Development of a CFD model for an oscillating hydrofoil

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Abstract

Unsteady two-dimensional flow about an oscillating hydrofoil is investigated computationally as a preparatory stage for three dimensional fluid structure interaction studies. A dynamically deformed mesh at static incidence angles was used to assess grid independence in preparation for unsteady runs. The computation used a high resolution advection scheme with a shear stress transport turbulence model. Validation was conducted using steady and dynamic experimental results. Lift coefficients normalised for all pitch oscillations to fall on to a single phase trajectory at reduced frequencies of 0.78, 1.57 and 3.14.

Introduction

The motivation of the present analyses is to investigate the hydraulic response of marine propellers. These often operate in an unsteady wake region generated by the hull and control surfaces. This causes the propeller to be subjected to unsteady loading [26]. In this investigation the propeller problem has been simplified to a single hydrofoil response to an oscillation in pure pitch indicative of the propeller passing through the wake deflection generated by control surfaces. Hydroelasticity is a multidisciplinary study of dynamics, elasticity and fluid dynamics [3, 12]. This study investigates a rigid two-dimensional (2D) oscillating foil in pure pitch. The effectiveness of ANSYS CFX to predict unsteady dynamics of attached flow up to and including 10° incidence with no cavitation is also evaluated. Reduced frequency is defined as \( k = \omega c / 2U_{\infty} \) where \( \omega \) is circular frequency, \( c \) = chord and \( U_{\infty} \) = free stream velocity.

NASA in the late 1970s and early 1980s conducted a number of experiments into dynamic stall and unsteady loading of airfoils [1, 2, 11, 14, 15, 18]. These studies obtained lift, drag and pitching moment measurements by integrating surface pressures. They also investigated boundary layer transition, separation and reattachment characteristics, as well as flow reversal and chordwise unsteady pressures. McCroskey et al. [19] found that in general, unsteady motion is more important than airfoil shape when determining dynamic stall characteristics. In 1982 McCroskey and Puccio [18] conducted ten specific experiments on foil sections NACA 0012, Vertol VR-7 and NLR-7301 undergoing oscillations to evaluate unsteady viscous and computation methods. McCroskey et al. [18, 17] identified four distinct regimes of viscous-inviscid interactions corresponding to varying degrees of unsteady flow separation. If a foil oscillates with a maximum incidence angle (\( \alpha \)) below static stall angle, the boundary layer on both upper and lower surfaces will remain fully attached, except for a small separation bubble near the upper surface on the leading edge for \( \alpha < 5^\circ \), which produces transition from laminar to turbulent flow. Kochosekihami [13] demonstrated experimentally that thrust production for a foil due to pitching motions occurs only above certain reduced frequencies. He also found that the structure of the wake can be substantially modified by amplitude of oscillation, frequency and shape of the wave form. In 1993 Piziali [20] conducted a comprehensive set of experiments investigating the pressure distributions on a foil undergoing pitching motions for 2D and three-dimensional (3D) airfoils for the development of computational and empirical methods. In 1994 Hart [10] investigated experimentally unsteady flow induced by periodic change of incidence. These experiments provided details of the change in boundary layer profile on the suction and pressure sides and phase lag for 2D and 3D hydrofoils for varying \( k \).

Analytical solutions of note include: for thrust/drag force for an airfoil in heaving and pitching motion [8]; forces, moments and phase angles for a thin flat plate in an incompressible fluid with a trailing vorticity sheet as a function of \( k \) [24, 25]; and defining fluid dynamic behavior by \( k \).

McCroskey [16] conducted some of the earliest numerical investigations. He developed simple formulas to describe the detailed inviscid, incompressible flow field of an unsteady airfoil with thickness and camber. The next detailed numerical analyses were conducted to investigate the use of k-\( \omega \) and Shear Stress Transport (SST) k-\( \omega \) models for predicting dynamic stall [5, 6]. It was generally observed that none of the turbulence models could predict the hysteretic effect due to the downstroke. It has been shown that upwind-biased schemes, even though more computationally intensive, provide an improved solution of unsteady flows because they have no dependence on the specified numerical dissipation parameters and they appear to have less grid sensitivity compared with central difference schemes [5]. More recently a series of numerical simulations of dynamic stall for 3D foils using various planform shapes were completed providing detailed information on the interaction of dynamic stall and the tip vortex [21, 22, 23].

