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NUMERICAL INVESTIGATION OF 3-D EFFECTS ON THRUST GENERATION OF FLAPPING AIRFOILS

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ABSTRACT

2-D and 3-D flows over flapping airfoils are computed, and thrust generation and propulsive efficiencies are compared. The flapping motion of the airfoils is described by a combined harmonic plunge and pitch motion. The flows are computed for flapping motions which produce maximum thrust and propulsive efficiency, predicted by a gradient based optimization algorithm using a 2-D flow solver. 2-D and 3-D flow computations are both performed in parallel. PVM and MPI message passing libraries are used. 3-D simulations resulted in slightly higher thrust and efficiency values than 2-D predictions. Both 2-D and 3-D numerical simulations show that high thrust may be obtained at the expense of reduced efficiency. For high propulsive efficiency, the large scale formations at the leading edge are prevented.

INTRODUCTION

Due to bird and insect flight, flapping wing propulsion has already been recognized to be more efficient than conventional propellers for very small scale vehicles, so-called micro-air vehicles (MAVs). MAVs with wing spans of 15 cm or less, and flight speed of 30 to 60 kph are of recent interest for military and civilian applications. Current studies in the research and development community are 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[10, 17]. Lai and Platzer[18] and Jones et al.[19] conducted water tunnel flow visualization experiments on flapping airfoils to analyze the wake characteristics of thrust producing flapping airfoils. The significance of the phase shift between plunging and pitching in maximizing the propulsive efficiency is shown by Anderson et al.[20] in their experimental study. The experimental and numerical studies by Jones et al.[7, 9, 8], and Platzer and Jones[13] on flapping-wing propellers point at the gap between numerical 2-D flow solutions and the actual 3-D test flight conditions. In the comparison of 2-D and 3-D panel-code results, Jones et al.[8] observe less 3-D thrust and efficiency values than 3-D ones. However, 3-D results rapidly approach 2-D results as AR, the aspect ratio of the wing increases from $AR = 4$ to $AR = 100$. They also observe a phase lag in 2-D and 3-D thrust variation along time. The wake structures and hydrodynamic performance of finite aspect-ratio flapping foils are explored by Dong et al.[2]. 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.

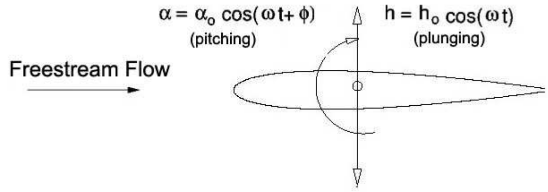

Figure 1: Flapping motion of an airfoil

The present authors have been involved in numerical investigation of unsteady aerodynamics, and have performed studies of flapping/moving airfoil/wing. Tuncer et al.[22, 21, 12] and Isogai et al.[14, 11] studied the effect of flow separation on thrust and propulsive efficiency of a single flapping airfoil in combined pitch and plunge oscillations. Tuncer and Kaya[5, 6] optimized the harmonic flapping motion of a flapping airfoil for maximum thrust and propulsive efficiency. Barakos and Drikakis[15, 16] investigated unsteady turbulent 3-D flow over moving bodies while Spentzos et al.[3, 4] performed CFD studies on 3-D dynamic stall. Although their studies were designed

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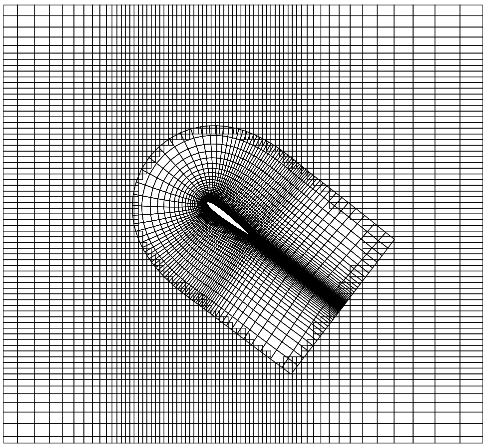

Figure 2: Grid system used in 2-D flow computation

to address dynamic stall in helicopter problems the principles of the employed numerical techniques are applicable to the study of MAVS. 3-D CFD computations can be expensive in terms of CPU time and in this work 3-D CFD was mainly used to complement the 2-D study looking at the effect of the wing aspect ratio and establishing the validity of the 2-D computations for motion optimization purposes.

In this study, Navier-Stokes computations are performed for 2-D and 3-D lifting surfaces flapping in a combined pitch and plunge motion (Figure 1). The flapping motions giving the maximum thrust and the propulsive efficiency are studied. The optimum motions are obtained by a gradient based optimization algorithm which uses a 2-D unsteady, viscous flow solver[6, 5]. The optimized flowfields are, then, independently computed by a 3-D unsteady, viscous solver. Finally, the simulations obtained by 2-D and 3-D flow computation topologies are compared with each other.

