Separation Control on Oscillating Airfoils Using Moving Surface Control

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Abstract

A numerical investigation has been conducted to study the effectiveness of Moving Surface Control method in controlling dynamic stall in oscillating airfoils. The momentum imparted by the moving surface to the free shear layer is utilised for dynamic stall vortex suppression. In this way, effective flow control is achieved and adverse effects of dynamic stall are eliminated. The results are of interest as they provide insight into flow control for airfoils operating under unsteady conditions. Particular emphasis has been laid on the applicability to delaying / suppressing dynamic stall on rotorcraft blades to avoid extreme stresses and broadband noise radiation. The numerical study was based on the solution of 2D RANS equations using Baldwin-Lomax turbulence model and a solver based on Beam-Warming approximate factorization technique. The effect of moving surface flow control was analysed with reference to control strength as well as reduced frequency of airfoil oscillation. For the first time, moving surface control was applied successfully to achieve effective control of the dynamic stall phenomenon in oscillating airfoils at a realistic Reynolds' number (Re=106).

Keywords: Dynamic Stall, Flow Control, Stall Delay, Moving Surface Control.

Introduction

Dynamic stall refers to a deep stall that occurs on oscillating airfoils during the retraction cycle. In such flows, separation is inhibited during pitch-up and results in delayed stall and a higher maximum lift coefficient. However, as the retraction (pitch-down) cycle begins, a separation region rapidly forms near the leading edge of the airfoil. This separation region grows quickly and later bursts causing a massive drop in lift. The effect of dynamic stall continues nearly throughout the retraction cycle causing hysteresis loop behaviour of the force and moment coefficients. It reduces airfoil lift, causes large unsteady pitching moment, increases drag and leads to strong vibrations with generation of high level noise. It also results in high control loads as the sudden excessive pitching moment leads to increased torsion on the rotating blade and can lead to structural failure.

Dynamic stall phenomenon severely restricts the performance of rotorcrafts and wind turbines. In today's environment, such restrictions on the performance envelope of modern vehicles and devices are considered unacceptable. Thus, a large body of ongoing research is directed towards understanding the mechanism of dynamic stall with the aim to control and, if possible, to eliminate dynamic stall and its adverse effects. Several flow control techniques are being studied to evaluate their effect on the onset of normal as well as dynamic stall of airfoils.

Background

The origin of scientific study on flow control can be traced back to Prandtl's efforts in the beginning of the twentieth century. Prandtl used boundary layer suction to control flow separation. According to one of the most comprehensive reviews in this area [1], flow control is still an area of active research. Modern flow control techniques [2-25] employ active, passive or reactive methods and their application varies from pre-determined strategies to feed-forward or feed-back mechanisms. The control strategy is generally based either on elimination of boundary layer separation or the generation of a large vortex on the upper surface of the airfoil. The methods used for separation control involve energising the boundary layer through tangential blowing [26, 27], surface motion [28-31] or suction of low energy fluid from the boundary layer [22-24]. Introduction of weak unsteady disturbances (e.g. acoustic waves [32], pulsating jet [33]) to excite and regulate the unstable mode in the boundary layer and production of an organised vortex structure to entrain energy from the outside the boundary layer have also been employed with some success. Another area of research involves maintaining a large vortex on the upper su rface [34] by various methods to boost lift generation. These studies highlight that in spite of advancement in flow control methods, a lot of research is needed before they can be applied efficiently to practical problems.

The current study is part of an ongoing numerical investigation into the effectiveness of *Moving Surface Control* in suppressing leading edge separation of oscillating airfoils. Previous studies [28-31] have generally investigated control of separation and static stall through surface motion in case of stationary airfoils. Therefore, the aim of this work was to investigate the effectiveness of this technique to control dynamic stall events and to suggest methods for establishing more effective control in such cases.

