The streamwise and spanwise effects of flow-excited Helmholtz resonators on a three-dimensional turbulent boundary layer

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Abstract

This paper evaluates the capability of a cylindrical flow-excited Helmholtz resonator for the manipulation of the disturbances within a three dimensional turbulent boundary layer in the streamwise and spanwise directions. Detailed investigation of the characteristics of the boundary layer downstream of the resonator has been accomplished through an extensive experimental study. The results showed that a reduction in the turbulence intensity of the streamwise velocity fluctuations and sweep events occurs immediately downstream of the resonator but this effect dissipates further away from the resonator orifice. This was hypothesized to be due to thinning of the boundary layer thickness downstream of the resonator in the streamwise direction and weakening of the spanwise vortices generated by the resonator. The results presented in this paper provide an improved understanding for further development of multiple adjacent resonators over an area as a possible alternative system for the purpose of turbulent flow control.

Introduction

At resonance, the large amplitude of the pressure fluctuations within the flow excited by a Helmholtz resonator induces a force into the shear flow to relieve the pressure inside the resonator cavity (Panton and Miller 1975; Nelson et al. 1981; Ma et al. 2009). This process can produce a small velocity pulsation, thereby manipulating the shear layer which is developed over the resonator orifice (Massenzi et al. 2008; Ghanadi et al. 2014a). It was observed that this oscillatory flow can attenuate the instabilities within the turbulent boundary layer downstream of the resonator (Ghanadi et al. 2014b). The Helmholtz resonator can potentially be used as a passive wall-based flow control device since it does not need an external energy source to be activated, and can be tailored to have a high bandwidth. However, it is necessary to identify the streamwise and spanwise extents over which stability improvements are maintained. For this reason, understanding the underlying physics of the flow within the boundary layer in the vicinity of the resonator orifice is of paramount importance. Through an extensive experimental investigation the maximum downstream distances in which a cylindrical flow-excited Helmholtz resonator can reduce the turbulent energy production within the boundary layer have been identified.

Experimental procedure

All measurements have been conducted in a closed-return-type wind tunnel, with a rectangular test section 2m long and a cross-section of 50cm × 50cm. The flow velocity was varied between 0m/s to 30m/s, with a low level of turbulence intensity ranging between 0.3% to 0.7%. An adjustable wall in the test section and a circulation flap downstream of the plate were used to minimize the streamwise pressure gradient along the working section. The pressure variation along the working section was less than ±0.5%. As can be seen in Figure 1, a cylindrical Helmholtz resonator was positioned underneath the flat plate and was set flush to the surface at a distance of 35cm from the leading edge. To ensure a fully developed turbulent boundary layer over the Helmholtz resonator the boundary layer was tripped by a 3mm diameter rod placed close to the leading edge. To characterise the velocity fields in the vicinity of the resonator orifice a hot-wire anemometer with a single wire and minimum thermal effects was utilized. To achieve appropriate temporal resolution of each measurement a sampling rate of 10kHz with a recording time of 10sec was applied.

The parametric study undertaken by Ghanadi et al. (2014b) in the previous experimental investigations showed that almost no excitation of the pressure field occurred when the ratio of the cavity depth (L) to diameter (D) of the Helmholtz resonator is less than 4. It was also observed that when the orifice length (l) equals the boundary layer thickness (δ) and the orifice diameter (d) approaches the thickness of the inner layer of the boundary layer, the resonator can reduce the instabilities within the turbulent boundary layer. Therefore, two different Helmholtz resonators that have these parameters were investigated in this paper (Table 1). As illustrated in Figure 1, three different locations in both the streamwise (ST1 to ST3) and spanwise (SP1 to SP3) directions have been selected to investigate the sustainability of the favourable effect of the resonator on the turbulence structure.

