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ASSESSMENT OF THE WAKE PATTERNS AND UNSTEADY LOADS FOR A NACA0012 AIRFOIL UNDER HEAVING AND PITCHING MOTION

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Abstract. *The present study presents numerical simulations of a NACA0012 airfoil under heaving and pitching motion. We employ a computational fluid dynamics tool which features low dispersion and dissipation characteristics. The current simulations are able to resolve unsteady flow features which may occur in the flight of insects, maneuvering aircraft and other biological and engineering systems. For example, it is possible to analyze the aerodynamic time-response of an airfoil subjected to external perturbations or forced movements such as a rapid increase in the airfoil angle of attack. The current study also provides a brief investigation of the Knoller-Betz effect for thrust and its correlation to flapping flight dynamics. Aspects of airfoils under heaving and pitching movements are studied analyzing the momentum variations and the flow patterns along the vortex wake. Moreover, in the post-processing phase, a wavelet analysis is applied in order to examine the spectral characteristics of the flow features which may be impulsive/non-periodical.*

Keywords: *Oscillating airfoils, dynamic stall, wavelets*

1. INTRODUCTION

Unsteady flows including heaving and pitching motion have always been an interesting topic for scientists and engineers, since many critical phenomena may occur under these conditions. Dynamic stall, for example, may occur when an airfoil experiences an abrupt change in its angle of attack, producing a large leading edge vortex that moves along the upper surface and interacts with the trailing edge vortex, causing a significant loss of lift forces. Studies of wake patterns and unsteady loads find application in several problems of biological and engineering interest, for instance, the flight of insects and maneuvering aircraft. Recently, the development of small scale flying objects has become an important topic of study in aeronautical and mechanical engineering. For example, the development of drones for military and civil applications, such as surveillance, is of paramount importance. Furthermore, the development of small scale flying robots require the understanding of low Reynolds aerodynamics phenomena including severe dynamic stall.

The first studies indicating a relation between an airfoil's wake pattern and the aerodynamic forces acting on its surface date back from the 30's, with von Karman and Burgers (von Karman and Burgers, 1935) indicating the possibility of producing either drag or thrust, depending on the periodicity and orientation of the vortices shed along the wake. Later, in 1953, Bratt(Bratt, 1953) conducted a series of experiments in order to characterize the flow patterns past an oscillating airfoil, as depicted in figure 1.

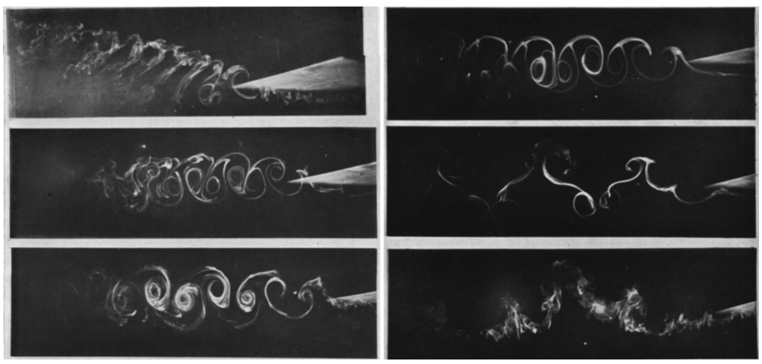

Figure 1. Different low patterns observed by Bratt's investigations Bratt (1953)

For small amplitude oscillations, vortex patterns depend mainly on the Strouhal non-dimensional parameter, which is proportional to the vortex spacing expressed as a number of obstacle diameters. As studied by engineers and zoologists interested in flapping flight dynamics, the great majority of animals that use oscillatory movements to propel themselves, like fish and birds, stroke their wings (or tails) at Strouhal numbers ranging between 0.2 to 0.4. This range of values represent a good initial target for simulations.

In the present work we perform numerical simulations of a NACA0012 airfoil under heaving and pitching motion. The computational fluid dynamics tool employed in the current analyses features low dispersion and dissipation characteristics and, therefore, the simulations are able to resolve the unsteady flow features of interest. For example, it is possible to analyze the aerodynamic time-response of an airfoil subjected to external perturbations or forced movements such as a rapid increase in the airfoil angle of attack. Here, we also provide a brief investigation of the Knoller-Betz effect for thrust and its correlation to flapping flight dynamics. Aspects of airfoils under heaving and pitching movements are studied analyzing the momentum variations and the flow patterns along the vortex wake. Moreover, in the post-processing phase, a wavelet analysis is applied in order to examine the spectral characteristics of the flow features which may be impulsive/non-periodical.

