PATH OPTIMIZATION OF FLAPPING AIRFOILS BASED ON NURBS

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ABSTRACT

The path of a flapping airfoil during upstroke and downstroke is optimized for maximum thrust and propulsive efficiency. The periodic flapping motion in combined pitch and plunge is described using Non-Uniform B-Splines (NURBS). A gradient based algorithm is employed for optimization of the NURBS parameters. Unsteady, low speed laminar flows are computed using a Navier-Stokes solver in a parallel computing environment based on domain decomposition. It is shown that the thrust generation is significantly improved in comparison to the sinusoidal flapping motion. For a high thrust generation, the airfoil stays at a high effective angle of attack for short durations.

INTRODUCTION

Based on observations of flying birds and insects, and swimming fish, flapping wings have been recognized to be more efficient than conventional propellers for flights of very small scale vehicles, socalled microair vehicles (MAVs) with wing spans of 15 *cm* or less. The current interest in the research and development community is to find the most energy efficient airfoil adaptation and flapping wing motion technologies capable of providing the required aerodynamic performance for a MAV flight.

Recent experimental and computational studies investigated the kinematics, dynamics and flow characteristics of flapping wings, and shed some light on the lift, drag and propulsive power considerations[1, 2]. Water tunnel flow visualization experiments on flapping airfoils conducted by Lai and Platzer[3] and Jones et al.[4] provide a considerable amount of information on the wake characteristics of thrust producing flapping airfoils. In their experiments, Anderson et al.[5] observed that the phase angle between pitch and plunge oscillations plays a significant role in maximizing the propulsive efficiency. NavierStokes computations performed by Tuncer et al.[6, 7, 8] and by Isogai et al.[9, 10] explore the effect of flow separation on the thrust generation and the propulsive efficiency of a single flapping airfoil in combined pitch and plunge oscillations.

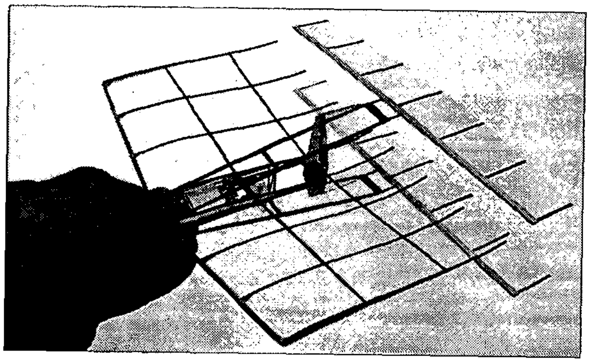

Figure 1: Flapping-wing MAV model(Jones and Platzer)

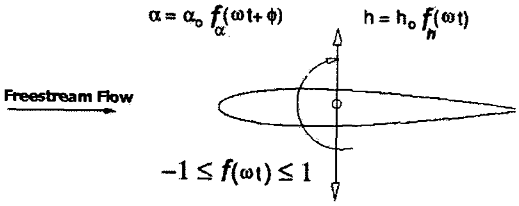

Figure 2: Flapping motion of an airfoil

Jones and Platzer[11] recently demonstrated a radiocontrolled micro air vehicle propelled by flapping wings in a biplane configuration (Figure 1). The experimental and numerical studies by Jones et al.[11, 12, 13] and Platzer and Jones[14] on flappingwing propellers points at the gap between numerical flow solutions and the actual flight conditions over flapping wings.

Most recently, Kurtulus et al.[15] obtained optimum parameters to generate maximum lift during a flapping motion of an airfoil in hovering flight, by using numerical and analytical models. The wake structures and hydrodynamic performance of finite aspect-ratio flapping foils are explored by Dong et al.[16]. The results of their numerical simulations indicate that the wake topology of the relatively low aspect-ratio foils is significantly different from that observed for infinite/large aspect-ratio foils. A recent work by Lewin and Haj-Hariri[17] indicates that the aerodynamic forces generated by flapping insects are very sensitive to the wing kinematics.