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Methodology

The study is based on numerical analysis of an oscillating NACA 0012 airfoil using a highly dense grid (214×300) with 0.0005c and 0.00005c minimum spacing in ξ and η directions respectively. The selected grid density was appropriate to capture trailing edge vortices generated at the lower surface boundary layer. These vortices have rarely been captured in previous numerical computations but they are important in explaining aerodynamic force generation using vorticity dynamics theory. The simulation was conducting using a finite-difference code based on Beam-Warming block approximate factorisation solution [35] of 2D Reynolds Averaged Navier-Stokes equations. The code was developed and validated as a part of this ongoing study. Baldwin-Lomax model [36] was used for representation of turbulence at all points in the viscous region.

The computational grid was generated using a special Poisson solver based on the TTM method [37] with modifications incorporated by Liu [38]. The solver uses a multi-regional approach to determine the source term, resulting in better control of grid line distribution. For the cases in which the airfoil is pitching or oscillating, instead of re-calculating the grid at each time instance, the body-fitted grid is moved using time-dependent coordinate transformation (moving grid). A representative grid from the current study is presented in Fig. 1.

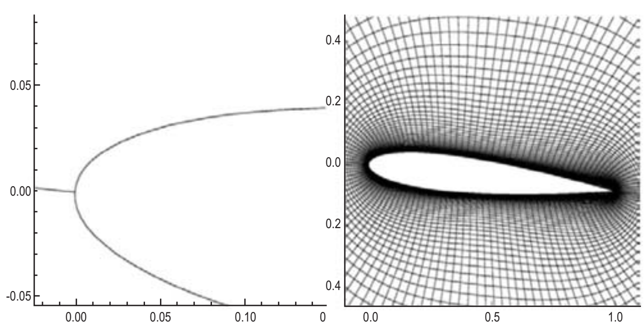


Fig. 1. Representative Computational Grid and Control Geometry

The moving control surface was modelled as an endless belt forming a part of the upper surface of the airfoil. This belt, placed around two pulleys, could be rotated by a motor or other mechanical means. The location of the belt was pre-determined based on a tangential blowing simulation. The moving surface was placed at 1% to 8% of airfoil chord and covered about 8% of the airfoil upper surface. This mechanism is shown in Fig 1. Numerically, the motion of the belt was represented as a finite tangential velocity of the airfoil surface instead of the no-slip inner boundary condition.

Flow parameters were calculated for a NACA 0012 airfoil in oscillation about a mean angle of attack of 15°, with 10° oscillation amplitude. The flow Reynolds number simulated was Re=1.0x10^6 at a free stream Mach number of 0.2. Calculations were conducted for two reduced frequencies of kc^+=0.15 and kc^+=0.25. Fig. 2 and Fig. 3 show the calculated results in comparison with the experimental data [1].