2. NUMERICAL METHODS

2.1 Flow Simulations

In the present flow simulations, the general curvilinear form of the compressible Navier-Stokes equations is solved in a non-inertial frame of reference. The numerical scheme for spatial discretization is a sixth-order accurate compact scheme (Nagarajan *et al.*, 2003) implemented on a staggered grid. Compact finite-difference schemes are non-dissipative and numerical instabilities arising from mesh non-uniformities and interpolation at grid interfaces have to be filtered to preserve stability of the numerical schemes. The high wavenumber compact filter presented by Lele (1992) is applied to the computed solution at prescribed time intervals in order to control numerical instabilities. This filter is only applied in flow regions outside of boundary layers.

The time integration of the fluid equations is carried out by the fully implicit second-order scheme of Beam and Warming (Beam and Warming, 1978) in the near-wall region in order to overcome the time step restriction due to the usual near-wall fine-grid numerical stiffness. A third-order Runge-Kutta scheme is used for time advancement of the equations in flow regions far away from solid boundaries. No-slip adiabatic wall boundary conditions are applied along the solid surfaces and characteristic plus sponge boundary conditions are applied in the far field locations. The numerical tool has been previously validated for several simulations of compressible flows involving sound generation and propagation (Wolf *et al.*, 2012, 2013). Calculations are performed using non-dimensional quantities, using the freestream density, temperature and speed of sound as reference quantities, and the airfoil chord as reference length.

2.2 Post-Processing

Wavelets represent a useful post-processing technique used to obtain spectral information of non-periodical events. Rather than considering a signal as periodic, such as a conventional Fourier transform, a wavelet analysis interprets a signal by stretching and translating a general wavelet form. Thus, it is possible to know when a certain event at a specific frequency occurred and what was its intensity. The method has been increasingly applied in fluid dynamics, in topics such as turbulence analysis, where signals may look very disorganized in a first view. As an example, in figure 2 a frequency mapping was obtainted for the normalized lift coefficient also shown in the figure. In the final version of the manuscript,

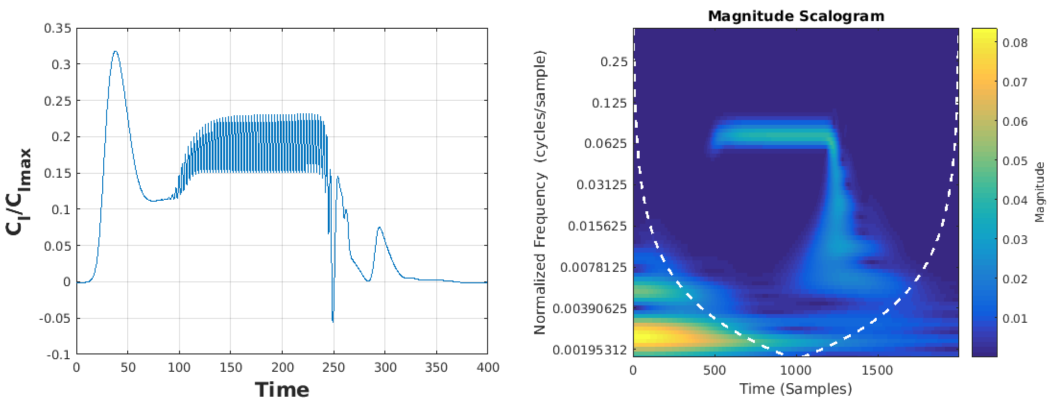

Figure 2. Continuous wavelet transform.

we will present results obtained by analyses of the unsteady loads along the moving airfoils. Wavelets will be employed for such studies.

3. RESULTS

3.1 Accelerating airfoil

The aerodynamic response of an airfoil accelerated from rest to Mach number 0.2 and, then, decelerated again to rest is depicted in figure 3. The body experiences peaks of drag and lift, which may be much greater than the steady flow values and such variation is linked to the boundary layer development.

