19th Australasian Fluid Mechanics Conference
Melbourne, Australia
8-11 December 2014

Experimental Investigation of the Application of a Self-excited Cylindrical Helmholtz Resonator for Turbulent Drag Reduction

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Abstract

An experimental investigation has been undertaken to investigate the suppression of the turbulent events within a boundary layer by different Helmholtz resonators. The flush-mounted cylindrical resonators were installed within a flat plate and excited by a fully developed turbulent boundary layer. The characteristics of the oncoming boundary layer and the velocity fluctuations in the vicinity of the orifice were measured using hot-wire anemometry. A 12% reduction in turbulent intensity was observed downstream of the resonator for the case when the ratio of the resonator orifice length to the boundary layer thickness was approximately unity. This was accompanied by 5% reduction in sweep intensity. When the diameter and length of the resonator orifice are approximately equal to the thickness of the inner layer, y^{+}=300, the velocity fluctuations are more positive and spiky resulting in an 11% reduction in sweep intensity. Attenuation of the turbulence production demonstrates the potential of the flow-excited Helmholtz resonator as a novel flow control device.

Introduction

Self-sustained oscillations of the flow within the Helmholtz resonator change the structure of the grazing flow in vicinity of the resonator orifice. Numerous studies have been conducted to control the undesired effects of the flow fluctuations created by a Helmholtz resonator in industrial applications such as aerospace and transportation [3, 13]. However, limited studies exist which focus on using flow induced pulsation of a Helmholtz resonator to reduce the instabilities which naturally occur within the grazing flow [10, 16]. In the present paper, different resonators have been examined for the purpose of suppression of the instabilities within the boundary layer in the vicinity of the resonators. The Helmholtz resonator does not need an external energy source and can be simply fitted to existing airframes. Hence it can potentially be an ideal solution for a wall-based flow control device.

At low Mach numbers a Helmholtz resonator can be excited when one of the instability frequencies within the shear layer equals the resonance frequency of the resonator, f_r [17, 19]. A chain of events occurs when a Helmholtz resonator is excited by the grazing flow; convection of the vortical fluctuations within the shear layer, interaction of the vortices with the trailing edge of the orifice, and creation of new instabilities within the oncoming flow [20, 21]. In a flow-excited Helmholtz resonator, strong pressure fluctuations within the resonator change the velocity field within the shear layer [6, 9, and 22]. The characteristics of the boundary layer affect the excitation of the resonator. It has been observed that when the diameter of eddies in the flow is around twice the resonator orifice diameter, the boundary layer can excite the resonator [23]. The geometry of the Helmholtz resonator also has significant impact on the flow fluctuations inside and outside the resonator, such that a streamwise slot reduces the pressure fluctuations within the resonator compared to a circular orifice [24]. It was also observed that the vortices enter the resonator neck and travel close to the trailing edge of an orifice with sharp edges [5]. In this study the resonator orifice also has sharp edges and its diameter, d, is less than the boundary layer thickness, δ, such that $0.2 < d/\delta < 1$.

Turbulent drag reduction has also gained renewed interest due to the significance of its effect on many engineering applications [7, 14]. It was observed that the movement of high momentum fluid toward the surface (sweep), caused by quasi-streamwise vortices, is responsible for production of the turbulent kinetic energy within the boundary layer [15]. Therefore attenuation of sweep events leads to a reduction in energy production within a turbulent boundary layer. Weakening of the quasi-streamwise vortices has been achieved through several techniques, including using streamwise longitudinal microgrooves over the surface, and generating travelling waves with plasma actuators or wall oscillations [1, 8 and 12]. In this study, manipulation of the sweep events downstream of a flow-excited Helmholtz resonator has been investigated. The next sections detail the changes within the turbulent boundary layer in the downstream vicinity of the resonator. The results provide an insight into the potential of a Helmholtz resonator as a flow control device.

Experiments

The experiments comprised a cylindrical Helmholtz resonator mounted flush with a flat plate which has a super-elliptical leading edge to eliminate possible separation and an adjustable angle trailing edge flap to ensure that the stagnation point is on the measurement side of the plate. The grazing flow was generated by a closed-return-type wind tunnel in the subsonic regime, with a low level of turbulence intensity, 0.5%. A 3mm diameter wire trip was also used to establish a fully developed turbulent boundary layer over the resonator. Using a Constant Temperature hotwire anemometer the streamwise velocity fluctuations directly downstream of the resonator, 100 wall units from the downstream edge of the resonator orifice, were measured (Figure 1). The wind tunnel was used to calibrate the probe and an error of less than 7% was observed for low velocities in the calibration curve.

