Numerical Investigation of the Post-stall Flow Patterns over a NACA 0021 Hydrofoil with Sinusoidal Leading Edge

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Abstract As passive flow-control devices disrupting flow separation, leading-edge protuberances can provide superior hydrodynamic performance to hydrofoils at high angles of attack. Most experimental and numerical investigations carried out for low Reynolds number conditions have related the relative improvements observed post-stall to “bi-periodic” flow structures, developing over tubercles pairs. In this study, a numerical approach is employed to show the emergence of higher-order patterns in the flow over a stalling NACA 0021 hydrofoil with sinusoidal leading edge. The effect of the number of sinusoidal tubercles defining the leading edge of the hydrofoil model on the prediction of “bi-periodic” or “tri-periodic” flow structures is particularly analyzed to interpret the uncertainty found on the resulting hydrodynamic performance.

1 Introduction

Initially inspired from the pectoral flipper of the humpback whale [4], hydrofoil designs including leading-edge protuberances have been investigated for their potential benefits in terms of hydrodynamic performance and flow control, particularly for low Reynolds number conditions [2, 5]. In general, most experimental and numerical studies have shown that scalloped leading edges allow mitigating the drop in lift generated on an hydrofoil occurring at high angles of attack with an unmodified leading edge. This relative performance improvement has been linked to complex flow patterns generated by the tubercles that disrupt flow separation on the suction surface of the hydrofoil. In particular, “bi-periodic” flow structures developing over tubercles pairs at high angles of attack have been observed both experimentally [3], with high aspect-ratio airfoils spanning over the entire width of the wind-tunnel test section, and numerically [1, 2], with symmetric or cyclic boundary conditions used to dis-

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count the effects of tip vortices on the flow properties. Further numerical analyses have indicated that the lift curves predicted for scalloped leading edges were fluctuating over the post-stall range of angles of attack [1]. This numerical study aims to demonstrate that this uncertainty on the lift predictions can be linked to higher-order flow patterns that can emerge post-stall. It focuses on the influence of the number of sinusoidal leading-edge tubercles included in the model on the predictions of "bi-periodic" or "tri-periodic" flow structures, and of the associated hydrodynamic performance.

2 Methodology

Simulations of the flow over NACA 0021 hydrofoil models with unmodified leading edge and with sinusoidal leading edge of peak-to-peak amplitude of 10% of chord length and wavelength of 50% of chord length (see Fig. 1) were carried out for a Reynolds number of 120,000. The computations were performed using OpenFOAM 2.4 with a finite-volume discretization of the steady RANS equations. Spalart–Allmaras turbulence model was used to solve the problem in non-dimensional form with the SIMPLE algorithm. The flow domain was discretized with a hexahedral structured C-mesh refined near the hydrofoil to obtain typical maximum and average y^+ values of about 0.68 and 0.25, respectively. The resulting number of cells was 3.25 millions per tubercle included in the model. A no-slip boundary condition was applied on the hydrofoil surface, and standard velocity inlet and pressure outlet boundary conditions were specified on the freestream outer boundaries. A symmetry boundary condition was used on both ends of the hydrofoils along the spanwise direction to discount the tip vortices effects on the flow properties. Simulations were performed for hydrofoils with 0.5, 1, 1.5, 2, 3, 4, 6 and 8 trough-to-trough and crest-to-crest sinusoidal leading-edge tubercles, and unmodified hydrofoils of corresponding spans to evaluate the lift and drag coefficients at angles of attack between 0 and 25°.

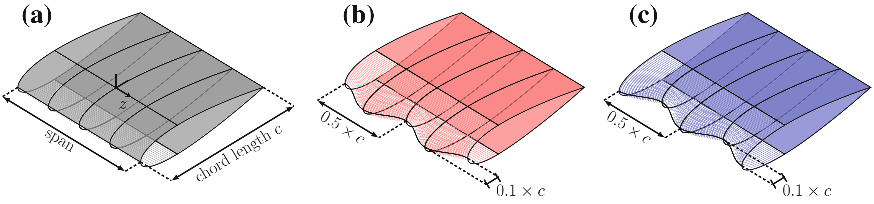

Fig. 1 Characteristics of the NACA 0021 hydrofoil models with **a** unmodified leading edge, **b** trough-to-trough sinusoidal leading edge and **c** crest-to-crest sinusoidal leading edge. The models shown include two tubercles