NUMERICAL METHOD

Unsteady viscous flowfields around a flapping airfoil and a flapping wing are computed by solving the Navier-Stokes equations on overset grids and a multi-block grid system, respectively. All unsteady computations are performed in parallel based on domain decomposition. PVM and MPI message passing library routines are used in the parallel solution algorithm. The computed flowfields are analyzed and compared in terms of aerodynamic loads, instantaneous distribution of flow variables, and unsteady particle traces.

Overset grids are used to discretize the 2-D computational domain. C-type grid around the airfoil is overset onto a Cartesian background grid (Figure 2). 3-D flow solver uses a multi-block structured grid system. The flapping motion of the lifting surface is imposed by moving the surface and the computational grid around it. The flapping motion in plunge, h, and pitch, α, is defined by ([1])

$$\begin{aligned} h &= -h_0 \frac{s_h \cos(\omega t)}{\sqrt{s_h^2 \cos^2(\omega t) + \sin^2(\omega t)}} \\ \alpha &= -\alpha_0 \frac{s_\alpha \cos(\omega t + \phi)}{\sqrt{s_\alpha^2 \cos^2(\omega t + \phi) + \sin^2(\omega t + \phi)}} \end{aligned} \quad (1)$$

where the angular frequency, ω is given in terms of the reduced frequency, $k = \frac{\omega c}{U_\infty}$. The pitching motion is about the mid-chord location. Note that for $s_h = 1$ and $s_\alpha = 1$, the flapping motion becomes sinusoidal.

Parallel Computation

2-D Solver: The parallel algorithm is based on domain decomposition in a master-worker paradigm. The computational C-grid is decomposed into overlapping subgrids, and the solution on each subgrid is obtained in parallel. Intergrid boundary conditions at the overlapping boundaries are exchanged among subgrid processes. PVM (version 3.4.5) library routines are used for inter-process communication. Computations are performed in a cluster of PCs with dual processors and Linux operating system.

3-D Solver: For 3D computations the PMB solver of Glasgow University was used. This is again a parallel CFD solver based on multi-block structured grids. Parallelization is achieved by allocating blocks to processors in a systematic way which allows balanced computations across many processors. MPI (version 5) library routines are used for inter-process communication and computations have been performed on the Beowulf cluster of Glasgow using up to 24 processors for this case. All Beowulf nodes are Pentium 4 machines at 2.5 GHz.

The PMB code is capable of solving flow conditions from inviscid to fully turbulent using the Reynolds Averaged Navier-Stokes (RANS) equations in three dimensions. Detached eddy simulation and large eddy simulation options are available in addition to an array of turbulence closures based on linear and non-linear two-equation eddy-viscosity models. Due to the flow conditions considered here, laminar flow conditions were used. To solve the RANS equations, multi-block grids were generated around the wing geometry, and the equations were discretized using the cell-centered finite volume approach. For the discretisation of the convective fluxes Osher's scheme has been used. A formally third order accurate scheme is achieved using a MUSCL interpolation technique. Viscous fluxes were discretized using central differences. Boundary conditions were set using two layers of halo cells. The solution was marched in time using an implicit second-order scheme and the final system of algebraic equations was solved using a preconditioned Krylov subspace method.

RESULTS

In this work, the unsteady flowfields around a flapping airfoil and a flapping wing of several aspect ratios, (ranging from $AR = 2.5$ to 10), are computed. All the flows are assumed to be laminar, and computed at a low Mach Number of $M = 0.1$ and a Reynolds number of $Re = 10000$.

Table 1: Flapping motions studied to quantify effects of aspect ratio

Case	k	h_0	$\alpha_0(^o)$	$\phi(^o)$	s_h	s_α
1-Datum	1.0	0.5	10.0	90.0	1.0	1.0
2-High Thr.	1.0	0.5	10.3	90.0	2.1	1.1
3-High Eff.	1.0	0.5	14.1	90.0	0.9	1.4

Table 2: Flapping motions studied to compare 2-D and 3-D results

Case	k	h_0	$\alpha_0(^o)$	$\phi(^o)$	s_h	s_α
1-Datum	1.0	0.50	5.00	30.0	1.0	1.0
2-Max. Thr.	1.0	1.60	23.6	103.	1.0	1.0
3-Max. Eff.	1.0	0.83	35.6	86.5	1.0	1.0

The reduced frequency of the periodic flapping motions, is $k = 1.0$. The corresponding unsteady flowfields are analyzed in terms of particle traces, the variation of the thrust/drag coefficient, and the average thrust and the propulsive efficiency of the flapping motion. The parallel 2-D computations with 4 processors take about 1 hour of wall clock time while 3-D computations on 24 processors require about 30 hours on the average, depending on the employed CFD grid.

