying h/c , and this function becomes readily available by changing the h/c between 0.0 and 0.2.

Fig. 6. An airplane developed with a slide-type split wing.³⁾
The wing area is 0.29 m^2 independent of the existing space. The dihedral and weight are 10° and 182 g , respectively. The width of the spaces is 4.5 cm , and this value is 17% of the mean aerodynamic chord.

Fig. 7. An airplane developed with the slit-type split wing.³⁾
The wing areas when the wing has no spaces and two spaces are 0.34 and 0.29 m^2 , respectively. The dihedral and weight are 12° and 190 g , respectively. The width of the spaces is 8 cm , and this value is 25% of the mean aerodynamic chord.

5. Flight Tests

As stated in the Appendix, the slit-type of split wing can have the same functions as the slide-type. Accordingly, we have developed airplanes with a split wing as shown in Figs. 6 and 7. The former and latter airplanes have slide-type and slit-type split wings, respectively. For the former, the two outer wings slide using one servomotor because they are connected by a thread. For the latter, the narrow wings between the squares are rotated by one servomotor. In these airplanes, the aspect ratios of the inner wing and outer wings are approximately 2 and 1, respectively. Therefore, these airplanes do not have the same characteristics as the split wing defined above. The indoor flight tests conducted using these airplanes confirmed that an airplane with a split wing can fly stably when the width of the spaces is varied.

6. Conclusion

We have proposed a split wing composed of several square wings. Two types of split wing are introduced. One is the slide-type and the other is the slit-type. For the former, the distances between the square wings are varied by sliding them along the span according to flight conditions. For the latter, slits between the square wings are opened and closed

Fig. A1. Split wing ($n = 3$ as an example).
The slits between the square wings are opened/closed. This type of split wing is called the slit-type.

according to flight conditions. In a flight where high efficiency is required, the distances are 0 and the characteristics of the whole wing are those of a wing with an aspect ratio equal to the number of square wings n for the slide-type or larger than n for the slit-type. On the other hand, when gusts are encountered, the distance between the square wings is larger than 20% of the chord length, and the characteristics of the whole wing become closer to that of a square wing. The split wing can enhance the flight stability of MAVs. This enhanced stability will increase the opportunities in which MAVs can be utilized.

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Appendix: Slit-type Split Wing

Figure A1 shows a slit-type of split wing. This split wing is composed of n sheets of square wings arranged along the span. The square wings do not touch each other. The slits between the square wings can be opened and closed. Under no wind gust, the distance between the square wings is 0, enabled by closing the slits. The aerodynamic characteristics of this split wing are similar to a wing with an aspect ratio larger than n . On the other hand, when there are wind gusts, the distances between the square wings becomes larger than 0 by opening the slits. At that time, the aerodynamic characteristics of the split wing become closer to those of the square wing owing to the existing spaces.

The wing area decreases when the slits are opened. Either or both of the V and C_L are increased to produce a trimmed flight. The $C_{L_{\max}}$ also increases. The C_L , that is α , is determined so that the difference between $\bar{\alpha}$ and $\hat{\alpha}$, that is $(C_{L_{\max}} - C_L)/a$, is larger. Furthermore, the variation in lift coefficient $a(w/V)$ when the slits are opened is expected to be small. This is because a is smaller and V might be larger as the result of splitting the square wings.