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Effect of flow regime change from subsonic to transonic on the air loads of an oscillating airfoil

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ABSTRACT

In this research, the effect of flow regime change from subsonic to transonic on the air loads of a pitching NACA0012 airfoil is investigated. To do this, the effect of change in flow regime on the lift and pitching moment coefficients hysteresis cycles is studied. The harmonic balance approach is utilized for numerical calculation due to its low computational time. Verifications are also made with previous works and good agreements are observed. The assessment of flow regime change on the aforementioned hysteresis cycles is accomplished in the Mach number range of $M=0.65$ – 0.755 . The reduced frequency and pitch amplitude also vary from $k=0.03$ to 0.1 and $\alpha_0=1$ – 2.51° , respectively. Results show that the effect of increase in Mach number is to increase and decrease the lift coefficient during downstroke and upstroke, respectively, whereas at low reduced frequencies, the effect of increase in Mach number may lead to a reverse manner when airfoil moves toward its extremum angle of attack. Results also reveal that as the pitch amplitude varies, the shape of lift coefficient hysteresis cycle depends more on the pitch amplitude than on the appearance of shock. It is shown that as the Mach number increases, the incidence angles correspond to the extremum pitching moment, and depending on the reduced frequency, lie between zero and extremum angle of attack. These incidence angles shift toward the extremum angle of attack as the reduced frequency decreases. Results also show that the increase in pitch amplitude at low Mach number, in such a way that leads to the formation of shock around the extremum angle of attack, causes the extremum pitching moment to appear around these angles and at high Mach number, depending on the reduced frequency, the extremum pitching moment incidence angles would be between zero and extremum incidence angle.

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1. Introduction

The change in flow regime from subsonic to transonic may be observed in many periodical flow fields such as turbo-machineries or aerodynamic applications. The most significant feature occurring in transonic flows is the larger losses than subsonic ones due to the formation of shock waves. The high nonlinear effects occurring in transonic flows compared with subsonic ones causes the change in flow condition from subsonic to transonic to has a significant effect on the aerodynamic performance of blades or wings used in the above-mentioned context.

The effect of flow regime change from subsonic to transonic on some flow features or aerodynamic forces was the subject of some researches. In these works, the change in flow regime was mainly due to the increase in Mach number. For example,

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Nomenclature

a	control volume velocity
C	airfoil chord
C_L	lift coefficient
C_m	pitching moment coefficient
C_p	pressure coefficient
e	internal energy
$\vec{f}$	convective term
$\vec{F}$	vector of convective and viscous terms
F_d	artificial dissipation term
g	viscous term
i	imaginary unit ($i = \sqrt{-1}$)
k	reduced frequency
l	lift force
m	pitching moment
M	Mach number
N	number of harmonics
p	pressure
q	heat flux
Q	summation of fluxes and dissipation terms
Re	Reynolds number
$\vec{S}$	surface of control volume
$\vec{s}$	surface vector
t	time
T	temperature
u	velocity component in x direction
U	solution vector

v	velocity component in y direction
V	free stream velocity
$\vec{V}$	velocity vector of fluid in the cell near the wall
$\vec{V}^{ghost}$	velocity vector in the ghost cell
$\vec{V}_{wall}$	wall velocity vector
x, y	spatial coordinates

Greek symbols

ρ	density (kg/m ³)
λ	thermal conductivity
τ	shear stress
μ	viscosity (N s/m ²)
K	wave number
ω	frequency of oscillation
α	instantaneous angle of attack
α_m	mean value of angle of attack
α_0	pitch amplitude
Ω	volume

Upper hat symbols

$\sim$	values in the frequency domain
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Subscripts

∞	free stream values
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Lepicovsky et al. (2002) conducted an experiment to measure the unsteady pressures in a fan cascade due to oscillation of a single airfoil. In their experiment, the incidence angle of cascade was 10°. They acquired the data on three stationary blades on each side of the interior blade that was oscillated with an amplitude of 0.6°. In their experiments, the inlet Mach numbers were chosen to be $M=0.5, 0.8$ and 1.1 , which covered the subsonic, transonic and supersonic flow regimes and the oscillation frequencies were 200, 300, 400, and 500 Hz. Barakos and Drikakis (2003) investigated the subsonic and transonic turbulent flows around oscillating and ramping airfoils. In their study for oscillating airfoils, they focused on the dynamic stall conditions. Their work was concerned with limited numbers of Mach number, reduced frequency and oscillation amplitude. Bennett and Walkner (1993) conducted an experiment for a rectangular wing consisting of a supercritical airfoil section. In their research, they studied the parametric variations of oscillation frequency and Mach number from subsonic to transonic flow. In their work, the surface pressure measurement for the lower and upper airfoil sections was carried out. Babinsky and Fernie (2002) presented an experimental setup to study the effect of change in free stream Mach number from subsonic to transonic on a NACA0012 airfoil pressure distribution at a fixed angle of attack. They focused on the harmonic-like change of free stream velocity at different frequencies. Cornelia et al. (2004) investigated the interaction of structural and aerodynamic forces on a 2-D supercritical rectangular wing section oscillating in pitch at transonic flow experimentally. They investigated the free and forced oscillations. They measured the surface pressures and aerodynamic forces while the wing section was oscillating in pitch. In their experiments, the wing model was oscillating about mean incidence angles of 0–2° while the Mach number varied from $M=0.50$ to 0.85 , which corresponded to the Reynolds numbers of $Re=1.5 \times 10^6$ – 2.2×10^6 . Zhou and Wolff (2004) analyzed an oscillating linear cascade of advanced design blades. In their research, they calculated the skin friction and pressure coefficient at Mach numbers of $M=0.5$ and 0.8 while the frequency of oscillation ranged from 200 Hz to 500 Hz. Lee (2008) reported the effect of viscosity on flutter boundary and especially on the limit cycle oscillation characteristics of 2D airfoil sections. In his study, Mach number varied from $M=0.3$ to 0.92 whereas Reynolds number was fixed to $Re=12.3 \times 10^6$. Exploring literature reveals that although the studies on aerodynamic loads in flow regime change from subsonic to transonic may be observed in some researches, no comprehensive work has been performed to characterize the effect of this flow regime change on the significant air loads such as lift or pitching moment coefficient.

The time accurate methods are common ones for solving unsteady periodic flows. These methods are applicable in arbitrary geometries and flow conditions; however, these approaches generally take a large computational time. With the assumption of periodic flow conditions, various advantageous solution techniques could be employed to solve the unsteady motion (Peters and Ventura, 1985). In this context, the harmonic balance methodology could be considered as a significant

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