In our earlier studies[6, 8], the average thrust coefficient of a NACA0012 airfoil flapping sinusoidally in combined plunge and pitch was first obtained for a range of reduced frequencies and amplitudes of the flapping motion. The computational and experimental findings show that thrust generation and propulsive efficiency of flapping airfoils are

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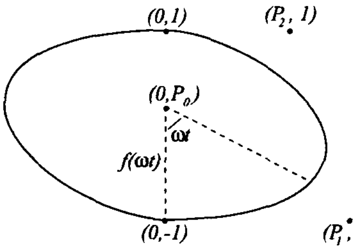


Figure 3: A closed curve defined by a 3^{rd} order NURBS

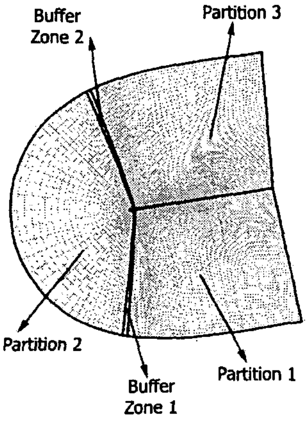


Figure 4: Domain decomposition with 3 partitions

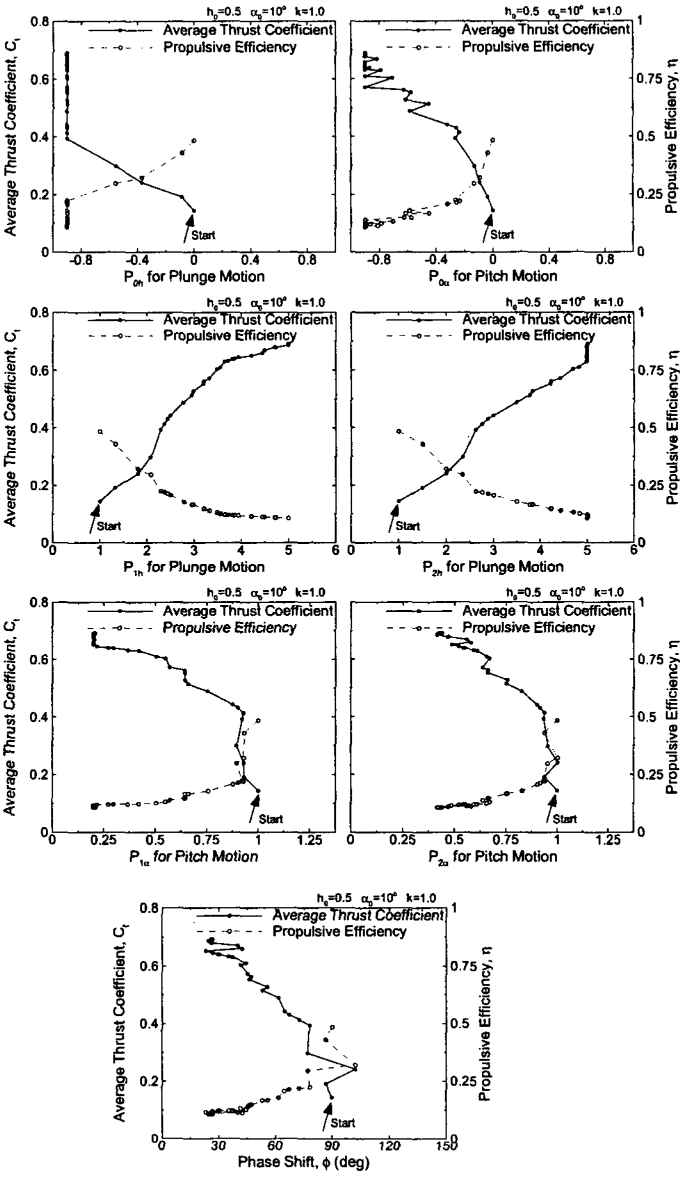


Figure 5: Optimization steps

closely connected to the flapping motion and flow parameters. In later studies[18, 19], we employed a gradient based optimization of sinusoidal flapping motion parameters; flapping frequency, the amplitude of the pitch and plunge motions, and the phase shift between them to maximize the thrust and/or the propulsive efficiency of flapping airfoils. It should be noted that in the sinusoidal motion, the pitch and plunge positions are based on the projection of a vector rotating on a unit circle, and the maximum plunge and pitch velocities occur at the mean plunge and pitch positions. In a later study[20], the sinusoidal periodic motion was relaxed by replacing the unit circle with an ellipse, and introducing the flatness coefficient as the ratio of the axes of the ellipse.

