An Experimental and Computational Study of Flow over a NACA 0021 Airfoil with Wavy Leading Edge Modification

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Abstract

Flow control by means of tubercles, which are spanwise-periodic protrusions observed on the Humpback whale’s flippers, has been previously shown to exhibit beneficial aerodynamic traits. Understanding the mechanism that yields the desirable results among nominally two-dimensional airfoils has led to the design of an alternative leading edge configuration. In the present work, this novel variation on tubercles was employed to modify a NACA 0021 airfoil for wind tunnel pressure measurement tests in the transitional flow regime. In addition, a Computation Fluid Dynamics study was performed using the SST transitional model in the context of unsteady RANS at several attack angles. The results from the numerical investigation are in reasonable agreement with those of the experiments, and suggest the presence of features that are also observed in flows over tubercled foils, most notably a distinct pair of streamwise vortices for each wavelength of the tubercle-like feature.

Introduction

Nature with its elegance and mystique has always served as a generous source of inspiration and creativity. One peculiar instance that has intrigued fluid mechanists and zoologists for the past decade is the Humpback whale’s ability to turn around tight angles in its bubble-net feeding strategy [7].

To determine whether the scalloped leading edge of the Humpback’s flippers plays a role in the Humpback’s swift mobility, Fish and Watts [14] carried out a computational fluid dynamics study. For this purpose, an inviscid flow solver was developed to compare the performance of a scalloped finite-span wing based on the NACA 634-021 profile against its unmodified equivalent at a 10 degree angle of attack. The results showed the overall superior performance of the scalloped wing with a 4.8 % increase in lift, and a 10.9 % reduction in induced drag.

A second numerical study as reported by Fish et al. [6] was carried out by Paterson et al. [10] in which an unsteady RANS simulation was performed on a tubercled and an unmodified NACA 63-021 baseline foil. The Reynolds number, based on the chord length, was 1,000,000. At an incidence angle equal to 10 degrees, the results demonstrated a dramatic change in the pressure contours on the tubercled model along with large vortices posterior to the troughs. Flow separation was observed to have been delayed behind the peaks to almost the trailing edge, preventing the onset of stall.

Miklosovic et al. [9] carried out wind tunnel force measurement tests on half-span scale models of an idealized Humpback whale flipper (1/4 scale) with and without tubercles on a NACA 0020 baseline foil. The Reynolds numbers for the tests were between 505,000 and 520,000, which fall in the operating range of Humpback whales. The experiments yielded a 40% delay in the stall angle for the wing with tubercles accompanied by a 6% increase in the maximum lift coefficient and lower drag coefficients in the post-stall regime. The authors concluded that a vortex-generating mechanism similar to that employed by vortex generators on an aircraft wing may explain the higher lift characteristics. It was hypothesized that through energizing the scalloped flipper’s boundary layer, tubercles inhibit chord-wise separation that accounts for earlier stall on an otherwise smooth wing.

In order to evaluate the influence of tubercles in flow separation and the vorticity field, a numerical simulation was carried out by Pedro and Kobayashi [11] on the scalloped and unmodified flipper models set up for the experiments by Miklosovic et al. [9]. In this CFD study, a Detached Eddy Simulation scheme was employed to analyse the flow at a Reynolds number of 500,000. The simulation was run at angles of attack between 12 and 18 degrees since the main differences had been reported to occur in this range. The contours of vorticity showed a chaotic outboard region towards the tip for both wings due to flow separation, however in the midsection of the flippers the differences became evident. The scalloped wing displayed higher values of the magnitude of vorticity compared to the unmodified model in that region, suggesting the presence of streamwise vortices that aligned themselves with the tubercles. Similar findings were reported by Weber et al. [15].

Rostamzadeh et al. [12] used Prandtl’s non-linear lifting-line method to demonstrate that the aerodynamic benefits of tubercles can be obtained via a novel wavy leading edge modification employing an analogous flow mechanism. Wind tunnel force measurement results confirmed that full-span wavy wings exhibit gradual stall compared to a wing with a smooth leading edge.

The present work is aimed at investigating how pressure and vorticity fields are affected by the incorporation of the wavy leading edge on a NACA 0021 baseline foil. To this end, wind tunnel pressure measurement experiments were conducted in the transitional flow regime, and used to validate the results from a CFD study.