At first, a parametric study was conducted using three cases of aspect ratios 10, 5 and 2.5 in 3-D in order to quantify effects of aspect ratio. The results for a datum case (see Table 1 for details) are shown in Figure 4 and as can be seen the aspect ratio appears to have a significant effect especially for the lowest values of 5 and 2.5. This is common across all cases studied. The motions applied to the wing were flapping cases which provide high thrust and efficiency values. Figure 3 presents the thrust histories for all cases of Table 2. As can be seen, the trends of the curves for the various values of the aspect ratio are similar with differences near the thrust peaks. From this figure it becomes evident that results for aspect ratios of 10 and 5 are relatively close while results for the smallest value of 2.5 clearly underestimate the thrust peaks.

Figures 4, 5 and 6 present contours of the surface pressure on the wing at four time instances during the period of the oscillation, near the peak values of the thrust coefficient. Two contour plots are shown for each surface, upper and lower, of the wing. As can be seen, for the datum and the thrust-optimized cases the surface pressure shows the footprint of vortical structures present on the wing. This is not the case for the efficiency-optimized case (Figure 6) where the surface of the wing appears clean with suction and pressure sides clearly present during the cycle. The vortical structure present on the mid-span of the wing, appears to be similar to the one obtained via 2-D simulations with the tip-flow effects confined in the near-tip regions. In fact, vortices running almost in parallel to the wing are obtained and these appear to terminate very close to the wing tips by bending towards the moving surface. This is clearly shown in Figure 7 where the vortex core has been extracted. Due to the fast flapping motion of the wing, the tip vortices appear to have a lesser effect on the surface pressure as indicated by the brighter color

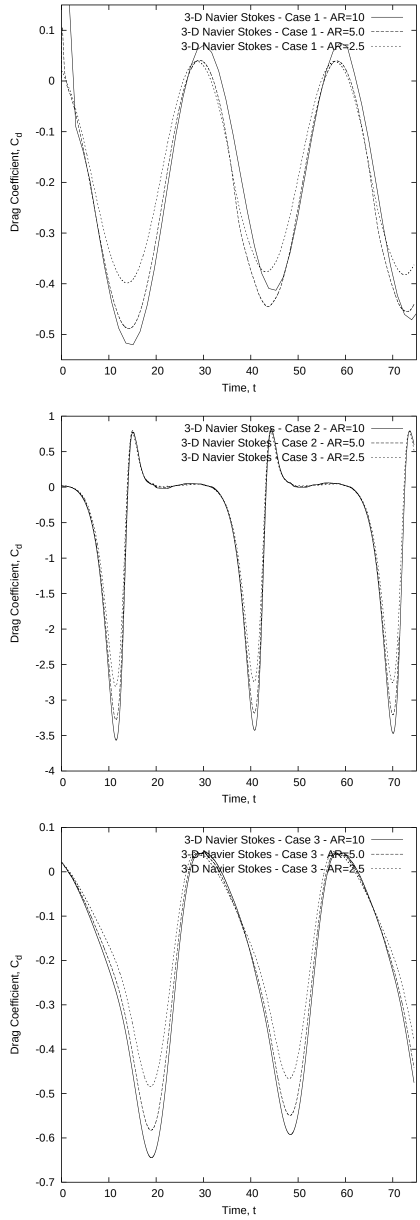

Figure 3: Effect of aspect ratio on thrust for the datum, thrust and efficiency cases of Table 2.

of the pressure contours near the tips. Analyzing the obtained results, it become evident that the formation of vortical structures and their trajectory over the wing are indeed depended on the wing's aspect ratio. Figure 8 presents a comparison between surface pressure contours for the lower surface of the wing for the datum case at different aspect ratio wings. As can be seen, the wing of the lowest aspect ratio has a smaller vortex near the mid-span which seems to delay (i.e. it appears closer to the leading edge at the same time instance during the motion cycle) in comparison to the other two wings. It is also evident that the effect of the tip flow is now stronger with quasi-2D flow confined in the mid-span of the wing. Results for the wing of aspect ratio five indicate that the effect of the tip flow may still be important at this aspect ratio. This effect of the AR on the flow structure was found to be constant for all cases computed including the ones optimized for thrust or efficiency. A similar plot for the thrust-optimized case is shown in Figure 9.