3 Results and Discussion

The lift and drag curves in Fig. 2a, b show that stall for the standard hydrofoil is characterized by abrupt and severe loss of lift and increase in drag between angles of attack of 13° and 14°. For the scalloped hydrofoil, stall is occurring for a lower angle attack but leads to a smaller drop in lift. Post-stall, the lift and drag coefficients corresponding to the hydrofoil with a sinusoidal leading edge do not increase linearly with the angle of attack. As shown in Fig. 2c, d, the predictions of lift and drag coefficients can vary significantly depending on the number of tubercles included in the model and on the location, crest or trough of the tubercles, where the symmetry boundary condition is applied. By contrast, the predicted lift and drag coefficients for the unmodified hydrofoil remains constant for increasing span-to-chord-length ratios because of the flow's pseudo two-dimensionality.

For the scalloped hydrofoil, including only 0.5, 1 or 1.5 tubercles in the model appears to be too restrictive to allow predictions of relevant three-dimensional flow structures. With two or more tubercles, the location of the symmetry boundary condition has a significant impact on the periodicity of the flow structures predicted. Thus, for four trough-to-trough tubercles included in the model, a flow structure developing over tubercles pairs and being repeated along the span can be distinctly predicted, as

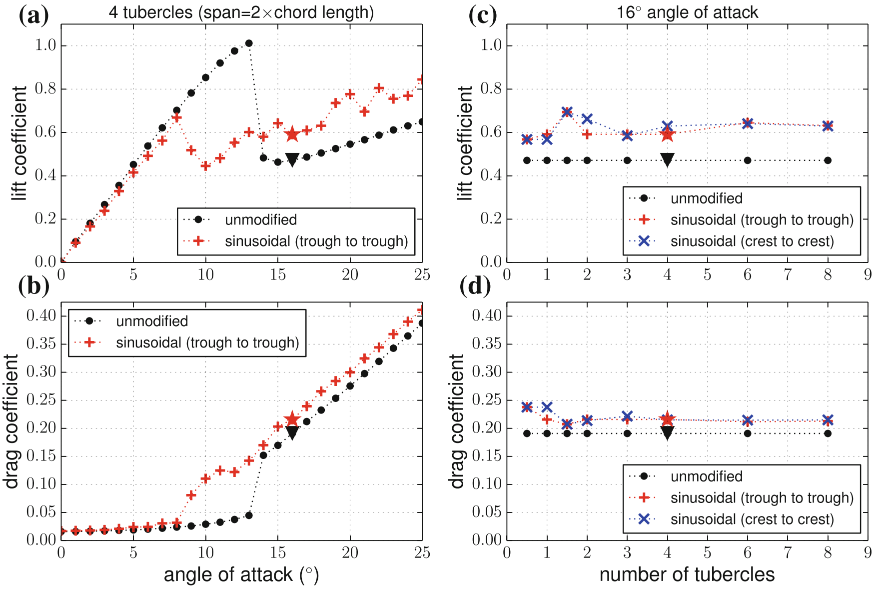

Fig. 2 Predictions for NACA 0021 hydrofoil at Reynolds number 120,000: **a** Lift coefficient and **b** drag coefficient as a function of angle of attack for four tubercles included in the model, and **c** lift coefficient and **d** drag coefficient at 16° angle of attack as a function of the number of tubercles included in the model. ▼ and ★ indicate data points found in both left and right graphs