Methodology

Steady state and dynamic numerical analyses were conducted. Steady state was used to determine boundary layer resolution and a comparison with experimental steady state forces. The computed boundary layer properties for steady flow were compared with XFOIL [4] predictions and published experimental data [9]. A displacement diffusion mesh deformation model was used to deform the mesh to the required incidence. Dynamic validation was conducted against experimental results contained in [20], which used 2° oscillation amplitude (\( \Delta \alpha \)) in pure pitch around a mean incidence (\( \alpha_{\infty} \)) of 4°, Reynolds number (\( Re_{\infty} = \rho U_{\infty} c / \nu \)) of 1.98x10⁶ and a pitch center at 1/4 chord (c) for a NACA 0015. Oscillating hydrofoil studies of a NACA0009 were conducted for \( \Delta \alpha = 2°, 5° \) and 10° at \( \alpha_{\infty} = 0° \) and pitch center at 1/2c.

CFD Setup

The unsteady flow field was solved with the commercially available package ANSYS CFX version 12.1 with a 2D one layer deep structured mesh consisting of hexahedral elements. The inlet had specified velocity components and an isotropic turbu-
Figure 1: C-grid topology for NACA 0009

Figure 2: Temporal independence

Figure 3: Comparison of computed and experimental chordwise pressure coefficients for a NACA 0012 α=6°

Grid Independence and Temporal Convergence

Grid independence and temporal convergence studies were conducted on the NACA 0009 and a similar mesh was then used to model the NACA 0012 and NACA 0015. A displacement diffusion mesh deformation model was used to generate the mesh for steady flow computations at 0, 2, 5 and 10° incidence Re of 2.8x10^5 and 9.4x10^5. It was found that a grid with 27284 elements had an average error of 0.2% using Richardson extrapolation. Figure 2 shows the temporal convergence plot. The grid was then used to assess time step convergence with a k of 0.25 and Re, 2.8x10^5. The temporal convergence of 100 time steps per period of selection to ensure the average Courant number on the foil remained less than 1 for the duration of one cycle. This resulted in a maximum Courant number of approximately 600 in the domain. All results were run out for 5 cycles, the first cycle contains transients from the steady start up solution and the second and the third cycle are identical.

Mesh Development

The structured grid was constructed using a C-topology within an H-topology at the trailing edge as shown in figure 1. The inlet velocity boundary is 2.5c upstream. The outlet pressure opening is 11.5c downstream. The first cell height was 0.02%c.

Validation

Gregory and O’Reilly [9] presented results for the distributions of the pressure coefficient Cp on a smooth NACA 0012 at a Re of 2.8x10^5. Results from these experiments were compared with XFOIL and the k-ε, k-ω, and SST turbulence models, as shown in figure 3. Piziali [20] conducted a detailed series of oscillating wing aerodynamic tests with fast response pressure transducers. The lift, drag, and moment coefficients (CL, CD and CM) were calculated from the pressure normal to the chord neglecting skin friction. The moment was calculated by integrating these pressures over the chord neglecting any moment due to the thickness of the foil. The three Reynolds Average Navier-Stokes models were compared with the experimental results of [20]. Results compared well for k values of 0.131 and 0.188 for all turbulence models. However, for the lower k of 0.038 using the k-ε and k-ω models and at a k of 0.093 using the k-ε model, for an Δα of 2 and 4° and a α∞ of 4° the model was unstable. Although convergence was reached it had a large mean offset from the original data. The results compared well for all cases using the SST model. Results are presented for comparison for the case of Δα=2° and α∞=4°. A slight over estimate of CL and underestimate for CD was apparent in the upstroke, but the downstroke compared well for both CL and CD, (see figures 4 and 5). For Cm, the results compared well on the upstroke but with the reversal of direction the change in the Cm slope is not as large as in experimental data figure 6. This resulted in a lower moment in the downstroke.

Results

The results were produced by rotating a NACA 0009 about a pitching axis at 1/2c. The test matrix variables consisted of α∞=0° Δα∞=2, 5 and 10° and Re=2.8x10^5 and 9.389x10^5. It was found that there was no Re dependence for this matrix. All CL phase trajectories were found to fall on one line when normalised by maximum incidence and the corresponding static lift
Figure 4: Comparison of computed and experimental $C_L$ for a NACA 0015 at $k=0.188$, $\alpha_m=4^\circ$, and $\Delta\alpha=2^\circ$

Figure 5: Comparison of computed and experimental $C_D$ for a NACA 0015 at $k=0.188$, $\alpha_m=4^\circ$, and $\Delta\alpha=2^\circ$

Figure 6: Comparison of computed and experimental $C_M$ for a NACA 0015 at $k=0.188$, $\alpha_m=4^\circ$, and $\Delta\alpha=2^\circ$