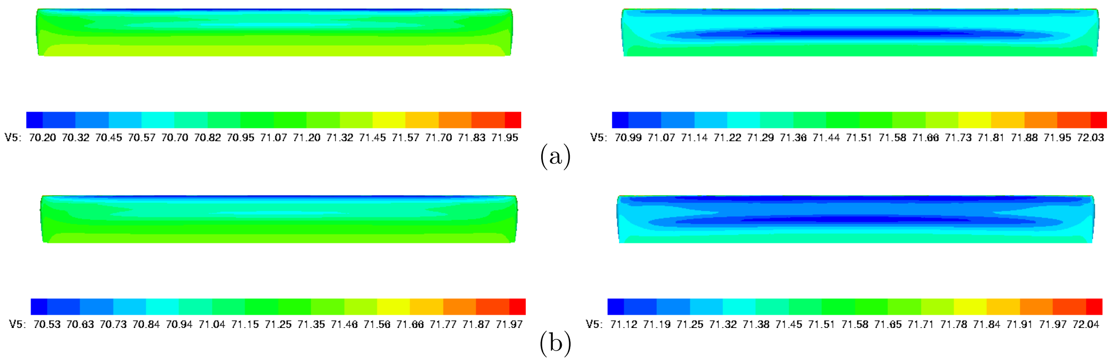

Figure 4: Surface pressure contours on the lower (a) and upper (b) surfaces at two instances during the cycle. The formation of a vortical structure on the surface is evident (Case 1 of Table 1)

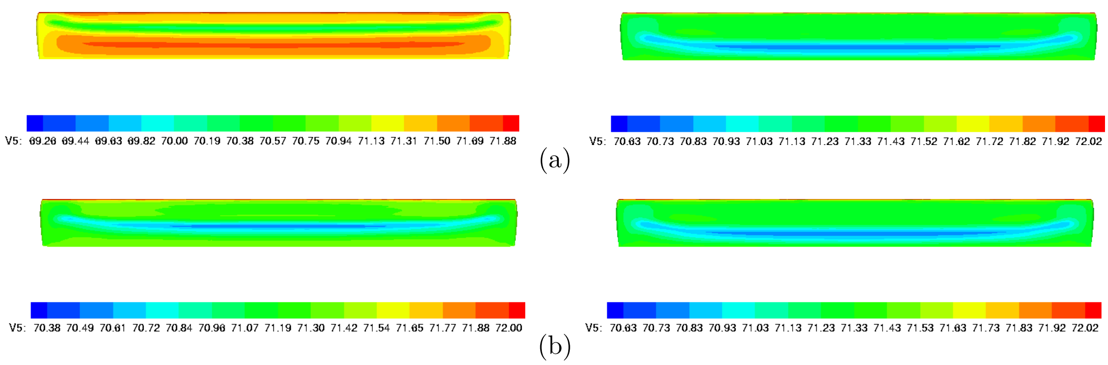

Figure 5: Surface pressure contours on the lower (a) and upper (b) surfaces at two instances during the cycle. The formation of a vortical structure on the surface is evident (Case 2 of Table 1)

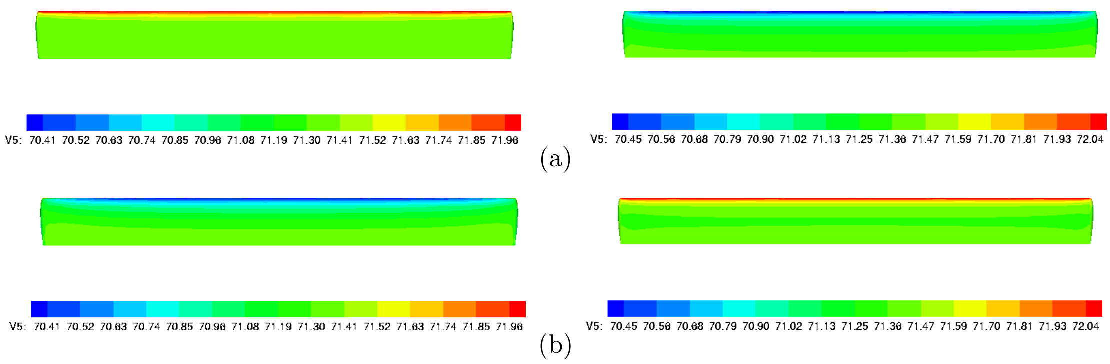

Figure 6: Surface pressure contours on the lower (a) and upper (b) surfaces at two instances during the cycle. The formation of a vortical structure on the surface is evident (Case 3 of Table 1)

