Proceedings of 2007 JSASS-KSAS Joint International Symposium on Aerospace Engineering

Incorporating the International Sessions of 2007 JSASS Aircraft Symposium and 2007 KSAS Fall Conference

October 10-12, 2007
Kitakyushu International Conference Center
Kitakyushu, Japan

The Japan Society for Aeronautical and Space Sciences (JSASS)
The Korean Society for Aeronautical and Space Sciences (KSAS)
# SYMPOSIUM SCHEDULE

## October 10, 2007

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An Aerodynamic Model for Flapping Wing Aircraft Using Modified Strip Theory

Dae-Kwan Kim, Jin-Young Lee, Jun-Seong Lee and Jae-Hung Han*

* Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Korea
(Tel: +82-42-869-3723; E-mail: jaehunghan@kaist.ac.kr)

Abstract: Biological and artificial flapping-wing flyers have flexible wings with chordwise and spanwise anisotropic flexibilities. During the wing motion, passive or active deformation of the flapping wing is produced due to a complicated interaction between the structural flexibility and the aerodynamic flow around the wing. This wing deformation plays an important role in the determination of the aerodynamic performance. Therefore, the fluid-structure interaction of the flapping wing should be considered in design of an optimal flapping wing or control of a flapping flight. However, it is not easy to treat the complicated interaction with sufficient accuracy. In the present study, an aerodynamic model for flapping-wing flight is proposed, which is available not only for the performance prediction but also for analysis of the fluid-structure interaction. The aerodynamic model based on the modified strip theory is improved to consider the high relative angle of attack, and the delayed stall model is also modified. This aerodynamic model is verified with the experimental data of a flat plate wing. The comparison of the aerodynamic results shows good agreements between the predicted and the measured data. Using the aerodynamic model proposed in this study, an aeroelastic analysis of the flexible flapping wing will be followed in the future works.

Keywords: Flapping-wing, micro air vehicle, aerodynamic model, modified strip theory, delayed stall

1. INTRODUCTION

In past few decades, flapping flight of birds, bats and insects has fascinated many researchers in various fields such as biology, aeromechanics and engineering because of highly efficient maneuverability and aerodynamic benefits especially in a low Reynolds number flight regime. Numerous efforts have been made to make flapping-wing vehicles such as ornithopters or flapping micro air vehicles (MAV), and many analytical and experimental studies on flapping wings have also been performed to understand the aerodynamic characteristics and flight mechanisms of the wings. However, these studies have been mostly conducted by using rigid wing models.

Actually, the biological flyers have spanwise-chordwise anisotropic flexible wings, and they use complicated wing motions such as flapping, twisting, folding, sweeping or rotating motions. By adaptation of the skeletal and muscular systems, they can generate additional flight motions such as modification and reversal of camber between upward and downward strokes, wing area expansion and contraction, and transverse bending [1]. These wing motions induce complicated unsteady aerodynamic characteristics such as leading edge vortex, delayed stall, and wake capture [2, 3]. The artificial flyers also have very thin and flexible wings structurally similar to those of the nature’s flyers, and they are operated with a positive flapping axis vectored by adjusting the mass center or the stabilizer to achieve a necessary lift force and a positive trim angle [4]. Their main wing motions are the flapping and passive motions generated by the wing flexibility. However, the deformation of these flapping wings is strongly coupled with aerodynamic forces generated by the wing motion [5, 6].

In order to consider this complicated fluid-structure interaction, aerodynamic and structural analysis technologies must be applied simultaneously. However, it needs very expensive computational cost and is still extremely difficult to analyze accurately the fluid-structure interaction of the biological or artificial flexible flapping wings. Therefore, for the realization of efficient optimal design and real-time control, an applicable aerodynamic model of flapping wings is indispensable.

In the present study, a numerical aerodynamic model based on the modified strip theory is suggested not only for the performance prediction but also for preliminary design and control of flexible flapping wings. The aerodynamic model is improved to consider a high relative angle of attack, and a delayed stall model is suggested. Finally, the aerodynamic model proposed in this study is verified with experimental data.