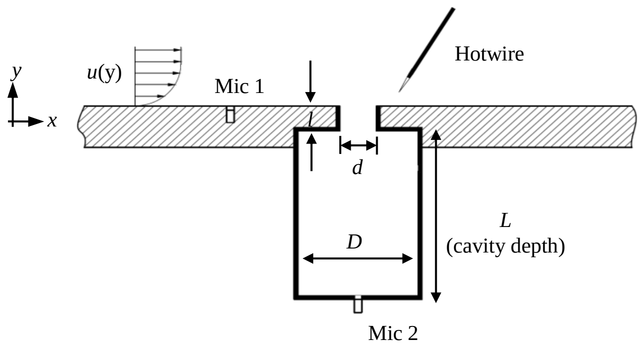

Figure 1. Cross-section of the arrangement of the hotwire and microphones in relation to the cylindrical Helmholtz resonator (l is the orifice length and D is the cavity diameter).

Two microphones, one located upstream of the orifice and the other inside the cavity, were used to measure the resonance frequency of the resonator and the pressure fluctuations within the resonator. The parametric study conducted by Ghanadi et al. [10] showed that when L/D = 4, the instantaneous pressure field within the cavity has a maximum peak very close to the resonance frequency. Therefore, in this paper four Helmholtz resonators with different orifice shapes, as presented in Table 1, have been investigated.

Helmholtz resonator designation	Resonator parameters		f_r (Hz)
	l (mm)	d (mm)	
HR1	5	20	712
HR2	5	5	402
HR3	2	10	605
HR4	15	10	550

Table 1: Resonance frequency and geometry of resonators [10]. Cavity depth is L=100mm and cavity diameter is D=25mm, in all cases.

The pressure spectra within the resonator also showed that when the flow velocity, U_∞, is less than 15m/s no excitation occurs and thus all measurements have been conducted for 15m/s $< U_\infty <$ 30m/s. Consequently the thickness of the turbulent boundary layer and the Reynolds number based on the friction velocity were in the range of 17mm $< \delta <$ 21mm and 873 $< \mathrm{Re}_\tau <$ 1568, respectively.

Modification to Turbulent Boundary Layer

A reduction in the velocity fluctuations within the logarithmic region of the boundary layer is a common feature in most drag reduction techniques [11, 12]. In this paper the averaged streamwise velocity fluctuations downstream of each resonator was also compared with the no-resonator case. The results show that when the orifice diameter is equal to the boundary layer thickness, $d \approx \delta$, the peak turbulence intensity is increased by up to 24% compared with the flat plate with a resonator at Re_τ= 873 (Figure 2a). Downstream of this resonator, the instabilities within the logarithmic region are reduced by further increasing the flow velocity. Interestingly, Figure (2b) shows that at Re_τ= 873, a 16% reduction in velocity fluctuations occurs downstream of the orifice, which has a diameter approximately equal to the inner layer of the boundary layer, $d \approx 0.2\delta$, although increasing the Reynolds number to Re_τ=1568 amplifies the turbulence intensity by up to 26%. The results also demonstrated that the reduction in the turbulence intensity downstream of HR1 is maintained up to 200 wall units and 100 wall units in the streamwise and spanwise directions, respectively. It was also observed that the orifice length also has a significant effect on the structure of the boundary layer. Downstream of HR3, which has the shortest orifice length of the resonators considered, $l \approx 0.1\delta$, the turbulence intensity is slightly increased (Figure 2c). It should be noted that in experiments conducted by Ghanadi et al. [10], the pressure fluctuations within this resonator have the maximum peak value compared with the other resonators. As can be seen in Figure (2d), at $\mathrm{Re}_\tau = 890$ a 12% reduction in the streamwise velocity fluctuations occurs downstream of the orifice, which has a length approximately equal to the boundary layer thickness, $l \approx \delta$. It is postulated that skin friction inside the longer orifice decreases the pressure fluctuations within the resonator and results in increase in the suction area in the vicinity of the resonator. However, increasing the Reynolds number to $\mathrm{Re}_\tau =$ 1785 causes the turbulence intensity to remain unchanged downstream of this resonator. It was observed that the boundary layer is essentially unchanged beyond 100 wall units from the orifice of HR4 in both the streamwise and spanwise directions. The reduction of the turbulence intensity for both HR2 and HR4 reveals that they have capability to modify the turbulent boundary layer and thus the further analysis has been focused on the turbulent boundary layer downstream of these two resonators.