In this study, the periodic motion is further relaxed using a Non-Uniform Rational B-Splines (NURBS) based closed curve instead of an ellipse. The new closed curve representing the flapping path is produced employing a 3^{rd} order NURBS for the half stroke. It is defined by 3 parameters. The first parameter (P_0) defines the center of the closed curve while the remaining two (P_1 and P_2) control the flatness level of the closed curve according to the center (Figure 3).

Parallel Computation

In the optimization process, the evaluation of the gradient vector components of the objective function, which requires a few periods of an unsteady flow solution over a flapping airfoil, is done in parallel. In addition, a coarse parallel algorithm based on domain decomposition is implemented for unsteady flow solutions. The computational C-grid is decomposed into overlapping subgrids (shown as partitions in Figure 4), and the solution on each subgrid is obtained in parallel. Intergrid boundary conditions at the overlapping boundaries (shown as buffer zones in Figure 4) are exchanged among subgrid processes. PVM (version 3.4.5) library routines are used for inter-process communication. Computations are performed in a PC cluster operating on Linux.

RESULTS

In this optimization study, the optimization variables are chosen as the NURBS parameters defining the plunging and pitching paths, P_{0h}, P_{1h}, P_{2h}, $P_{0\alpha}$, $P_{1\alpha}$ and $P_{2\alpha}$ (Figure 3), and the phase shift between the pitch and plunge motions, ϕ. As the airfoil is set to a flapping motion in plunge and pitch on the NURBS paths, the NURBS parameters are optimized for maximizing the thrust. A gradient based steepest descent method is employed for

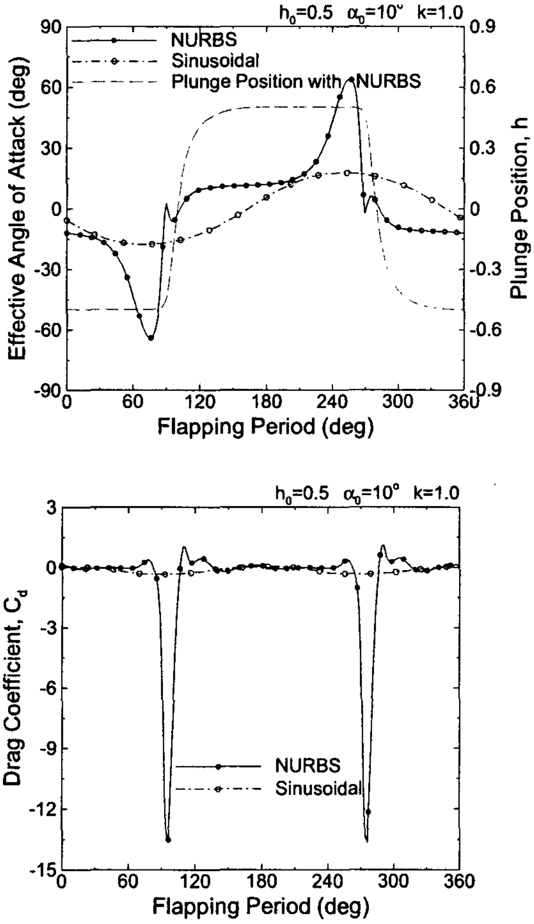
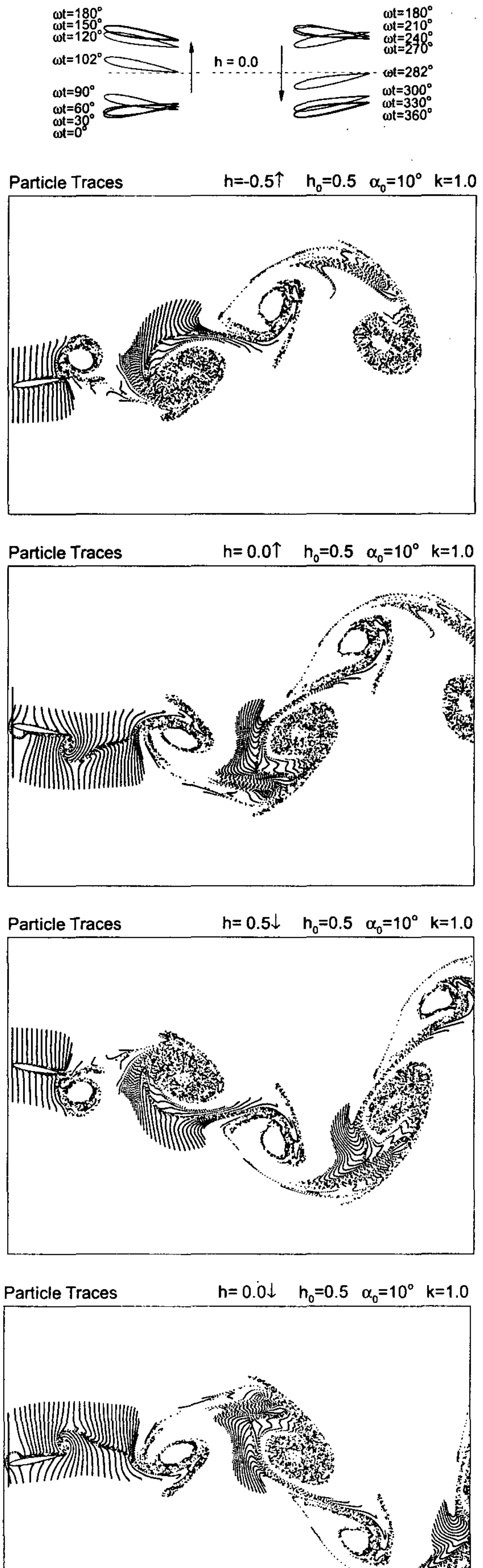