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Results and discussion

To provide a detailed measure of the characteristics of the turbulent boundary layer downstream of the resonators, the averaged turbulence intensity of velocity fluctuations, \( u' \)\( u' \)rms, at different locations in the vicinity of each resonator was compared against the no-resonator case obtained by Marusic et al. (2003). As can be seen in Figure 2(a), in the streamwise direction a significant reduction of up to 16\% in the turbulence intensity occurs immediately downstream of HR1, and can still be observed at ST2 (1.5d). This demonstrates that the maximum extent of the streamwise variation is almost equal to the thickness of the logarithmic region of the boundary layer. However, at the measurement location further away from the trailing edge of the resonator orifice (ST3=3d), the turbulence intensity values within the logarithmic region of the boundary layer are not significantly altered compared with the no-resonator case. The local influence of HR1 on the boundary layer has also been analysed in the spanwise direction. The results presented in Figure 2(b) show that the boundary layer is only modified significantly in the vicinity of the orifice and the instabilities at locations away from the orifice edge (SP2 and SP3) are essentially unaffected. Hence, it was concluded that the favourable effect of this resonator in the streamwise direction is greater compared with the changes in instabilities within the boundary layer in the spanwise direction. Moreover, the area affected by the resonator in spanwise direction is less than for the streamwise direction. The turbulence intensity of the streamwise velocity fluctuations downstream of HR2 was also analysed, and it was observed that the boundary layer is essentially unchanged beyond 1.5d from the resonator orifice in both the streamwise and spanwise directions. The energy of turbulence eddies within the logarithmic region of the boundary layer downstream of both resonators has also been investigated. The result supports the aforementioned conclusion such that at ST1 the large eddies transfer more energy to the small eddies compared with other spanwise and streamwise locations for both of the resonators examined.

To assess the influence of the flow-excited resonator on the structure of the turbulent boundary layer in more detail, it is also useful to analyse the intensity and duration of the sweep events. Using the variable interval time averaging (VITA) technique (Ghanadi et al. 2014b), attenuation of the sweep events was analysed at different spatial locations within the logarithmic region of the boundary layer. Downstream of HR1 at ST1, an 11\% reduction in sweep intensity and a 5\% reduction in sweep duration were observed, with the significantly less reduction further from the resonator orifice at ST2 and ST3. A slight reduction in the intensity and duration of the sweep events also occurs very close to the orifice edge of HR2 (at SP1), although the modification decays at SP2 (1.5d) and SP3 (3d). In the spanwise direction, both resonators cannot attenuate the turbulence energy, consequently the sweep events remain unaltered. The results also demonstrate that increasing the velocity of grazing flow amplifies the generation of the turbulent events and therefore reduces the area affected by the resonators.

It is concluded that through the use of the flow-excited Helmholtz resonator the turbulent boundary layer is only stabilized close to the resonator orifice in both the streamwise and spanwise directions. Hence, by incorporating a second, subsequent and identical resonator downstream of the first, it is anticipated that the stability improvements could be maintained. The results presented in this paper are only the beginning of the development of a novel approach to control the turbulent boundary layer and a significant amount of potential work exists as a result of the conclusions of this research.

References


Table 1: Characteristics of the resonators and their resonance frequencies. The depth and diameter of the cavity are 100 mm and 25 mm in all cases.

<table>
<thead>
<tr>
<th>Helmholtz resonator designation</th>
<th>$l$ (orifice length)</th>
<th>$d$ (orifice diameter)</th>
<th>$f_r$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR1</td>
<td>5</td>
<td>5</td>
<td>398</td>
</tr>
<tr>
<td>HR2</td>
<td>15</td>
<td>10</td>
<td>550</td>
</tr>
</tbody>
</table>

Figure 1: Schematic of cross-section experimental setup and the locations for measurements.

Figure 2: Turbulence intensity profiles within the boundary layer downstream of the resonators at different locations; a) in streamwise direction; b) in spanwise direction. Experimental data (circle), results obtained by Marusic et al. (2003) (solid line).