A Review on Aerodynamics of Flapping Wings

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Abstract - *The recent interest in flapping wing air vehicle is motivated by the notion that flapping wing may offer some unique aerodynamic advantages over a fixed wing solution. In the future, this technology may be integrated into new plane designs and even retrofitted into existing planes. This is very exciting for the future of flight technology, but more tests are needed before we start seeing these wings on commercial aircrafts. In this paper we have reviewed the aerodynamics modeling of flapping wing such as kinematics of wing, Navier-stokes equation. Also the mathematical formulation of normal forces, chord-wise forces, total forces, lift and thrust has been reviewed. In the last it has been shown that the flexible wing is much more beneficial than rigid wing.*

Key Words: Flexible wing, Aerodynamics, Flapping, Forces, deformation.

1. INTRODUCTION

We all have dreamed of flying with flexible wings like birds having wings. We are trying to design such a wing from a long time but got a little success. Although completely flexible wings are feasible and practical for some applications, for others performance and other characteristics may need to be improved by the judicious addition of local stiffening. Consequently a complete spectrum of wing shapes and degrees of stiffening is being developed to fill the gap between the conventional parachute and the rigid wing. To include this complete spectrum in one definition, we can define flexible wings as wings made with very loose or slack membranes whose configurations in flight are determined primarily by the aerodynamic forces on the membranes and the reactions from the load suspension system.

Flap wings up and down to produce lift and thrust at the same time. People are highly interested in researching of the flapping flight, for the entire flying birds take the flapping as their means to flight. People have done much research work on flapping wing by experimental, theoretical, and computational means.

The idea behind the flexible flap is to create a wing that can be fine-tuned throughout flight with a precision unavailable to conventional flaps. The result should be simpler, quieter, more reliable, and more fuel-efficient. In 2006, FlexSys attached a prototype of the flexible wing to the underside of Scaled Composite's White Knight aircraft and flew test runs over the Mojave Desert. Results from that test led Kota to estimate that eventually, in new aircraft built to take full advantage of the flexible wings, the technology could cut fuel consumption by 12 percent. As Kota wrote, in an industry that burns 16 billion gallons of jet fuel a year that could be significant.

When Orville Wright first took to the air on Dec. 17, 1903, he didn't have ailerons or flaps to control his airplane. Instead, the Wright brothers had chosen to twist or "warp" the wingtips of their craft in order to control its rolling or banking motion. Rather than using one of the craft's two control sticks to make the wingtips twist, they had devised a "saddle" in which the pilot lay. Cables connected the saddle to the tips of both wings. By moving his hips from side-to-side, the pilot warped the wingtips either up or down, providing the necessary control for the Wright Flyer to make turns.

NASA's Dryden Flight Research Center, Edwards, Calif., in cooperation with the U.S. Air Force Research Laboratory (AFRL) and Boeing Phantom Works, researched a high-tech adaptation of the Wright Brothers rudimentary "wing warping" approach to aircraft flight control in the Active Aeroelastic Wing (AAW) flight research program. The focus of AAW research was on developing and validating the concept of aircraft roll control by twisting a flexible wing on a full-size aircraft. The test aircraft chosen for the AAW research is a modified F/A-18A obtained from the U.S. Navy in 1999. The aerodynamic forces acting on the F/A-18s traditional aircraft control surfaces, such as ailerons and leading-edge flaps, were used to twist a more-flexible wing to provide aircraft roll manoeuvring control.

The first test flight was on 6 Nov 2015, conducted to-date included speeds at 0.75 Mach at 20,000 and 40,000ft altitude and various banking manoeuvres up to 1.7G (continuous load) and high dynamic pressures subjecting the FlexFoil control surface to various load conditions.

The technology has the potential to take aviation to new heights. The adaptive wing significantly increases the fuel economy of the airplanes and thus may decrease the amount of fuel used by as much as 12%. Air travel currently contributes a large amount of pollution to the atmosphere, so this advancement is good news for the environment.
People living under air-traffic hotspots can also rejoice: Where old planes with rigid wings have fewer options to

reduce drag and as a result are rather noisy, these new sleek wings minimize drag, making them slightly quieter.

1.1 Aerodynamic Characteristics of Flapping Wings

The computational model for the unsteady aerodynamics of flapping wing using strip theory approach has been developed and clarified. The proposed method is used to solve the mechanical flying ornithopter (SlowHawk 2) of flexible wing membrane. In doing so, the model is verified through the computations performed on a mechanical flying Pterosaur replica as well as smaller biological species including the Corvus monedula and Larus canus.