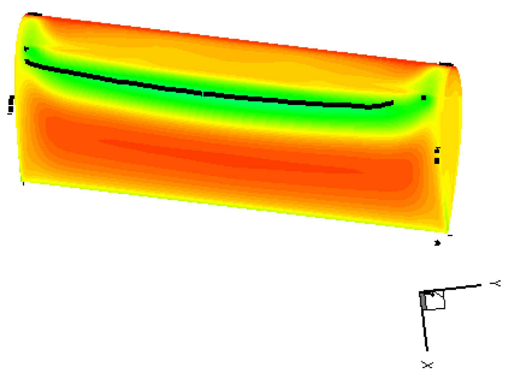

Figure 7: Vortex core extracted from the CFD solution for Case 1 of Table 1

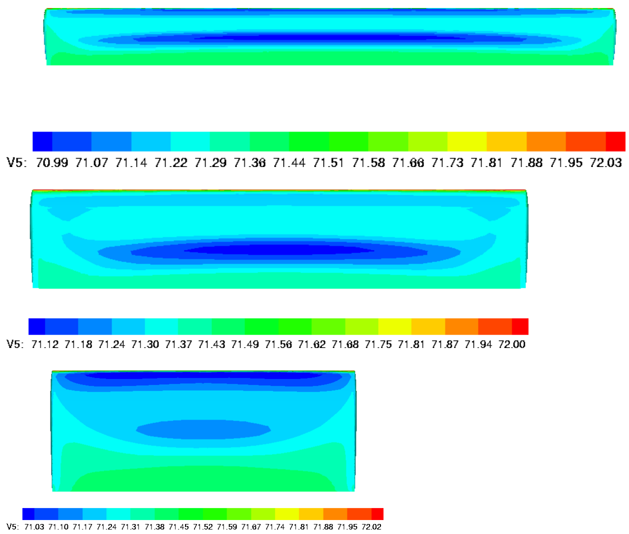

Figure 8: Surface pressure contours on the lower surface of three wings with aspect ratios of 10, 5 and 2.5 (Case 1 of Table 1)

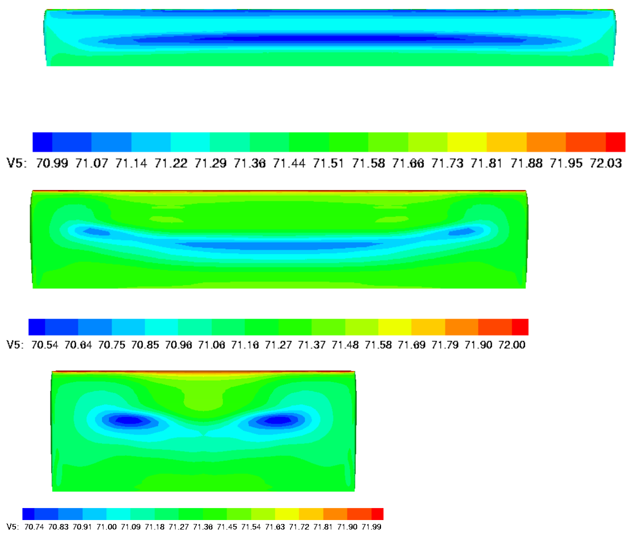

Figure 9: Surface pressure contours on the lower surface of three wings with aspect ratios of 10, 5 and 2.5 (Case 2 of Table 1)

Moving into comparisons with the 2-D cases, Table 2 gives the flapping motions[5] studied. Case 1 is the starting case for the optimized motions given in Cases 2 and 3[5]. Cases 2 and 3 provide the optimum thrust and propulsive efficiency, respectively. The computed average thrust coefficient and propulsive efficiency values are given in Table 3. As seen from the table, 3-D thrust and efficiency (obtained on a wing of aspect ratio, $AR = 10$) are slightly higher than the 2-D ones for all cases computed. The history of drag(negative thrust) coefficient for Case 1 obtained from 2-D and 3-D computations is given in Figure 10. As seen from the figure, 3-D computations produce slightly higher thrust values than the 2-D along the flapping periods. This result is not in agreement with the panel code results obtained by Jones et al.[8]. Moreover, no phase differences have been observed between