Experimental Work

Pressure measurement tests were performed at a chord-based Reynolds number equal to 120,000 in the 500(mm)×500(mm) test section of the KC wind tunnel at the University of Adelaide. The test subject was a full-span wavy foil with a 6.5 (deg) peak-to-peak angular amplitude and a wavelength equal to 30(mm) shown in Figures 1 and 2. To ensure 2D flow near the free-end wing tip, a wall clearance of 3 (mm) was maintained [2]. The turbulence intensity of the flow stream ahead of the wing was measured at 0.8%.

Pressure taps were drilled onto the top surface of the foil in three rows along the 70-milimeter-chord lines corresponding to a trough, a peak and a middle cross-section. Of the thirty bored taps, two were blocked including one at the stagnation point on a peak and therefore not used in the experiments.
A series of PVC tubes, embedded in the foil, connected the surface pressure taps to the head-ports of a controller-modulated Scanivalve. To achieve high-precision pressure measurements, a 10-Torr MKS Baratron (model 220BD) with a resolution of 0.01% of the full scale range was utilised.

At higher angles, flow separation seems to have dominated the suction side, however the leading edge of the trough cross-section, maintains low values of pressure that account for lift being generated in the post-stall zone.

![Figure 1. Wavy wing section with three pressure tapping rows, showing the wavelength, W(mm)](image)

The free-stream speed and static pressure were measured at 25 (m/s) and 0.8 (Torr) below the ambient pressure. For a given incidence angle, 2,000 data points (per pressure port) were collected at a sampling rate of 200HZ. It was observed that 200HZ was sufficient to establish a typical small standard error of $2.5\times10^{-1}$ (Torr) in estimating the population mean.

**Experimental Results**

As the taps were placed on one side (upper surface) of the wing, the data from the negative attack angles were used to determine the pressure values for the lower surface. Care was taken to ensure that the peak and trough pressure distributions were correctly matched.

At $\alpha = 2^\circ$ (Figure 3a), the wavy foil’s trough experiences lower pressure on the suction side than the peak. The abrupt change in pressure gradient at $x/c=0.4$ on the suction side of the trough, and $x/c=0.6$ on the lower side of the peak, indicates the presence of Laminar Separation Bubbles (LSB). This flow feature is often observed at low Reynolds numbers where separation due to strong adverse pressure gradients gives rise to Helmholtz-instabilities whose breakdown result in separation-induced transition, and the formation of LSBs [5].

Increasing the angle of attack, forces the LSB to move towards the trough’s leading edge, as a drop in pressure occurs on the suction surface. Meanwhile, the pressure on the lower surface of the peak rises, and the LSB on this side moves towards the trailing edge, indicating that the separation point has translated further downstream (Figure 3b).

At $\alpha = 12^\circ$ (Figure 3c), the overall shape of pressure distribution begins to alter, especially for the suction surface of the middle cross-section. The flatness of the pressure curve past $x/c=0.3$ on the middle cross-section signifies that flow separation begins to affect a larger area on the airfoil as stall is initiated gradually.

![Figure 2. Side view of the wavy wing section, showing the peak-to-peak angular amplitude, $\theta$ (deg)](image)

![Figure 3(a-d). Chord-wise pressure distribution on a peak, trough and mid cross-section at different attack angles](image)
Using the trapezoidal rule for integration, the amount of lift generated at each cross section was estimated. Since there were no data available for the stagnation point on the trough, a shape-preserving interpolant curve-fit was applied to account for the error incurred. Also, the contribution of shear forces to lift, which in most cases is negligible, is not included.

![Figure 4](image)

Figure 4. Calculated sectional lift coefficient as a function of attack angle

Figure 4 shows that both prior to and post stall, the trough produces more lift than the two other sections. Pre-stall the mid cross-section contributes to lift generation more than the peak however loss of lift is more prominent in this cross-section post-stall. It must be noted that the total amount of lift on the wing section can not be regarded as the average lift of the three sections as the flow structure is complex, and direct force measurement tests as reported by Rostamzadeh et al. [12] is the most reliable method.