Figure 7: Effect of varying $k$ on computed $C_L/C_D$ phase trajectory for varying $k$; for a NACA 0009 $\alpha_m=0^\circ$ and $\Delta\alpha=2^\circ$

Figure 8: Effect of varying $\Delta\alpha$ on computed $C_D/C_J$ phase trajectory; for a NACA 0009, $\alpha_m=0^\circ$ and $k=0.785$

coefficient $C_{L_0}$, for each $k$, as shown figure 7. $C_D$ and $C_M$ do not however normalise in this manner. From figure 7 the phase lag is shown by the point at which the maximum $C_L$ is reached on the hysteresis loop. It is noted that as $k$ increases the phase lag becomes greater and the hysteresis loop becomes more circular. Figure 8 shows $C_D$ to be symmetric about $\alpha_m=0^\circ$ similar to static $C_D$. Both $C_L$ and $C_D$ lead the pitch oscillation in all cases. Figure 9 shows that $C_M$ lags and opposes the pitching motion.

Conclusions

NACA 0009 and NACA 0015 profiles were investigated using a structured deforming grid. k-e, k-omega and SST models were compared to Piziali [20] with the SST model using a high resolution advection scheme showing the closest comparison. This model compared well for $C_L$ and $C_D$, but under-predicted $C_M$ on the downstroke. Lift coefficients normalised for all pitch oscillations to fall on to a single phase trajectory at reduced frequencies of 0.78, 1.57 and 3.14.
Figure 9: Effect of varying $\Delta\alpha$ on computed $C_M/C_{M0}$ phase trajectory; for a NACA 0009, $\alpha_m=0^\circ$ and $k=0.785$

Acknowledgments

This project is supported by The Australian Defence Science and Technology Organization (DSTO) and Australian Maritime College (AMC). The first author (SRH) is an Australian Postgraduate Award recipient.

References


24 September 2010

Dear Mrs Suzanne Hutchison,

On behalf of the organising committee for the 17th Australasian Fluid Mechanics Conference, I would like to advise that the following paper has been accepted for inclusion in this year’s proceedings, however some revisions are required.

Please provide an updated copy of your paper and a one hundred word summary of your abstract for inclusion in the conference handbook by email to 17afmc@auckland.ac.nz by Thursday 13 October.

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<td>Authors:</td>
<td>Mrs Suzanne Hutchison Assoc. Prof. Paul Brandner Dr. Jonathan Binns Dr. Alan Henderson Prof. Gregory Walker</td>
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The following comments were made regarding the edits required on your paper:

**REVIEWER 1:**
Please attend to the corrections as indicated by the reviewers. Also attend to as many of the suggestions as possible.

**REVIEWER 2:**
A reasonable paper that achieves the goals that it sets for itself: the development and validation of a CFD model of a 2D pitching aerofoil. The paper is well-presented although the authors should follow the paper the template in respect of formatting of the References section and the citation of these references in the text. The paper could be improved by adding a short paragraph at the end of the Introduction section that commences with "In this paper..." and outlines what (new) work is being undertaken that contributes to the literature just discussed. The Conclusions section could be improved by summarising what has been learned in the model development (that is the real thrust of this paper). A couple of minor corrections are needed. In a couple of places an incorrect indefinite article ("a" or "an") has been used and, "under predicted" in the Conclusions should be "under predicted", and in the second paragraph of the Introduction it is important to mention the airfoil section used when arriving at the broad conclusions contained therein.

**REVIEWER 3:**
A nicely written paper with attention paid to validation. The line in the abstract beginning 'The two dimensionl mesh is currently being used as a basis... refers to future work which I expect we shall see at the conference but which is not mentioned elsewhere in the paper. This line should be deleted.

Some points were not clear:
Page 1 column 2 last line on this page 'mass momentum boundary' does not make sense.
Page 2 column 1 'auto computed length scale'- please specify what length scale and how it is computed. 'opening pressure boundary' does not make sense.
'symmetric boundaries' did not mean anything to me in the context of an outlet boundary.

Registration is now open with early-bird rates available until midnight, 30 September (NZ time). Please click [here](https://www.amc.edu.au/zimbra/h/printmessage?id=12501) to register. You will need to provide the Abstract Number, as shown in the table above, for each abstract you are presenting.

Please note: If you are presenting more than one abstract or paper you must pay the 'additional presentation fee' per presentation or another registered delegate must present this abstract.

To keep up to date with the latest conference information please visit [www.17afmc.com](http://www.17afmc.com) or contact [17afmc@auckland.ac.nz](mailto:17afmc@auckland.ac.nz) for assistance.

Yours sincerely,
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