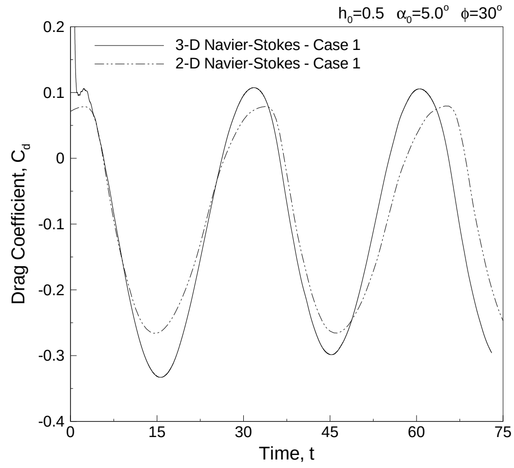

Figure 10: Thrust history for Case 1 of Table 2

Table 3: Optimization results

Case	C_t	$\eta[\%]$
1	0.09	20.3
2	1.41	28.3
3	0.18	67.5

2-D computation

Case	C_t	$\eta[\%]$
1	0.094	21.1
2	1.49	29.7
3	0.21	69.2

3-D computation

the 2-D and 3-D results. The agreement between the two sets of computations for this case, is apparently due to the high aspect ratio of the wing (10 for this case) which makes the effects of the tip flow secondary. The CFD grids, employed for computations may also play a role.

Figure 11 gives the instantaneous 2-D flowfield at the four plunge positions for Case 1. The leading edge vortex formation along the flapping period is clearly observed. The flowfield is periodic, and antisymmetric along the upstroke and the downstroke. This was also observed near the mid-span of the 3-D computations as can be seen from Figure 12 where instantaneous pressure contours are shown in the mid-span of the wing and the near-tip region. The flow configuration in the mid-span is remarkably close to the 2-D results while the results near the tip indicate the presence of a very weak vortex as explain in the previous paragraphs.

The unsteady particle traces for Case 2 is shown in Figure 14. The flowfield is observed to be highly vortical with strong leading edge vortices. The leading edge formation in Case 1 is promoted along optimization steps to reach the optimized flapping motion of Case 2 [5]. Variation of drag along flapping periods is given in Figure 13. Figure 16 shows the efficiency optimized flowfield(Case 3). In Case 3, it is observed that the leading edge vortex formation is prevented, which incidently maximizes the propulsive efficiency. The unsteady flow becomes more streamlined with the motion of the airfoil.

