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Experimental and numerical study of forced shock-wave oscillations in a transonic channel

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Abstract

The aim of the present investigation is to analyse the response of a transonic channel flow when the shock-wave is subjected to a periodic motion at a well defined and controlled frequency. The shock periodic motion was produced by means of a second throat whose section was varied thanks to a rotating elliptical or rectangular shaft located in the middle of the channel outlet section. The induced shock oscillations had amplitudes of about 10 times the incoming boundary layer thickness and frequencies several orders lower than turbulence frequencies. Schlieren visualizations and unsteady pressure measurements, coupled with a spectral analysis, made it possible to highlight the rotating shaft shape influence on the shock oscillation in the channel. Conditional two component laser Doppler velocimeter probing was carried out for a shock oscillation frequency of 40 Hz produced by the elliptical shaft only. Phase-averaged field results have allowed a precise description of the unsteady flow field showing both the wave propagation in the core flow and the response of the boundary layer subjected to an oscillating shock-wave. In the shock oscillation region, no phase lag was observed between velocities in the core flow and in the boundary layers whereas a significant one has appeared in the downstream subsonic region. Numerical simulations of the channel flow were made by means of a two-dimensional unsteady Reynolds averaged Navier–Stokes solver using a dual time-stepping method and several two-equation transport turbulence models. The shock oscillation frequency of 40 Hz was only produced by the rotating elliptical shaft. Apart from some discrepancies in the interaction regions, the cycle of the shock oscillation is well reproduced by the computations. The good agreement between the evolutions of the measured and computed fluctuating quantities has allowed to confirm the assumption about the quasi instantaneous adaptation of the turbulence to the mean flow variations in such channel flows.

Keywords: Unsteady flow; Transonic flow; Shock-wave; Turbulence; Laser Doppler velocimetry

1. Introduction

In modern aerodynamics, there are a large number of circumstances where shock-waves are present. On subsonic transport aircraft, a nearly normal shock terminates the supersonic pocket present on the wing in certain flight conditions. This transonic situation is also encountered in turbomachine cascades and on helicopter blades. Supersonic aircraft are much affected by shock-waves which are of prime importance in air intakes. Intense shock phenomena also occur in over-expanded propulsive nozzles where strong shocks may form at the nozzle lip if the exit pressure is much lower than the external pressure. Of special importance are the phenomena resulting from the encounter of a shock-wave with the boundary layer developing on the external and internal surfaces of a vehicle, the consequences of the so-called shock-wave/boundary-layer interaction being multiple and often critical for the vehicle or machine performance.

Much has been learned about the physical properties of steady shock-wave/boundary-layer interactions, at least for two-dimensional flows [12,13]. However, the situation is less satisfactory as far as the unsteady aspects of shock-wave/boundary-layer interaction are concerned, although the subject is of outmost importance because of their potentially dangerous effects on the vehicle behaviour and structural integrity. A distinction must be made between large-scale unsteadiness affecting the entire flow field and small-scale fluctuations affecting only the interaction region and the nearby flow. There is

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Nomenclature

c	sound velocity
f	shock oscillation frequency
f_{c}	excitation (shaft) frequency
H_{i}	incompressible shape parameter
k	turbulent kinetic energy
M	Mach number
p_{st}	stagnation pressure
T	shock oscillation period
T_{st}	stagnation temperature
U	mean streamwise (longitudinal) velocity
u'	streamwise (longitudinal) velocity fluctuation
V	mean normal velocity
v'	normal velocity fluctuation
$-u'v'$	cross correlation of velocity fluctuations (turbulent shear stress)
X	streamwise coordinate along the channel lower wall, origin at the half-nozzle throat
Y	coordinate normal to the channel lower wall
δ	boundary layer physical thickness
δ^*	boundary layer displacement thickness
ε	turbulent dissipation
θ	boundary layer momentum thickness

Operators

$\langle\rangle$	phase-averaged operator
$-$	ensemble-averaged operator
$\sim$	cyclic operator
$'$	fluctuating operator

a close correlation between the second type of fluctuations and the fluctuating nature of a turbulent boundary layer. In some circumstances, the above mechanism is much amplified, the entire flow field being affected by large-scale fluctuations, periodic or not, depending of the conditions. This phenomenon is at work in transonic airfoil buffeting where the normal shock moves over a significant portion of the chord length, the separated bubble disappearing and reappearing in a periodic manner. A similar scenario is at work in supersonic air-intake buzz where the unsteadiness is a periodic large amplitude motion of the shock system.

The aim of the present investigation is to analyse the response of a transonic channel flow when the shock is subjected to a periodic motion at a well defined and controlled frequency. The interest of such an experiment is to focus on the unsteady shock-wave/boundary-layer interaction, particularly on the boundary layer response, in a circumstance where the origin of the shock motion is well known. This can facilitate both the understanding of the interaction mechanism and the modelling of the flow by providing a test case where the boundary conditions are well defined. Similar investigations were made in a transonic diffuser flow by considering the shock response to imposed downstream perturbations [6,22,23] as also its self-excited oscillations [7,9]. Experiments were performed by Ott et al. [21] for a transonic shock excited by a rotating elliptical shaft, at a frequency in the range 0 to 180 Hz. Schlieren visualizations and unsteady pressure measurements along a sidewall of the wind tunnel were performed. Results have shown that no phase lag was observed between the shock-wave oscillation and the correlated unsteady pressure signals. Moreover, the amplitude of the shock oscillation decreased when the excited frequency is increased in the experiments. Liou et al. [18] have performed a numerical simulation of a forced shock-wave oscillation at 300 Hz, the excitation being produced by a downstream sinusoidal pressure wave. The analysis of the results has pointed out that the 3-D effects need to be taken into account to improve the prediction of such channel flows. Gérolymos and Vallet [15] modelled the experiment of Ott et al. [21] (at the frequency 180 Hz) with a 3-D unsteady Navier–Stokes solver along with the k–ε model of Launder–Sharma. Numerical results have shown a good agreement on unsteady pressure levels, but the prediction of mean velocity and turbulent shear stress profiles were not satisfactory.

The study of an interaction in a transonic channel where the shock is produced by the choking effect of a second throat has been performed in the steady case by Bur et al. [8]. A detailed flow field analysis was obtained by means of laser Doppler velocimeter measurements, in particular in the shock-wave/boundary-layer interaction region, which has allowed to choose the mean shock location in the channel for the present study. Forced shock oscillations are obtained by adding to the experimental set-up a shaft near the second throat section. Rotation of this shaft allows varying in a periodic way the effective height of the second throat, thus inducing a periodic motion of the shock. The shock intensity has been chosen so as to coincide with no (or incipient) boundary layer separation in order to provide a case where the 3-D effects are nearly negligible. The precise aim of the present study was to obtain a thorough description of the flow field, both in space and time. For this purpose, two optical methods were used to qualify the unsteady flow field. The first one is a Schlieren system equipped with a short duration light source coupled with a drum camera. The second one is a two-component laser Doppler velocimetry (LDV) system whose acquisition was synchronised with a reference signal to allow conditional sampling. Continuous and unsteady wall pressure measurements were also performed.

A characterisation of the way by which low frequency downstream pressure waves influence the turbulence in a shock-wave/boundary-layer interaction is an expected result of the study. For this purpose, a modelling and a numerical simulation of the experiment is also performed whose goal was to obtain information on the physics that are not obtainable by the experimental techniques used. Numerical simulations of this channel flow are obtained by means of a two-dimensional un-