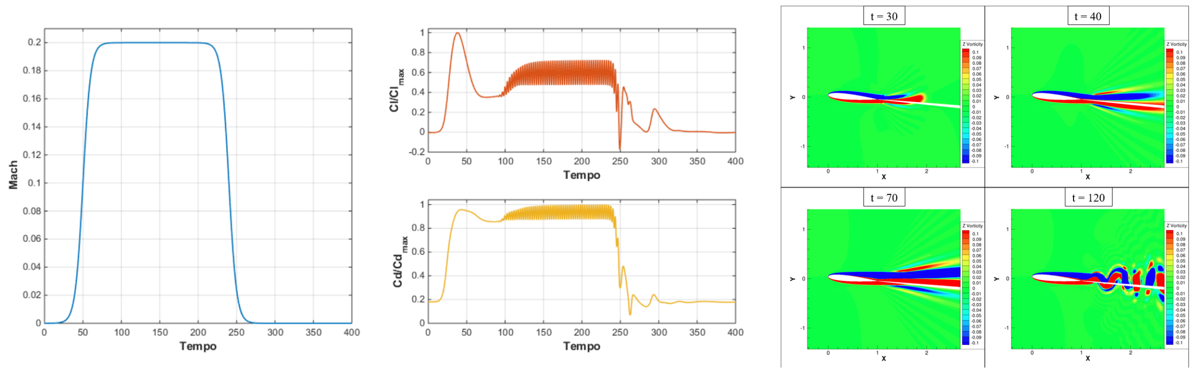

Figure 3. (a) Mach number along time (b) Normalized lift and drag coefficients along time.

3.2 Flapping flight

As an example of a flapping flight, we present results of a simulation for a Strouhal number of St = 0.2 and an amplitude of 0.15 times the characteristic airfoil length. Here, the movement of the NACA0012 airfoil includes a pure heaving. With these parameters, it is possible to create a thrust producing a pattern of wake vortices aligned downstream the airfoil. This wake is composed by alternating counter-rotating vortices, as depicted in the figure 4). The mean thrust during the simulation was calculated by acquiring the momentum on a path line distanced from the airfoil.

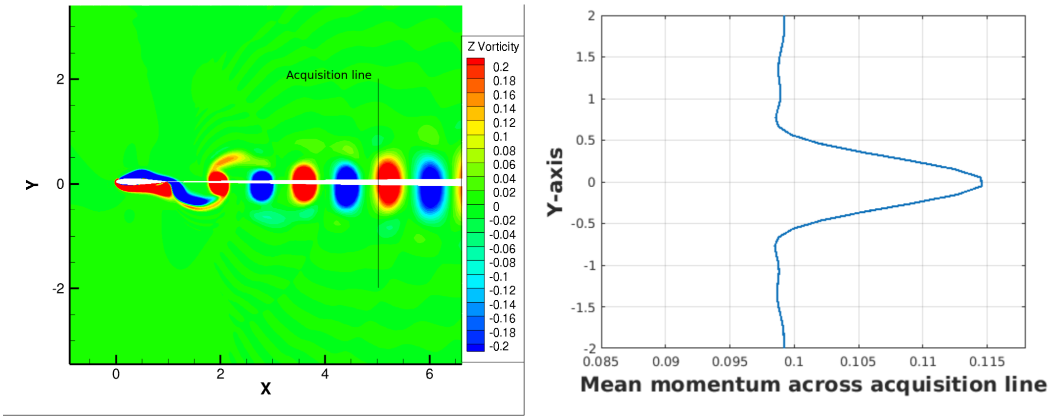

Figure 4. a) Vorticity pattern b) Momentum generated by the heaving motion.

4. CONCLUSIONS

The current paper presents numerical simulations for a NACA0012 airfoil under pitching and heaving motion. The main goal of this work is to investigate different effects and phenomena related to dynamic stall and thrust generation and to prove the feasibility of using computational fluid dynamics to perform simulations of unsteady flows in non-inertial frames.

In the final version of the manuscript, further simulation results will be presented and carefully analyzed, both for flapping flight and impulsive motions. The objective is to create a dataset of numerical simulation results for different parameters. This should allow an assessment of these parameters and flow features. Although the wavelet analysis is in a initial phase, other topics are envisioned.

5. ACKNOWLEDGEMENTS

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