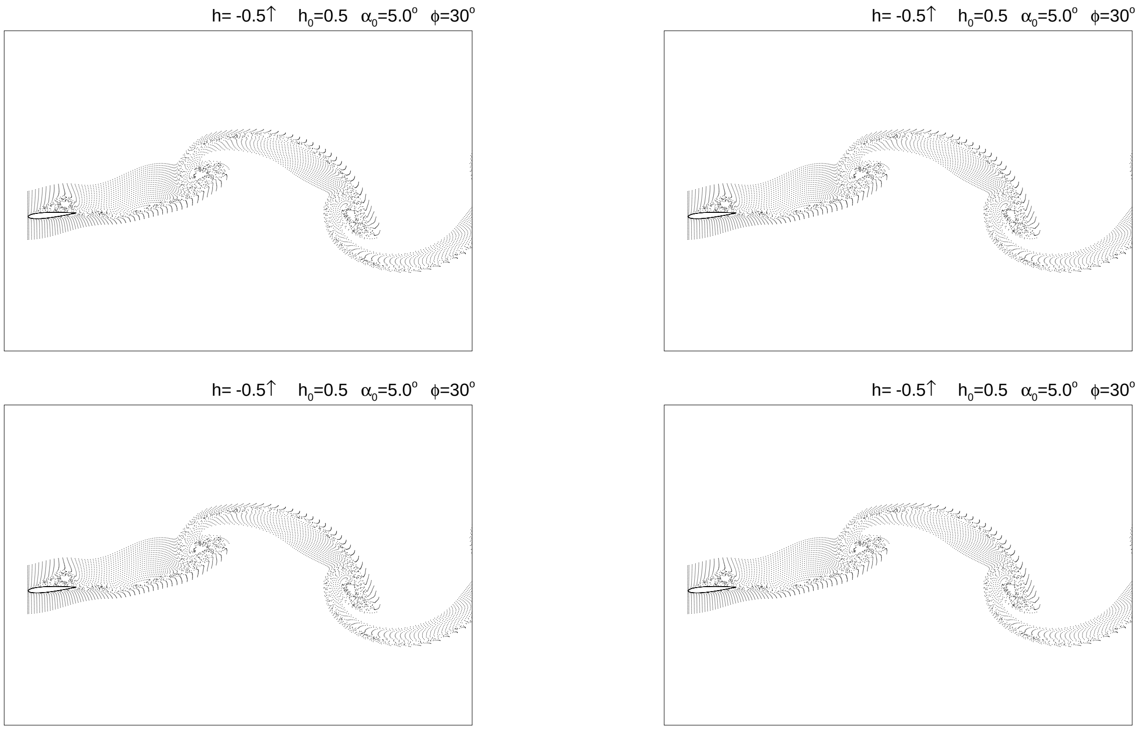

Figure 11: Instantaneous particle traces for Case 1 of Table 2

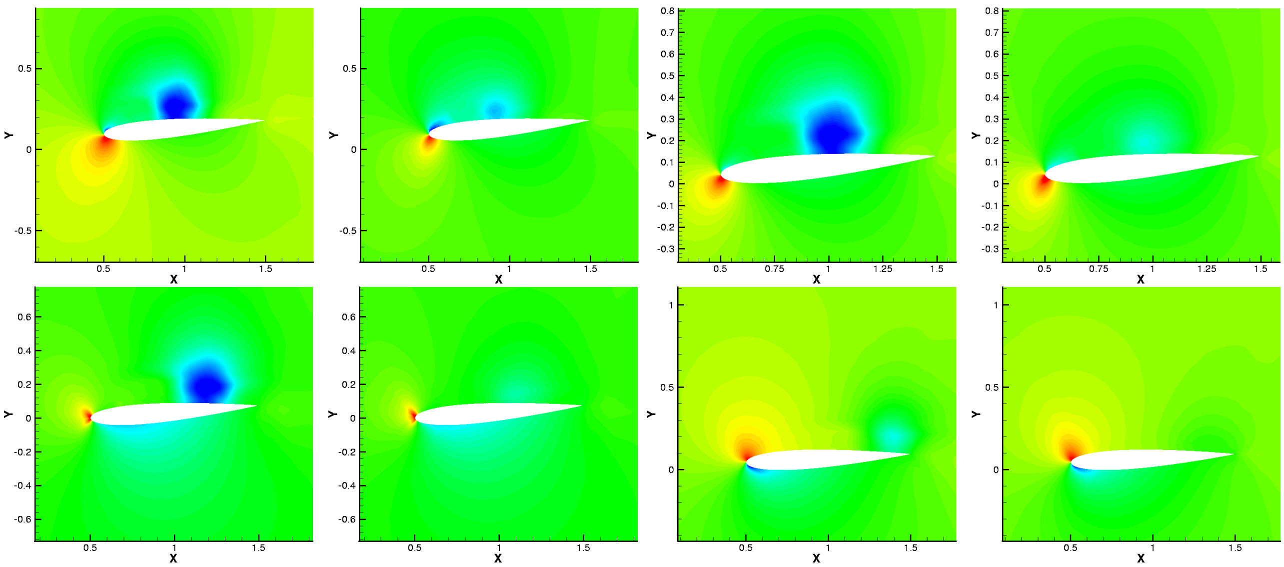

Figure 12: Pressure contours for case 1 of Table 2, showing the evolution of the vortex during the upstroke cycle. Two slices are shown corresponding to (a) the mid-span of the wing and (b) the near-tip region.