2. FLAPPING-WING AERODYNAMIC MODEL

Most previous studies on development of aerodynamic models can be broadly classified into the quasi-steady models [7, 8] and the unsteady models [9-14]. The former is only available in a quasi-steady flow condition where flapping frequencies are assumed to be slow and unsteady wake effects are ignored. The latter can account for the unsteady aerodynamic effects by modeling the wake effects. However, only a few aerodynamic models have been compared with limited experimental data of a rigid wing. In the present study, an improved aerodynamic model based on the modified strip theory [11] is suggested, in which a high relative angle of attack is considered and a delayed stall is proposed.

The aerodynamic forces of each section of a root flapping wing can be represented as shown in Fig. 1. Upon using the leading edge as a reference point, the section’s motion consists of a plunging motion, $\dot{h}$, and a pitching motion, $\dot{\theta}$, shown in Fig. 2. The flapping wing motion is assumed to be perpendicular to the flapping axis, but local deformation can be allowed.

Fig. 1 Root flapping wing and aerodynamic forces [11].

Fig. 2 Wing section aerodynamic forces and motion variables.
The section’s normal force generated by the circulation around the wing can be expressed as
\[
dN_x = 2\pi (\alpha' + \alpha_0 + \theta) \cos \frac{\rho UV}{2} \, \text{cdy}
\]  
(1)

where \( \rho \), \( U \), \( \alpha_0 \) are the atmospheric density, flight speed and angle of section’s zero-lift line, respectively. The mean pitch angle, \( \bar{\theta} \), is the sum of the angle of flapping axis, \( \theta_a \), and the mean angle of the chord, \( \bar{\theta}_a \).

The angle of attack, \( \alpha' \), the resultant flow velocity at 1/4 chord location, \( V \), and the relative angle of attack, \( \gamma \), can be expressed as follows:
\[
\alpha' = \frac{ARF'(k) + \frac{cAR}{2U} G'(k)}{2 + AR} \bar{\alpha} - 2(\alpha_0 + \bar{\theta})
\]  
(2)

\[
V = \sqrt{\left(U \cos \theta - \dot{h} \sin(\theta - \bar{\theta}_a)\right)^2 + \left(U(\alpha' + \bar{\theta}) - 0.5c\dot{\theta}\right)^2}
\]  
(3)

\[
\gamma = \tan^{-1} \left[ \frac{U(\alpha' + \bar{\theta}) - 0.5c\dot{\theta}}{U \cos \theta - \dot{h} \sin(\theta - \bar{\theta}_a)} \right]
\]  
(4)

where \( AR \), \( c \), and \( k \) are the wing aspect ratio, chord and reduced frequency, respectively.

The relative angle of attack at the 3/4 chord location, \( \alpha \), and the functions of the unsteady effects, \( F'(k) \) and \( G'(k) \), in Eq. (2) can be given by
\[
\alpha = \left[ \dot{h} \cos(\theta - \bar{\theta}_a) + 0.75c\dot{\theta} + U \sin \delta \theta \right]/U
\]  
(5)

\[
F'(k) = 1 - \frac{C_1 k^2}{k^2 + C_1^2}
\]  
(6)

\[
G'(k) = \frac{C_1 C_2 k}{k^2 + C_2^2}
\]  
(7)

where \( \delta \theta \) is the dynamic pitch angle (\( \theta = \bar{\theta} \)), and the coefficients in Eqs. (6) and (7) are expressed by using Scherer’s alternative formulation [15] as follows:
\[
C_1 = \frac{0.5AR}{2.32 + AR}
\]  
(8)

\[
C_2 = \frac{0.181 + 0.772}{AR}
\]  
(9)