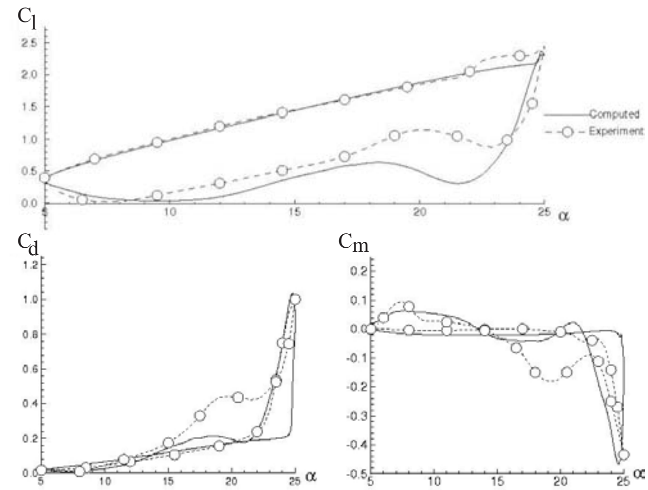


Fig. 2. Force / Moment Coefficients without Control: kc^+=0.15, M=0.2, Re=10^6

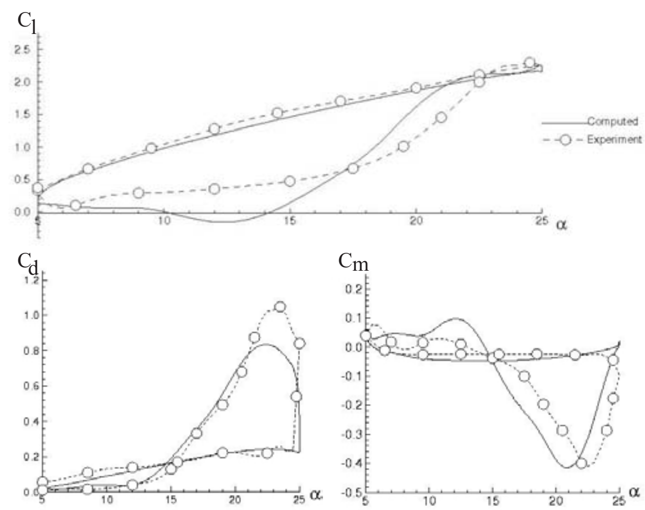


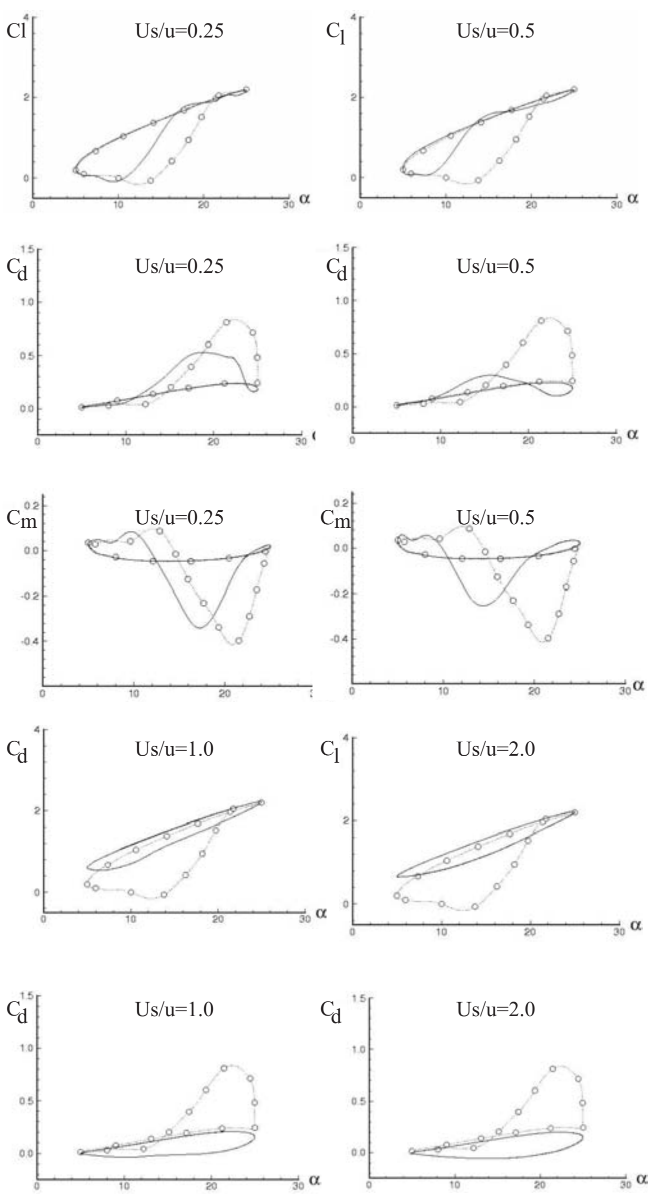
Fig. 3. Force / Moment Coefficients without Control: kc^+=0.25, M=0.2, Re=10

Results

Fig. 2 and Fig. 3 show that the computed results are in very good agreement with experimental data in all areas except regions in which separation is pronounced. Simulation results during the up-stroke are in very good conformity with experimental data for both reduced frequencies i.e kc^+=0.15 and kc^+=0.25. However, during down-stroke, when the separation region is large, the results duplicate only the qualitative behaviour of the flow. This divergence was expected as the Baldwin-Lomax turbulence model is known to give inaccurate results for highly separated flows. However, this inaccuracy in results was considered acceptable for two reasons. Firstly because the study was research oriented and its scope did not include quantitative analysis explicitly. The second that the flow control techniques being studied are designed to avoid flow separation. Therefore, most flows of interest will not have areas of large separation and the calculations will remain within the domain of reasonable accuracy.

