Application of a Helmholtz resonator excited by grazing flow for manipulation of a turbulent boundary layer

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Abstract

In most industrial applications involving flow the Reynolds number is typically sufficiently high such that the boundary layer is turbulent. Flow instabilities within the turbulent boundary layer can result in an excessive drag penalty which is considered to be the main parameter affecting the aerodynamic efficiency in numerous applications including aircraft and pipelines. The aim of this research is manipulation of the turbulent boundary layer through the oscillatory flow created by a flow-excited Helmholtz resonator for the purpose of minimising the flow instabilities. Attention has been given here to a cylindrical Helmholtz resonator as a possible alternative flow control device. The energy required to activate the Helmholtz resonator comes from the grazing flow and it can be fitted to existing airframes with minimal manufacturing requirements. Hence it can potentially be an ideal solution for a wall-based flow control device. This research provides an insight into the behaviour of the flow in the vicinity of the resonator and assesses the capability of a flow-excited Helmholtz resonator for reduction of disturbances within the boundary layer.

The excitation of flow in the vicinity of the Helmholtz resonator is associated with both the external pressure fluctuations within the turbulent boundary layer and the acoustic response of the resonator cavity. A model of the relationship between the pressure inside the cavity and the boundary layer was developed based on a momentum balance equation and combination of the vortex sheet with discrete vortex models. A parametric study of the resonator showed that when the orifice length is increased the pressure fluctuations within the resonator are reduced, potentially due to the larger skin friction inside the orifice. To understand the boundary layer features over a flow-excited Helmholtz resonator a Large Eddy Simulation (LES) of the three dimensional flow over a wide range of flow velocities was also conducted. It was demonstrated that when the boundary layer thickness equals the orifice length and is twice the orifice diameter, the flow suction within the orifice is greater than the flow injection area which results in a reduction in the turbulence intensity of up to 10%. Detailed investigation of the characteristics of the turbulent boundary layer downstream of the resonator has also been accomplished through an extensive experimental study in a subsonic wind tunnel with a low turbulence intensity level of 0.5%, for free stream velocities between 15 and 30m/s. Similar to the results of the numerical modelling, the experimental results showed that a resonator with an orifice length equal to the boundary layer thickness modifies near-wall structures such that the intensity of sweep is reduced by up to 5% and its duration by up to 8%. It was also demonstrated that when the orifice diameter approximately equals the thickness of the inner layer, $y^+ \approx 400$, the velocity fluctuations normal to the grazing flow can penetrate the boundary layer, which in turn causes the large eddies to transfer their energy to the smaller eddies within the logarithmic region, resulting in attenuation of turbulence production.

The results of this study provide an improved understanding for the further development of flow-excited Helmholtz resonators as a flow control device, an area that warrants further investigation in the future.

Contents

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Nomenclature

A	cross-section area of the riblets groove (m^2)
c	speed of sound (m/s)
C_q	suction coefficient: $\frac{V_w}{U_\infty}$
d	orifice diameter (m)
D	cavity diameter (m)
f	frequency (Hz)
f_b	bursting frequency (Hz)
F_c	Coriolis force (N)
F_{ext}	force exerted on the fluid inside the orifice (N)
f_n	natural frequency of the resonator (Hz)
f_r	resonance frequency of the resonator (Hz)
h	groove depth (m)
i	resonator mode number, imaginary number $\sqrt{-1}$
K	spring constant (N/m)
k	wavenumber (rad/m)
l	length of the orifice (mm)
L	cavity depth (mm)
l_e	effective length of the orifice (mm)
m	mass of fluid (kg)
Ma	Mach number

n	compliance of the resonator
P_{ext}	excitation pressure (Pa)
P_{res}	resonator pressure fluctuations (Pa)
P_t	acoustic power (W)
q_o	spatially averaged flow rate induced by flow over the resonator orifice (m^3/s)
q_r	spatially averaged acoustic volume flux through the resonator orifice (m^3/s)
R	damping constant
S	cross-section area of the orifice (m^2)
s	groove spacing (m)
St	Strouhal number
t	time (s)
T_{osc}	period of wall oscillation (s)
U, U_∞	mean free stream velocity (m/s)
u	streamwise flow velocity (m/s)
u_a	acoustic particle velocity (m/s)
u_c	convection velocity of the vortices (m/s)
u_{cs}	propagation speed of streaks (m/s)
u_τ	friction velocity (m/s)
T	time period (s)
v_t	local velocity (m/s)
v	cross-stream component of velocity (m/s)
V_c	cavity volume (m^3)
V_w	suction velocity (m/s)
x	indicates the x-direction (streamwise) (m)
y	indicates the y-direction (wall-normal direction) (m)
z	indicates the z-direction (spanwise direction) (m)

Z	spanwise spacing of streaks (m)
Z_c	total input impedance of the resonator (N.s/m^3)
Z_M	acoustic impedance (N.s/m^3)

Symbols

σ	standard deviation
Γ	circulation (m^2/s)
ζ	damping ratio
ω	angular frequency (rad/s)
ω_r	angular resonance frequency (rad/s)
Ω	vorticity (1/s)
ρ	density of air (kg/m^3)
φ	phase lag between the vortical flow and acoustic volume flow (rad)
λ	acoustic wavelength (m)
υ	kinematic viscosity (m^2/s)
δ	boundary layer thickness (mm)
θ	momentum thickness (mm)

Superscripts

$()'$	denotes the fluctuating part of ()
$\overrightarrow{()}$	denotes a vector
$\widehat{()}$	denotes Fourier transform of ()
$+$	denotes time scale ($\frac{\upsilon}{{u_\tau}^2}$) or length scale ($\frac{\upsilon}{u_\tau}$)