The other aerodynamic forces of the wing section shown in Fig. 2 can be expressed as follows:
\[
dN_a = \frac{\rho \pi c^2}{4} \dot{V}_2 \, \text{dy}
\]  
(10)
\[
dD_e = -2\pi \alpha_0 (\alpha' + \bar{\theta}) \cos \gamma \frac{\rho UV}{2} \, \text{cdy}
\]  
(11)

\[
dT_s = \eta_2 2\pi \left( \alpha' + \bar{\theta} - \frac{1}{4} \frac{c\dot{\theta}}{U} \right) \cos \gamma \frac{\rho UV}{2} \, \text{cdy}
\]  
(12)

\[
dD_f = (C_d) f \frac{\rho V^2}{2} \, \text{cdy}
\]  
(13)

where \( dN_a \), \( dT_s \), \( dT_f \), and \( dD_f \) are the additional force due to apparent mass, the chordwise force due to camber, the leading edge suction force and the chordwise friction drag due to viscosity, respectively. The time rate of change of the midchord normal velocity due to the wing motion can be expressed as
\[
\dot{V}_2 = \dot{h} \cos(\theta - \bar{\theta}_a) - \dot{h} \dot{\theta} \sin(\theta - \bar{\theta}_a) + 0.5c\ddot{\theta} + U \dot{\theta} \cos \theta
\]  
(14)

The stall condition of the flapping wing is assumed as
\[
\left[ \frac{\gamma - 3}{4U} \right] > \alpha_{\text{stall}}
\]  
(15)

When the attached flow range is exceedeed, it is assumed that the flow is totally separated and all chordwise forces are negligible. The normal forces in the stall condition are given by
\[
(dN_{e, \text{sep}}) = (C_d) \frac{\rho UV}{2} \, \text{cdy}
\]  
(16)

\[
(dN_{a, \text{sep}}) = \frac{\rho \pi c^2}{8} \dot{V}_2 \, \text{dy}
\]  
(17)

where \( \dot{V} \) and \( V_a \) are the resultant flow velocity and the normal flow velocity at midchord location, respectively, and these are given by
\[
\dot{V} = \sqrt{\left(U \cos \theta - \dot{h} \sin(\theta - \bar{\theta}_a) \right)^2 + \left(\dot{h} \cos(\theta - \bar{\theta}_a) + 0.5c\ddot{\theta} + U \sin \theta \right)^2}^{1/2}
\]  
(18)

\[
V_a = \dot{h} \cos(\theta - \bar{\theta}_a) + 0.5c\ddot{\theta} + U \sin \theta
\]  
(19)

Finally, the normal and horizontal forces of each section, \( dN = dN_e + dN_a \), and \( dF_e = dT_s - dD_e - dD_f \), can be obtained by using Eqs. (1), (10-13), (16) and (17). The section’s instantaneous lift, thrust and moment are given by as follows:
\[
dL(t) = dN \cos \theta + dF_e \sin \theta
\]  
(20)
\[
dT(t) = dF_e \cos \theta - dN \sin \theta
\]  
(21)
\[
dM_{ac}(t) = C_{mac} \frac{\rho UV}{2} c^2 \, \text{dy}
\]  
(22)
\[
dM_{aero} = dM_{ac} - dN_e \left(0.25c - e\right) - dN_a \left(0.5c - e\right) + dM_a
\]  
(23)
\( (dM_{\text{aero}})_{\text{sep}} = -\left[ (dN_c)_{\text{sep}} + (dN_d)_{\text{sep}} \right] (0.5c - e) \) (24)

where \( e \) is the distance of the elastic axis of the wing section from the leading edge. These section’s aerodynamic forces and moment can be integrated along the span to obtain the whole wing’s instantaneous lift, thrust and moment as follows:

\[ L(t) = 2 \int_0^c \cos \beta dL \] (25)

\[ T(t) = 2 \int_0^c dT \] (26)

\[ M_{\text{aero}}(t) = 2 \int_0^c dM_{\text{aero}} \] (27)

where \( \beta \) is the section’s instantaneous dihedral angle.

3. AERODYNAMIC MODEL VERIFICATION

To verify the aerodynamic model proposed in the present study, the aerodynamic forces calculated by the present model are compared with the experimental data of a plate wing [16]. The wing is a flat plate with \( AR = 6 \), \( c = 30 \text{mm} \) and \( t = 1.5 \text{mm} \). This experiment was performed in a low speed wind-tunnel and the airspeed was 3.7 \( \text{m/s} \) during the tests.