Steady moving surface control

Surface motion control was considered with various speeds i.e. U_s/U_∞=0.25, 0.5, 1.0 and 2.0, where U_s is the speed of the moving surface. Oscillation amplitude of the airfoil was taken as ±10° about a mean angle of attack of 15°. Two pitching rates corresponding to reduced frequencies of kc^+=0.15 and kc^+=0.25 were investigated. Results of the simulation are shown in figures below. Figure 4 shows the force and moment coefficients for the airfoil oscillating with a reduced frequency of kc^+=0.25. The results show a clear influence of speed ratio U_s/U_∞ on the behaviour of force and moment coefficients. At U_s/U_∞=0.25, dynamic stall induces a minor hysteresis loop effect on the force and moment coefficients. The effect of dynamic stall delays further as the strength of applied control U_s/U_∞ increases. Flow control is fully established for U_s/U_∞=1.0 for which the characteristic peaks of dynamic stall are eliminated from the drag and moment coefficients. Further increase in control strength has no discernible effect on the flow coefficients above the conditions at U_s/U_∞=1.0 as can be seen from Fig. **4**.



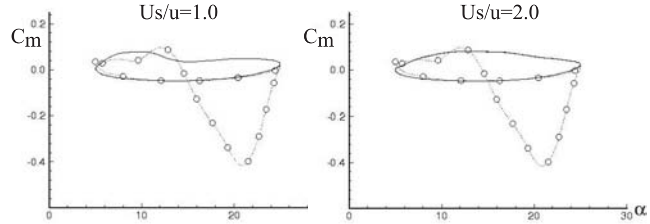


Fig. 4. Force / Moment Coefficients with Control @ kc^+=0.25. ---o---o--- Base airfoil ______ Controlled

Flow structures for various cases are shown in Fig. 5, Fig. 6 and Fig. 7. The flow structures clearly show suppression of dynamic stall vortex is suppressed and leads to a very small separation region at the trailing edge of the airfoil for U_s/U_∞=1.0. At this condition, flow remains completely attached over the rest of the airfoil both during pitch-up and retraction. The flow structures also highlight that increasing surface speed beyond U_s/U_∞=1.0 has no visible effect on the flow structure.