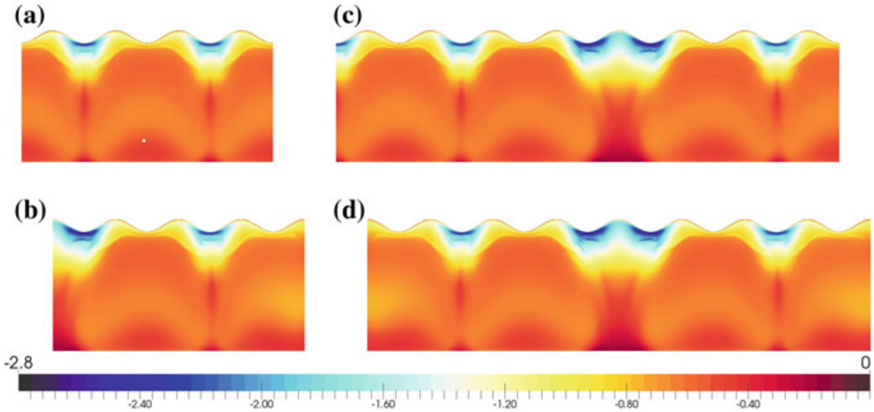

Fig. 3 Coefficient of pressure on the suction surface of the NACA 0021 hydrofoil models with sinusoidal leading edge of peak-to-peak amplitude of 10% of chord length and wavelength of 50% of chord length (Reynolds number 120,000 and 16° angle of attack): simulations carried out with **a** four trough-to-trough tubercles, **b** four crest-to-crest tubercles, **c** eight trough-to-trough tubercles and **d** eight crest-to-crest tubercles

indicated by the pressure-coefficient contours in Fig. 3a. This predicted “bi-periodic” flow pattern is in agreement with previous experimental observations [3] and CFD simulations [1, 2]. In Fig. 3b however, the predicted flow structure appears to differ on one of the two tubercles pairs for four crest-to-crest tubercles included in the model, suggesting that higher-order flow patterns might emerge. Indeed, for eight tubercles included in the model, the simulations allow prediction of a flow structure developing over three tubercles pairs and being repeated symmetrically along the span, as shown in Fig. 3c, d. As the number of tubercles increases, the effect of the imposed symmetry location, crest or trough of the tubercles, is diminished since the increased spanwise width of the flow domain provides the capacity to predict systematically “tri-periodic” flow structures.

Consequently, the estimated lift coefficient converges to a unique value when six or more tubercles are included in the model, as shown in Fig. 2c, d. The patterns generated by the leading-edge tubercles are associated to more complex flow separation and recirculation on the suction surface of the hydrofoil, particularly at high angles of attack. For instance, in the “tri-periodic” structure, the friction lines shown in Fig. 4c, d suggest that the fluid flowing over one of the crests remains attached to the surface of the hydrofoil almost down to the trailing edge. On the other hand, for the stalling unmodified hydrofoil, flow separation occurs at the leading edge, uniformly along the span. Therefore, the standard hydrofoil remains substantially more efficient pre-stall for moderate angles of attack while the tubercles provide superior performance at high angles of attack.

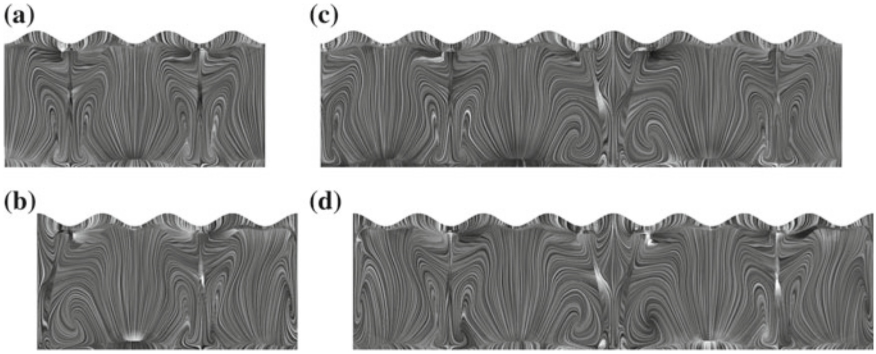

Fig. 4 Friction lines on the suction surface for the cases shown in Fig. 3

4 Conclusions

The flow over a NACA 0021 hydrofoil with leading-edge protuberances was numerically simulated to investigate the influence of the number of sinusoidal leading-edge tubercles included in the hydrofoil model on the lift and drag coefficients. At post-stall angles of attack, characteristic "bi-periodic" flow patterns cannot be systematically predicted when less than six tubercles are included. In this case, the location, crest or trough of the tubercles, of the symmetry boundary condition can affect the type of flow pattern developing along the span, leading to a significant uncertainty on the lift and drag values. With more than six sinusoidal protuberances, the symmetry condition effect is mitigated so that tri-periodic flow structures and more consistent hydrodynamic performance can be predicted.

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