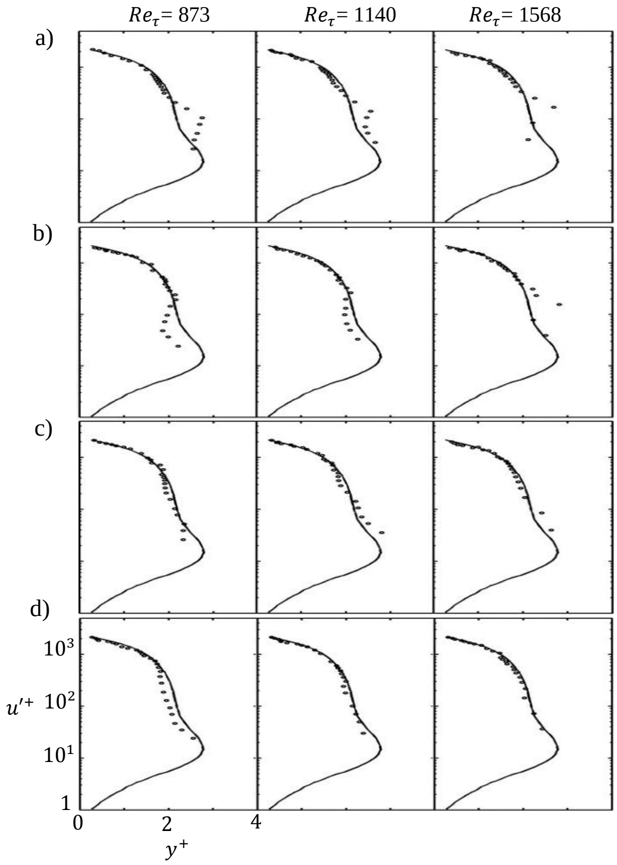

Figure 2. Streamwise turbulence intensity profiles within the boundary layer downstream of the resonators; (circle) experimental data, (line) results obtained by Marusic and Kunkel [18] for a flat plate, a) HR1, b) HR2, c) HR3 and d) HR4.

Using the Variable-Interval Time-Averaging (VITA) technique [2], changes in the structure of the turbulent boundary layer have been investigated with high fidelity. In this method a small window is moved across the streamwise velocity fluctuation signal and when the ratio of variance of the small window to the variance of the entire signal is larger than a threshold value, sweep and ejection events, are detected. The size of the small window was set to ${T_w}^+ = T_w {u_\tau}^2/\nu = 10$ and the threshold value to 1.2. In the most effective drag reducing flows, such as spanwise wall oscillation and travelling wave techniques [4, 25], attenuation of sweep events leads to significant reduction in turbulence energy production. In this study, the changes in the structure of these events downstream of HR2 and HR4 have also been investigated. To analyse the structure of each sweep at one location within the boundary layer an average of VITA events is required. The average has been calculated in a small window of size T^+_{ave}= -20 to 20 centred at the maximum value of the velocity gradient.

In the averaged VITA events, the peak-to-peak value of the results demonstrate that the intensity and the time difference between the peaks reveals the duration of the sweep events. Figure 3 shows the averaged sweep events downstream of HR2 and HR4 at y^+= 35 when Re_τ= 873. It can be seen in Figure (3a) that there is an 11% reduction in intensity and a 5% reduction in the duration of sweep events within the inner layer of the boundary layer downstream of HR2. When the boundary layer thickness is close to the orifice length, as in HR4, the results indicate that the sweep intensity at y^{+}= 35, is reduced by up to 5% while the duration is almost unaltered (Figure 3b).