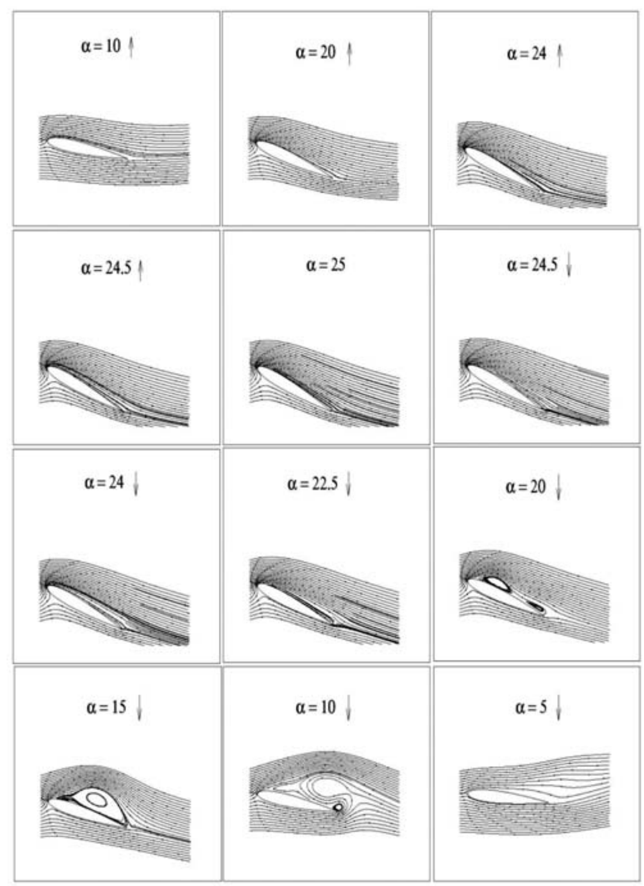


Fig. 5. Flow Structure for Oscillating Airfoil with Control: kc^+=0.25, U_s/U_∞=0.25

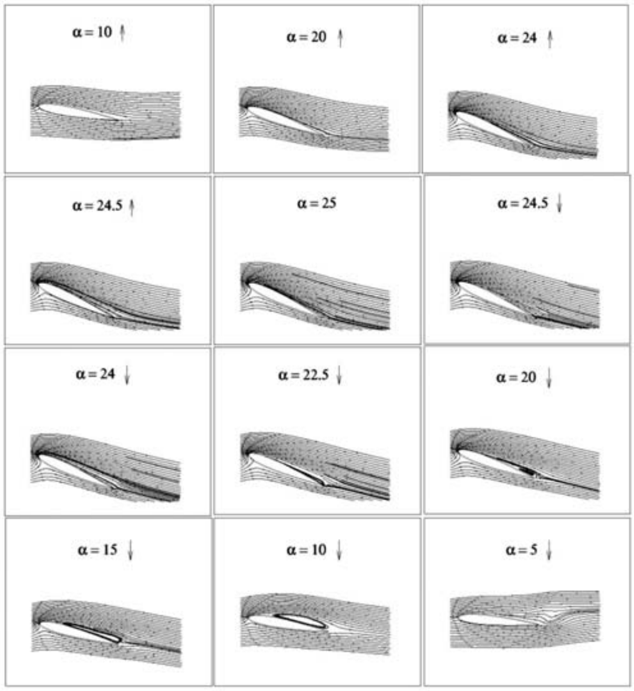


Fig. 6. Flow Structure for Oscillating Airfoil with Control: kc^+=0.25, U_s/U_∞=0.5

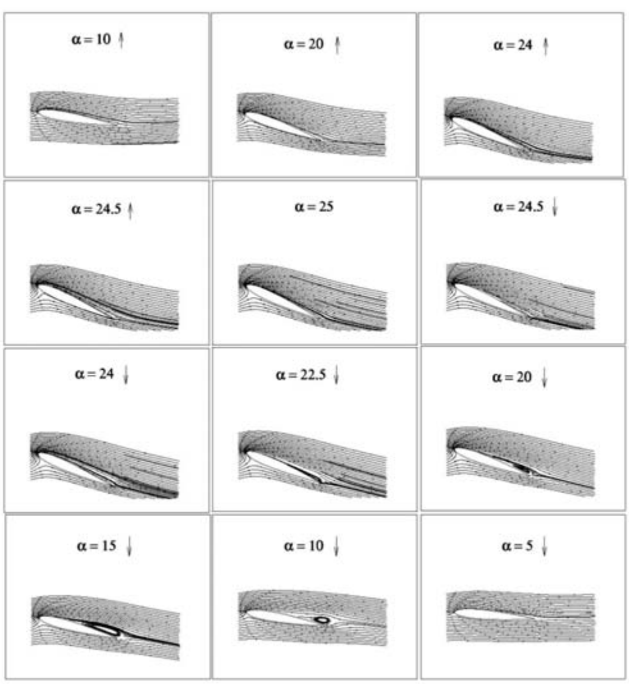


Fig. 7. Flow Structure for Oscillating Airfoil with Control: kc^+=0.25, U_s/U_∞=1.0

The analysis for a reduced frequency of kc^+=0.15 displayed the same qualitative features that were observed for the higher reduced frequency. However, the onset of dynamic stall and its development was more gradual. In this case also, control strength of U_s/U_∞=1.0 proved to be sufficient for controlling dynamic stall. Figure 8 shows the force and moment coefficients for various steady control strengths.