The effect of aerodynamic parameters on the performance of these biological flight vehicles is studied. The effect of Reduced frequency is studied defining an optimal design points for sustainable flight conditions (L > W). A manual optimization is performed on the developed code for the SlowHawk 2 in order to get predicted values to be used as an input data for calculating the optimum aerodynamic characteristics of it. Kinematic model is based on the model proposed by Delaurier, which is based on strip theory and used for predicting average Lift and Thrust for pterosaur replica. The wing is assumed to be rigid in the spanwise direction; this is suitable for wings with high aspect-ratio.
A continuous harmonic sinusoidal motion is assumed. So there is equal time for upstroke and downstroke, this is a simplifying assumption because in real biological flight the downstroke time is more than upstroke time. It also accounts for camber and leading edge suction effects, which is a phenomena associated with biological wings. Post-stall behavior is also accounted for in this model. With this theory, wing bending can be accounted for in the kinematic model, although bending effects are ignored in this particular model. The relative angle of attack will not fall below zero (no negative stalling), consequently the minimum stall angle of attack will not be specified. When the time dependence is included, the flow conditions for each strip will change in time, and hence the change in Lift and Thrust generated. The total Lift and Thrust for the wing is calculated by the summation of the contributions from each segment for a whole flapping cycle. Daniel et al. studied the effect of aerodynamic parameters based on Delaurier model the performance of a mechanical flying pterosaur replica as well as smaller biological species including Corvus Monedula, Larus Canus and Columba Livia. A design of an efficient Ornithopter wing was introduced by Bendict, using aeroelastic modeling and strip theory.

1.2 Governing Navier-Stokes Equation

The numerical simulations of solving Navier-Stokes equations are used more and more in the flapping wing research for its high precision. Neef and Hummel have investigated plunging and pitching NACA0012 airfoil in 2D and 3D flow. They solved the Euler equations for a rectangular wing in a sinusoidal flapping and twisting motion. Tuncer and Platzer used a 2D compressible Navier-Stokes/potential solver to predict thrust generation in flapping/stationary airfoil combinations in tandem. Lin and Hu developed a 3D Euler/Navier-Stokes solver for simulation plunging/pitching NACA0014 airfoil. Xie and Song developed a 3D Navier-Stokes solver to investigate the aerodynamic characteristics of flapping wing on the low speed and low Reynolds number.

The researches mentioned above have done much work on the flapping wing. And it is necessary to go further on the study about flapping wing. It is aimed to research the flapping wing air vehicle including the flapping wing, fuselage, vertical and horizontal stabilizers. A method should be developed to investigate the aerodynamic characteristics of whole flapping wing air vehicle. For unsteady flows an implicit dual time-stepping scheme is used. Implict residual smoothing is employed to accelerate convergence. The Baldwin-Lomax algebraic turbulent model is applied for calculating the turbulence flows.

For the complexity of the configuration, the chimera grid method is chosen to investigate the flapping wing air vehicle. The spatial discretization is characterized by a second-order cell-center method for finite volumes. A five-stage Runge-Kutta scheme is employed to achieve convergence of the solution by integration with respect to time. In chimera method, the tri-linear interpolation is used in the grid interface communication. A method is developed to investigate the aerodynamic characteristics of flapping wing air vehicle by solving the 3D Navier-Stokes equations based on the chimera grid. The grid system is based on the chimera grids which are composed of the motion wing grid and stationary background grid. The background grid includes fuselage, vertical and horizontal stabilizers. An efficient method, namely distance-decreasing searching method, is developed to apply on the hole-cutting and the interpolation cells searching of chimera grid pre- processing. Based on these numerical methods, the aerodynamic characteristics of flapping wing air vehicle can be researched.

The wing motion is composed of flapping and twisting. The flapping angle is defined as:

$$\psi (t) = \psi (z) \cos (\omega t)$$

The twisting angle is defined as:

$$\alpha (z, t) = \alpha_0 + \alpha_m (z) \cos (\omega t + \Phi)$$

$$\alpha_m (z) = = \alpha_{m,tip} \times z/b$$

The reduce frequency is:

$$k = \omega c/2U_\infty$$

Where, Ψ is the flapping angle, z is the relative distance to root on the wing, α is the twisting angle, α_0 is the mean angle of attack, $\alpha_{m, tip}$ is the twisting angle at wingtip, b is the half span of the wing, Φ is the phase shift between Ψ and α, ω is the angular velocity and U_∞ is the freestream velocity.

The flapping axis is x axis. The three wing positions are at top point, neutral point, and bottom point, respectively. The wing flaps from the top point to bottom point and go back to the top point is a flapping cycle (Figure 1). The t/T=0.0 means the beginning of a flapping cycle, also the end of upstroke or beginning of downstroke. And the t/T=0.5 means the end of downstroke or beginning of upstroke.