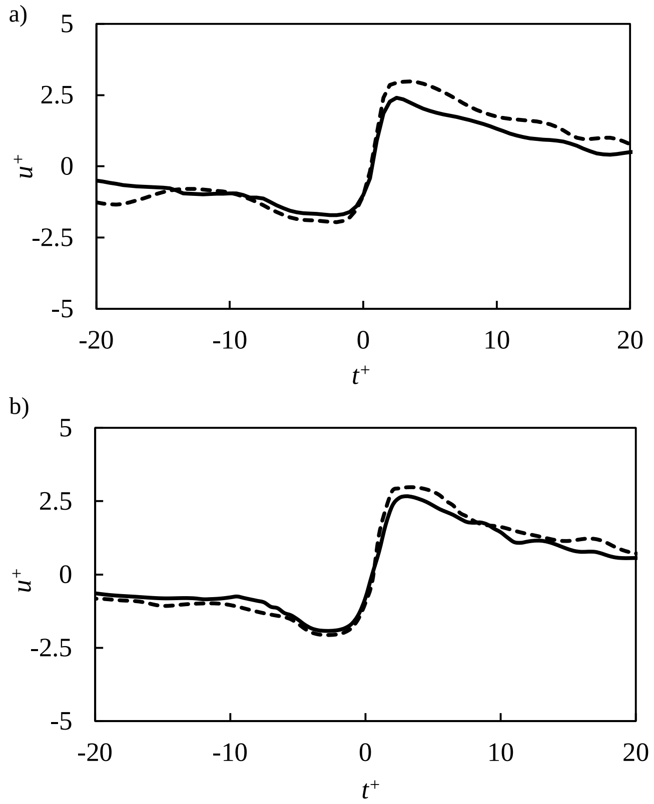

Figure 3: Averaged VITA sweep events, (line) with and (dash line) without Helmholtz resonator at y^{+}= 35 when $\mathrm{Re}_{\tau}=873$; a) HR2 and b) HR4.

The effect of the flow velocity on the effectiveness of the resonators has also been investigated. Figure 4(a) reveals that increasing the Reynolds number to Re_{τ}= 1140 has only a small effect on the sweep events such that the sweep intensity downstream of HR2 is reduced by approximately 7%; however, the duration remains unaltered. Increasing the flow velocity decreases the effectiveness of HR4, such that a maximum of only 3% to 4% reduction occurs in the intensity and duration of sweep events (Figure 4b).

Attenuation of the turbulent events has also been analysed by examination of the probability density function (PDF) of the streamwise velocity fluctuations. The PDFs reflect the changes in skewness and kurtosis of the u-component of the flow velocity. An increase in skewness and kurtosis within the logarithmic region is one common feature of most methods to control the turbulent boundary layer [4, 11]. As shown in Figure 5, there is a long tail of positive probability downstream of both HR2 and HR4, resulting in spiky excursions of the velocity signal within the inner layer of the boundary layer. It should be noted that increasing the flow velocity to either Re_{τ}= 1140 or 1568 reduced the effectiveness of the resonator to increase the skewness and kurtosis. The reduction in the duration and intensity of the sweep events downstream of HR2 and HR4 was observed over the interval $30 < y^{+} < 100$ which demonstrates that the resonators can modify the boundary layer within the lower part of the logarithmic region.