Figure 6: Effective angle of attack variation and unsteady drag/thrust coefficient

the optimization process. At each optimization step, the variation of the average thrust with respect to perturbed optimization variables are computed numerically to evaluate the gradient vector. For each perturbed optimization variable, unsteady flows are computed in parallel. In a typical optimization process, parallel computations take about $20-30$ hours of wall clock time using $4-8$ processors.

In this study, the location of the points P_1 and P_2 are constrained within the range 0.2 — 5.0 whereas P_0 is constrained in the range -0.9 — 0.9 in order to define a proper periodic motion. The optimization variables are optimized for fixed values of the reduced flapping frequency, $k \equiv \frac{\omega c}{U_\infty} = 1.0$, the plunge amplitude, $h_0 = 0.5$, and the pitch amplitude, $\alpha_0 = 10^o$. The unsteady laminar flowfields over the flapping airfoil are computed at a low Mach number of 0.1 and a Reynolds number of 10000. Unsteady computations are performed in parallel based on domain decomposition (Figure 4). PVM message passing library routines are used in the parallel solution algorithm. Flowfields are then analyzed in terms of the variation of the thrust/drag coefficient in a flapping period, the average thrust and the propulsive efficiency and unsteady particle traces.



Particle Traces h=-0.5↑ h_0=0.5 α_0=10° k=1.0

Particle Traces h= 0.0↑ h_0=0.5 α_0=10° k=1.0

Particle Traces h= 0.5↓ h_0=0.5 α_0=10° k=1.0

Particle Traces h= 0.0↓ h_0=0.5 α_0=10° k=1.0

Figure 7: Optimized flapping motion and the flowfield

Figure 5 shows the variation of optimization variables along the optimization process. As the optimization variables are incremented along the gradient vector, the average thrust coefficient increases gradually, and a maximum value of $C_t = 0.69$ is reached. The corresponding propulsive efficiency is about 11%.

In an earlier study, the sinusoidal flapping motion of the airfoil under the same flow conditions is optimized with respect to the phase shift, ϕ, only[20]. The maximum thrust value of $C_t = 0.15$, which is less than 1/4 of the value given above, is obtained at $\phi = 86.7^o$ with a propulsive efficiency of $\eta = 48\%$. The variation of effective angle of attack and drag(-thrust) histories for NURBS based and sinusoidal flapping motions are given in Figure 6. It is noted that although the maximum effective angle of attack occurs about mid-plunge positions in both cases, in the NURBS based flapping it reaches values about 3.5 times greater than that of the sinusoidal flapping for short durations.

Unsteady particle traces along a period of the optimized flapping motion and the motion of the airfoil are given in Figure 7. As seen the flowfield is highly vortical with strong leading edge vortices being formed and shed into the wake. It is also noted that in the non-sinusoidal flapping, the pitching motion mostly occurs at the minimum and maximum plunge positions, and much higher plunge velocities than the ones in the sinusoidal flapping are observed.

The study shows that the thrust generation of a flapping airfoil may be increased significantly by a non-sinusoidal flapping, however, it is achieved at the expense of a reduced propulsive efficiency. In the full paper, the maximization of thrust and propulsive efficiency together will be considered in detail.

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