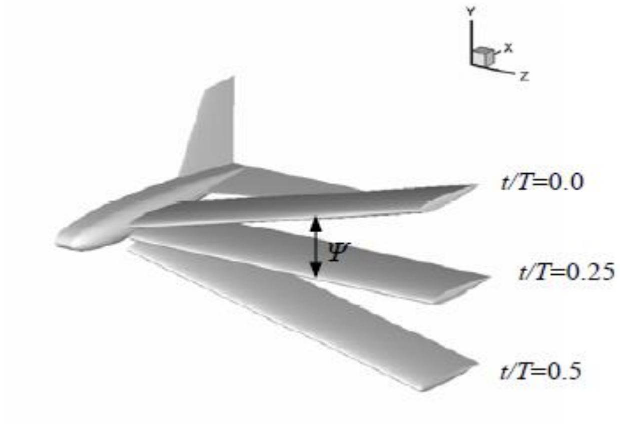

Fig -1: Wing motion of flapping wing air vehicle

1.3 Kinematics

The wing kinematics and wing sections are illustrated in Fig. 2. For a root flapping motion with no spanwise bending, as a result, the plunging motion is given by:

h = -(τy) sin (Φ)

Where, h is the plunging displacement, τ is the maximum flapping angle, Φ is the cycle angle, defined by (ωt) and ω is the angular flapping frequency in rad/s.

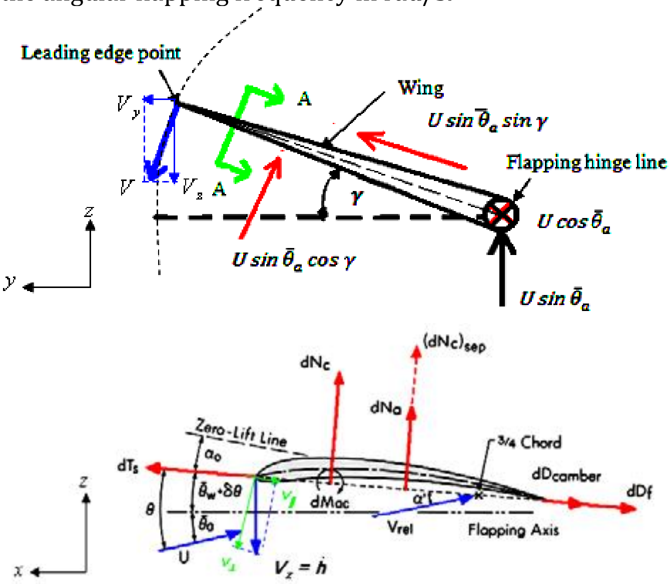

Fig -2: A front and section view of flapping wing

The dynamic twist is linearly proportional to the span, according to the following relation:

$\delta\theta = -(\beta_o y) \cos(\Phi)$

Where, δθ is the dynamic varying pitch angle and is given by

$\delta\theta = (\theta - \bar{\theta})$

Where, θ is the pitch angle of airfoil chord with respect to free stream velocity U, $\bar{\theta}$ is the section's mean pitch angle, and is given by:

$\bar{\theta} = \bar{\theta}_a + \bar{\theta}_w$

Where, $\bar{\theta}_a$ is the pitch angle of flapping axis with respect to U and $\bar{\theta}_w$ is the mean pitch angle of chord with respect to flapping axis. In the case of whole wing motion (no flapping axis), $\bar{\theta}$ will be the wing's mean pitch angle.

Upon using the leading edge as the reference point, the wing's motion consists of three discrete motions; these motions are the plunging motion, pitching motion and the forward motion relative to the freestream velocity (U). The component of plunging velocity 'h' in a direction perpendicular to the airfoil chord line seen at each instant of time is cos $(\theta - \theta_a)$. In pitching motion, ¾ of the chord point is the point of concern and then the radius of rotation is located at ¾ of the chord giving a rotational velocity equals ¾ cθ. Using wing motion discussed above, it can be easily calculated that the relative angle of attack 'α' is located at ¾ of the chord location due to wing's motion and is given by:

$\alpha = [h\cos(\theta - \bar{\theta}_a) + (3/4) C\theta + U(\theta - \theta_a)] / U$

2. FORCE CALCULATIONS

For calculation of the forces generated during a flapping cycle, the flow relative velocity and flow relative angle of attack should be determined first, using the derived expression of relative angle of attack at ¾ of the chord location due to wing's motion α, the flow's relative angle of attack α' at ¾ of the chord location is given by:

$\alpha' = [C(k)_{Jones}] \alpha - W_0/U$

Where, W_0 is the downwash velocity at ¾ of the chord location

The coefficient of α'in equation is derived by Jones accounts for the wing's finite span unsteady vortex wake by means of strip theory model. He used modified Theodorsen function for finite aspect ratio wings which is given by:

$C(k)_{Jones} = (\Lambda/(2+\Lambda))\, C'(k)$

Where, Λ is the wing aspect ratio.