For the application of the aerodynamic model, firstly, the aerodynamic coefficients in Eqs. (12), (13) and (16), and the zero-lift angle and the maximum stall angle should be defined. These necessary parameters can be also estimated by using the aerodynamic model and the experimental data. In this study, the parameters are estimated by using the static lift and drag coefficients measured in the static test as shown in Fig. 3 (square symbol). The least square method is also used to estimate the parameter values, and the estimated values are as follows:

\[ \eta_s = 0.07, \quad (C_d)_{t} = 2.6, \quad (C_d)_{f} = 0.072, \quad \alpha_0 = 0 \text{deg}, \]

\[ (\alpha_{\text{stall}})_{\text{max}} = 8.4 \text{deg}, \quad (\alpha_{\text{stall}})_{\text{min}} = -8.4 \text{deg} \]

The static lift and drag coefficients calculated by the aerodynamic model using the above values are also shown in Fig. 3 (circles symbol). There are some discrepancies between the experimental and the predicted results in the stall flow region, but it shows a very good agreement especially in the fully attached flow range.

The aerodynamic model of the plate wing is compared with the dynamic test results. In the dynamic test, the pitch angle of the wing was fixed at \( \theta = 6 \text{deg} \), and the wing was sinusoidally oscillated in vertical direction (plunging motion) with the amplitude of \( h = 14.1 \text{mm} \) and the reduced frequency at \( k = \omega a / 2U = 0.31 \). In this study, a low-pass filter of 30Hz is used and the wing is assumed to be a rigid wing.

Figure 4 shows the comparison of time histories of the aerodynamic force and moment coefficients between the experimental data (solid line) and the estimated values (dashed line). This figure clearly demonstrates that in fully attached flow range, the aerodynamic forces and the moment can be accurately predicted by the aerodynamic model suggested in this study, but in the stall flow range, there are some discrepancies between the predicted and the measured results like in the static results. This result means that the stall model represented by Eqs. (16) and (17) is not enough to predict the aerodynamic stall phenomena. This is probably because the plate wing does not have a passive pitching motion induced by the fluid-structure interaction between the chordwise flexibility and the aerodynamic forces, which reduces the relative angle of attack so that the stall condition is delayed. Therefore, it is evident from this result that the stall condition of the fixed plate wing can not be ignored, and an additional stall model should be applied to predict the stall phenomena.

4. DELAYED STALL MODEL

In the delayed stall condition, there is a leading edge vortex on the wing surface, and the separated flow from the leading edge reattaches before it reaches the trailing edge and the Kutta condition is maintained [2, 6]. This results in the development of the suction force normal to the wing and of the chordwise friction force. Using this delayed stall analogy, in the present study, the stall model is suggested by additionally introducing the suction force and the friction force in the stall condition as shown in Fig. 5. These additional forces are expressed as follows:

\[ (dF_l)_{\text{sep}} = \eta_{\text{stall}}^{\text{sep}} 2\pi \left( \alpha^t + \frac{1}{2} \frac{c \dot{\alpha}}{U} \right) \cos \gamma \frac{\rho L V}{2} \text{cdy} \] (28)

\[ (dD_d)_{\text{sep}} = (C_d)^{\text{stall}} \frac{\rho L^2 a}{2} \text{cdy} \] (29)

Because the coefficients in Eqs. (28) and (29) are parameters depending not only on the wing geometry but also on the wing motion, it is not easy to determine the coefficients. To investigate the feasibility of the stall model, the coefficients minimizing the errors of the lift and thrust coefficients are used. The estimated values are as follows:

\[ \eta_{\text{stall}}^{\text{sep}} = 1.49, \quad (C_d)^{\text{stall}} = 0.065 \]

The predicted results of the aerodynamic model modified in the stall condition are also shown in Fig. 4 (cross symbol). It shows that the aerodynamic results predicted by the modified model agree very well with the experimental data not only of the lift and thrust coefficients but also of the moment coefficient. Therefore, it is evident from this result that the aerodynamic model proposed in this study is suitable in the fully attached and the stall flow ranges. This aerodynamic model can be also applied to the fluid-structure interaction analysis for optimal flexible flapping-wing design and flapping-wing flight control.

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Fig. 3 Lift and drag coefficients of the flat plate.
agreements between the predicted and the measured data. We expect that this aerodynamic model proposed in this study can be applied to the fluid-structure interaction analysis for optimal flapping-wing design and flapping-wing flight control.

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