**Computational Fluid Dynamics Study**

This section presents a complementary CFD investigation performed using the commercial package ANSYS-CFX 12.1 suite [1] to model the unsteady flow over one wavelength of the wavy foil 06.5w30 at several incidence angles. To capture the transitional nature of the flow, the newly-formulated SST γ−Reθ [8] model that has been successful [3] in external aerodynamics was employed. The eight transport equations for this model can be found in [8], and have not been included here for brevity.

A C-Grid topology (Figure 5) with hexahedral elements was constructed to designate the computational domain. The angle of attack was changed at the Inlet via the velocity components and Periodic boundaries were assigned to the side planes since one wavelength of the wing was modelled.

A grid resolution study was performed to establish a mesh-independent solution. Of the three generated grids, the one with a total number of nodes equal to $3.5 \times 10^6$ proved to be sufficient for grid independence whose $y^+$ values near the foil were maintained below 1.

**Solution Strategy**

ANSYS 12.1 implements a finite control volume-oriented finite element method to discretise the partial differential transport equations. A second-order backward Euler scheme was selected for temporal discretisation, while an alternating first and second-order accurate scheme was implemented for spatial discretisation. Solution convergence of the eight transport equations was determined by achieving a maximum residual target of $10^{-5}$ per time step. In addition, the lift and drag coefficients were used as monitor points during the solution process.

The solution strategy comprised two different stages. Initially, a steady-state run was performed and the behaviour of the residuals were monitored. It was observed that the residuals diminished steadily down to $10^{-4}$ in the proximity of the seventieth iteration at which point an oscillating pattern emerged. Subsequently, the steady-state solution was used as the initial guess for the transient solver. A time-step equal to $5 \times 10^{-3}$ (s) with three inner loops was selected for the transient run. The results are presented at $t=0.01$ (s) where the lift and drag forces have stabilised.

**Validation Results**

Figures 6-7 show that correspondence between the numerical solutions with the data obtained from experiments is very satisfactory.

![Figure 5(a-b)](image)

Figure 5(a-b). The computational domain and grid system near the foil

![Figure 6(a-d)](image)

Figures 6(a-d). Comparison of the experimental and numerical pressure coefficient on a trough.
downstream of the trailing edge at zero incidence angle located at x=30 (mm), 60 (mm), 90 (mm) and 120 (mm).

Figure 8. Surface streamlines colored by vorticity on planes reported by the authors [12].

from the upper and the other from the lower wing surface, wake. Each vortex consists of smaller vortices, one originating that a distinct pair of counter-rotating vortices is realised in the flow direction at a zero attack angle (Figure 8). It is observed confirms the prediction by Prandtl’s lifting-line theory as convects downstream. The presence of streamwise vortices, towards each other, coming to a near-parallel orientation as it spreads outward from the cores. The pair appears to rotate the trailing edge, suggesting a diffusion process as vorticity vorticity at the cores of the vortices decreases with distance from imparting a slanted appearance to the pair. The magnitude of demonstrates that the low pressure region near the leading edge Figures 7(a-d). Comparison of the experimental and numerical pressure coefficient on a peak cross-section

Contours of surface streamlines colored by streamwise vorticity have been plotted on planes oriented normal to the free-stream flow direction at a zero attack angle (Figure 8). It is observed that a distinct pair of counter-rotating vortices is realised in the wake. Each vortex consists of smaller vortices, one originating from the upper and the other from the lower wing surface, imparting a slanted appearance to the pair. The magnitude of vorticity at the cores of the vortices decreases with distance from the trailing edge, suggesting a diffusion process as vorticity spreads outward from the cores. The pair appears to rotate towards each other, coming to a near-parallel orientation as it convects downstream. The presence of streamwise vortices, confirms the prediction by Prandtl’s lifting-line theory as reported by the authors [12].

Conclusions

The present experimental work on a full-span wavy foil demonstrates that the low pressure region near the leading edge on the trough cross-section produces the most lift post-stall, preventing a sudden loss of lift. This flow feature is analogous to the low pressure zone in the trough of a tubercled foil [4, 13]. In addition, the CFD investigation showed the presence of strong counter-rotating streamwise vortices in the wake of the wavy foil, pointing to another notable feature in the flow produced by wings with tubercles. Further work is required to examine the flow field in more detail to assess the role played by vortices in the gradual stall phenomenon.

References

1. ANSYS® Academic Research, Release 12.1