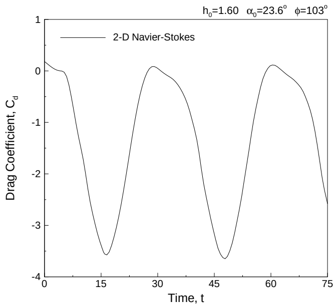

Figure 13: Thrust history for Case 2 of Table 2

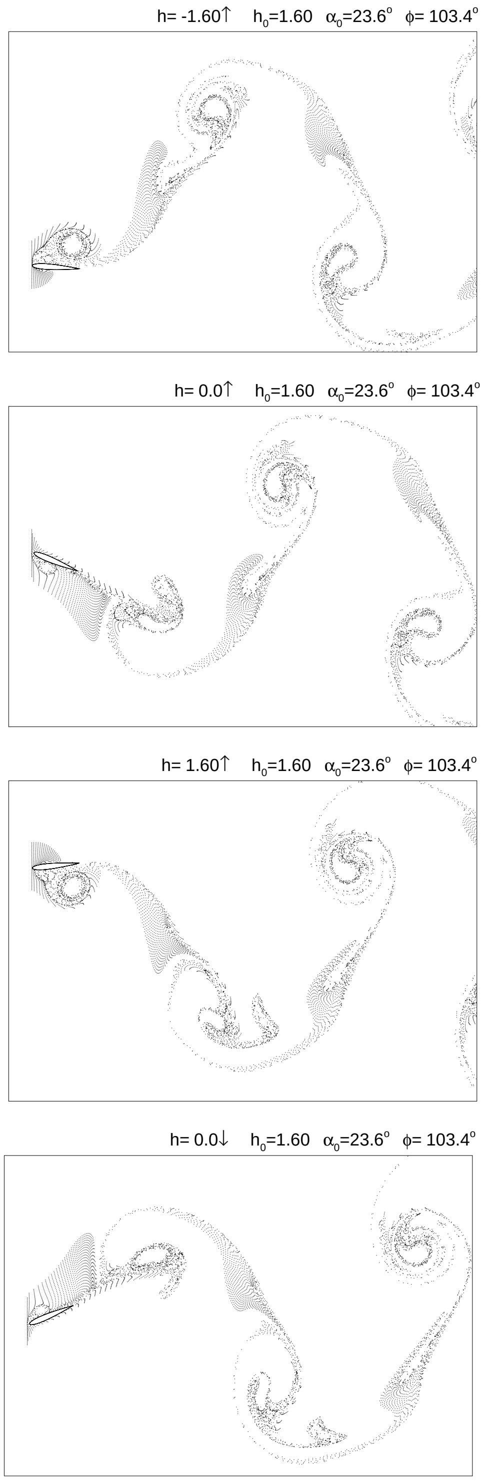

Figure 14: Instantaneous particle traces for Case 2 of Table 2

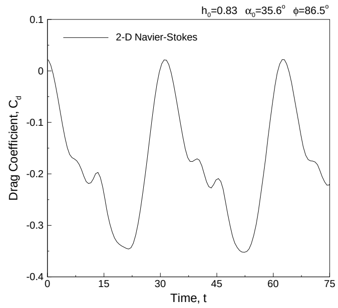

Figure 15: Thrust history for Case 3 of Table 2

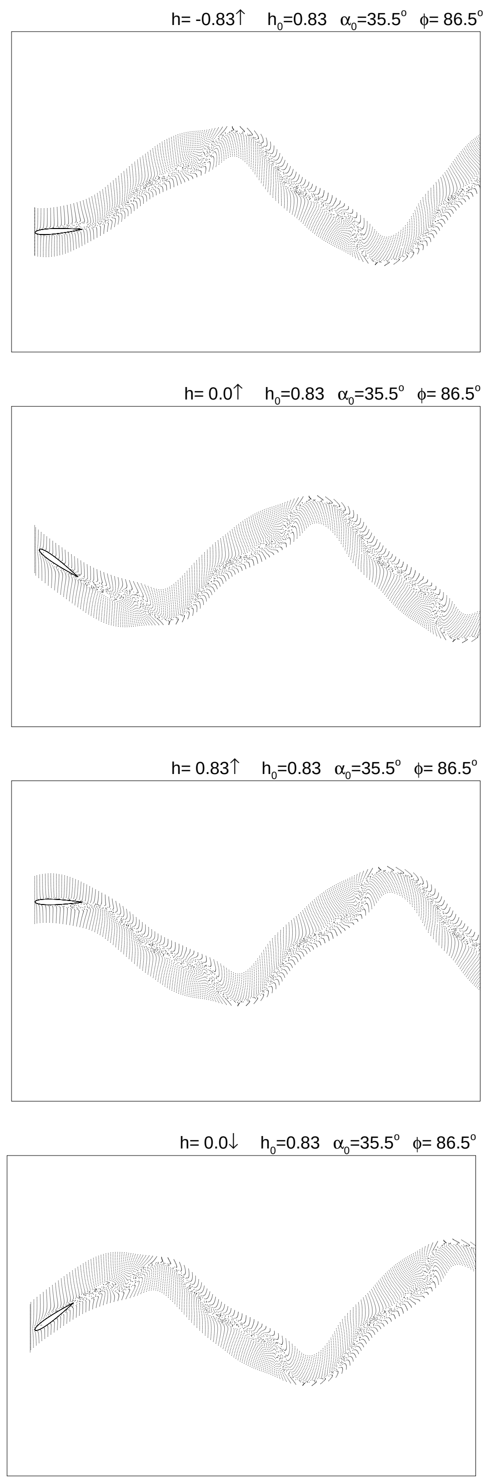

Figure 16: Instantaneous particle traces for Case 3 of Table 2

CONCLUDING REMARKS

The flowfields around a flapping airfoil and a flapping wing are computed using CFD and the Navier-Stokes equations. Two and three-dimensional simulation results highlighted the main flow features and the effectiveness of the optimization method used to derive the optimum motion parameters for the wing. The optimization was performed for the 2-D case and used for the 3-D computations without further modification since 3-D results for high aspect ratio wings were found to be similar to the 2-D ones. A study was then conducted with the aspect ratio reduced to 5 and 2.5. It is evident that as the AR decreases the effect of the tip flow and the three-dimensionality dominate. Although the first results are encouraging this is just a first step in an effort to analyze and understand the complex flows around flapping wings and further work is to be undertaken in order to establish the accuracy of the predictive methods and the flow mechanisms contributing to the generation of lift and thrust.

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