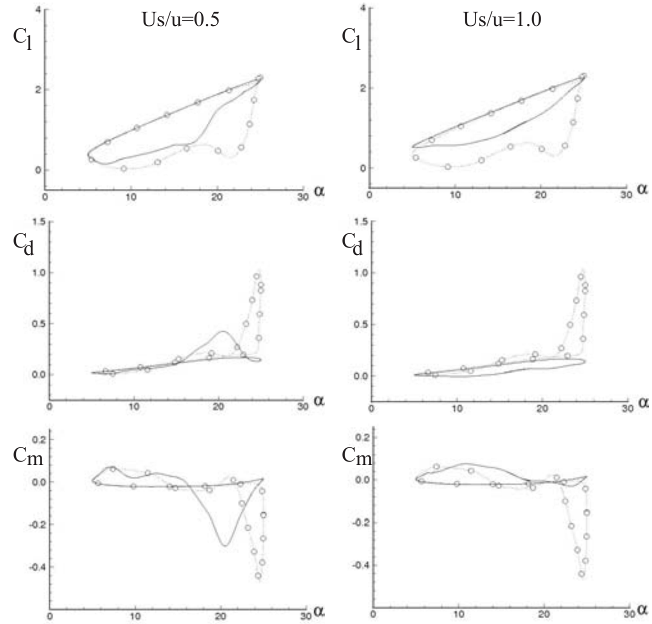


Fig. 8. Force / Moment Coefficients with Control @ kc^+=0.15. ---o---o--- Base airfoil ______ Controlled

Fig. 9 shows control structures for U_s/U_∞=1.0 for this reduced frequency. The results also show that for fixed control strength, an increase in reduced frequency improves flow control. This highlights that dynamic stall is more easily controlled at higher rates of oscillation by using the same control strength.

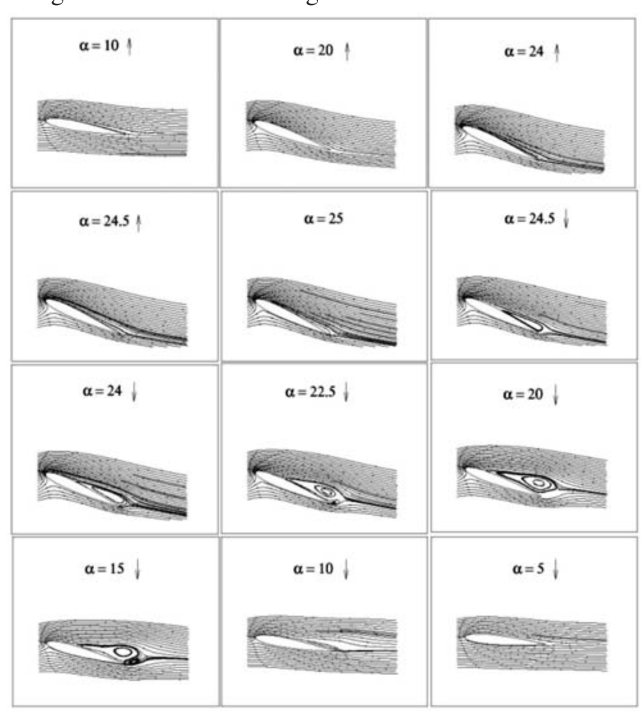


Fig. 9. Flow Structure for Oscillating Airfoil with Control: kc^+=0.15, U_s/U_∞=1.0

Conclusion

In this study, a computationally cheap numerical scheme has been successfully applied to predict flow behaviour over an oscillating airfoil and to assess the effectiveness of Moving Surface Control in suppressing dynamic stall. The qualitative features of the flow were found to be in good agreement with experimental results for most flow conditions. The results highlighted that effective separation control could be achieved with a minimum control strength corresponding to U_s/U_∞=1.0.

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