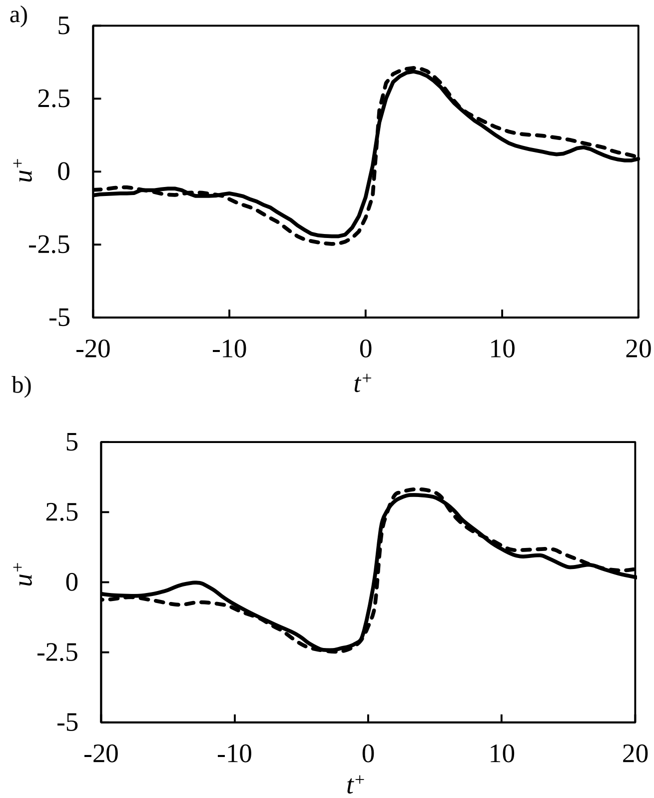

Figure 4: Averaged VITA sweep events, (line) with and (dash line) without Helmholtz resonator at y^{+}= 35 when $\mathrm{Re}_{\tau}=1140$; a) HR2 and b) HR4.

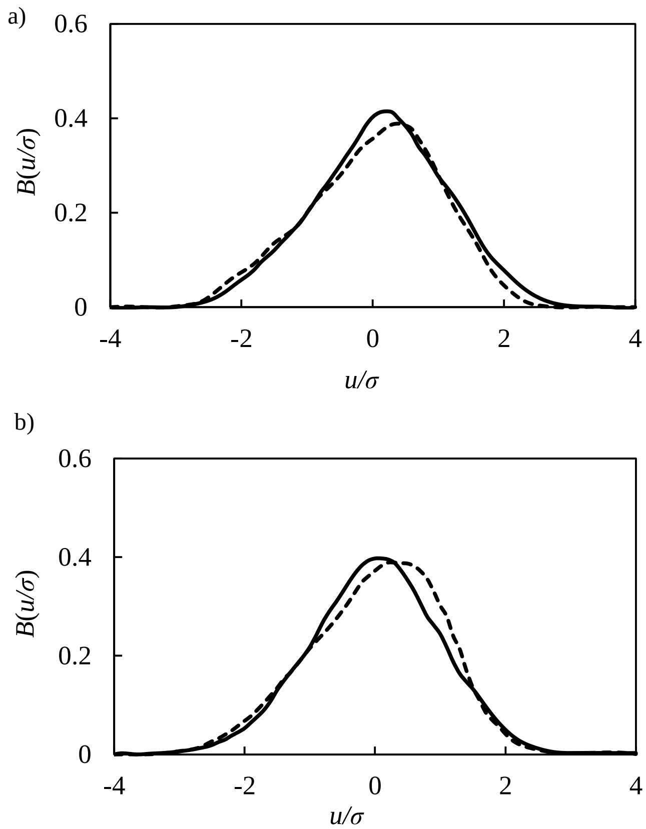

Figure 5: Probability density function of streamwise velocity fluctuations at $y^{+}=35$ when $\mathrm{Re}_{\tau}=873$, (line) with and (dash line) without Helmholtz resonator; a) HR2 and b) HR4.

Summary and Conclusion

In this study, a cylindrical flow-excited Helmholtz resonator has been investigated as a possible simple device for turbulent boundary layer control. Flow pulsations created by the resonator can manipulate the near-wall flow, and hence, it may be an appropriate device for wall-based flow control. The present study provides an insight into how the flow behaves in the vicinity of the resonator and assesses the capability of a flow-excited Helmholtz resonator to reduce innate disturbances within the boundary layer. Results showed that when the orifice diameter is approximately equal to the thickness of the inner layer, y^{+}= 300, the average streamwise velocity fluctuation is reduced by up to 16%. This was thought to be due to penetration of the cavity flow within the logarithmic region of the boundary layer. Turbulence energy production was also attenuated through a reduction in the intensity and duration of the sweep by up to 11% and 5%, respectively. Disrupting the instantaneous velocity fields was also investigated within the boundary layer downstream of the resonator with orifice diameter close to the boundary layer thickness. Modification of sweep events, and a slight increase in skewness and kurtosis, demonstrates that this resonator can also attenuate the turbulence energy production. This novel approach identifies a set of parameters for a flow-excited Helmholtz resonator to stabilize the turbulent boundary layer. These investigations are the first stage in the development of a flow-excited Helmholtz resonator as a flow control device, an area that warrants further investigation in the future.

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