$C(k)_{Jones}$ is a complex function, and it was found convenient to use Scherer's alternative formulation where the complex form of C'(k) is given by:

$C'(k)=F'(k)+iG'(k)$

2.1 Normal Force Calculations

The normal force calculations on the wing differs depending on whether the flow is attached or separated. Some modifications have to be made to treat the separated flow condition. To calculate the Normal force for attached flow, the section's normal force due to circulation is given by:

$dN_e = 0.5\rho UV\, C_n\,(y)\; c\; dy$

Where, the normal force coefficient is given by:

$C_n\,(y) = 2\pi\,(\alpha' + \alpha_0 + \bar{\theta})$

Where, α_0 is the airfoil zero Lift angle.

2.2 Chordwise Force Calculation

The section's circulation distribution likewise generates forces in the chordwise direction. The chordwise force due to camber is given by:

$dD_{camber} = -2\pi\,\alpha_0\,(\alpha' + \bar{\theta})\; 0.5\rho UV\; c\; dy$

Garrick had presented a theory where the leading-edge suction is examined for a two dimensional airfoil. Incorporating his theory to the strip theory model, we get an expression for the chordwise force due to leading-edge suction, which read as:

$dT_s = \eta_s\, 2\pi[\alpha' + \bar{\theta} - (c\,\theta/4U)]^2\; 0.5\rho UV\; c\; dy$

Where, η_s is the leading edge suction efficiency factor.

Viscosity also gives a chordwise friction drag as:

$dD_f = (Cd)_f\;\; 0.5\rho V_x\; c\; dy$

Where, $(Cd)_f$ is the drag coefficient due to skin friction.

Thus, the total chordwise force is given by:

$dF_x = dT_s - dD_{camber} - dD_f$

When the attached flow range is exceeded, totally separated flow is assumed to abruptly occur. For that condition, all chordwise forces are negligible.

3. LIFT AND THRUST

Now, the equations for the segment's instantaneous lift and thrust are:

$dL = dN\cos\theta + dF_x\sin\theta$

$dT = dF_x\cos\theta - dN\sin\theta$

These may be integrated along the span to give the whole wing's instantaneous Lift and Thrust for the whole wing as:

$L\,(t) = 2\int_0^{b/2} \cos(\gamma(t))\, dL$

Where $\gamma(t)$ is the section's dihedral angle at that instant in the flapping cycle

$T\,(t) = 2\int_0^{b/2} dT$

The wing's average Lift and Thrust are obtained by integrating L (t) and T (t) over the cycle.

$\bar{L} = 1/2\pi \int_0^{2\pi} L(\Phi)\, d\Phi$

$\bar{T} = 1/2\pi \int_0^{2\pi} T(\Phi)\, d\Phi$

4. CONCLUSION

The flexible wings can actually increase aerodynamic stability by damping unsteady forces/moments and storing elastic energy. Membrane mass has a major effect on performance. As changing from a nylon surface to a lightweight Toughlon surface, the performance increased for Thrust rather than lift. At zero forward speed modes the lighter wing performs better than the heavier one. Flexible wings have also been shown to be more advantageous than rigid wings, with having higher stall angles by performing adaptive washout, and providing smoother flight. The main advantage of flexible wings is that they facilitate shape adaptation, essentially adapting to the airflow to provide a smoother flight. A wing changes shape as a function of angle of attack and wind speed. With a decrease in relative airspeed, the angle of attack of the wing increases, and the wing becomes more efficient, resulting in near constant lift. This enables a UAV with flexible wings to fly with exceptional smoothness, even in gusty conditions. Increasing the angle of attack for equal flapping amplitudes, leads to increasing the Lift and decreasing the Thrust. Maximum value of Lift is obtained for a specific flapping angle for all cases. Propulsive efficiency increases as the flapping angle increases for all cases. Based on dynamic twist, the propulsive efficiency achieves an optimum value for all cases. A long wing can have smaller twist than a shorter one and still have enough twist to generate sufficient Thrust.
Increasing the flapping frequency leads to increasing both lift and thrust for equal flapping angle amplitudes. This is different from the behavior of shearflex wings, for which the lift is essentially invariant with flapping frequency. A best performance is obtained by setting the downstroke angle greater than the upstroke angle.

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