Interaction of a flow-excited Helmholtz resonator with a grazing turbulent boundary layer

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ABSTRACT

This study focuses on the characteristics of the flow oscillations induced by various Helmholtz resonators which are excited by a fully developed turbulent grazing flow. A full experimental investigation has been conducted in a subsonic wind tunnel with a low turbulence level. Detailed fluid dynamic and acoustic analyses of the flow inside the wall-mounted resonator and within the shear layer have been performed. The results reveal that the degree of excitation of the pressure and velocity fields is related to the resonator geometry, and that the pressure fluctuations within the resonator are most sensitive to the orifice length for the range of geometric parameters considered. Interestingly, the turbulent length scale over the orifice with the minimum diameter was found to be higher than the other cases investigated. This in turn causes a modification to the turbulent structures downstream of the resonator. The turbulence intensity and energy spectra of the velocity fluctuations within the turbulent boundary layer downstream of the resonators demonstrate that in a specific velocity range certain resonators have the potential to modify the flow instabilities within the turbulent boundary layer. The results provide information on the relationship between the pressure and velocity fluctuations within and downstream of the resonator and the geometric characteristics of the resonator and the properties of the grazing flow.

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1. Introduction

The pressure oscillation induced by the flow over a Helmholtz resonator has gained renewed interest due to the significance of its effect on many engineering applications [7,21,39]. These effects can be desired or undesired; an example in the aerospace industry is aircraft wheel-wells which are a strong source of sound during landing [24]. Flow induced pulsation of a Helmholtz resonator can also be observed in cars with an open sunroof, which changes the airflow behaviour both inside and outside the cabin [34]. Under certain conditions self-sustained resonance occurs and the airflow inside the cavity forces the shear layer that develops over the orifice. Despite such an effect on numerous applications, the behaviour of the interacting flow-excited Helmholtz resonator and the flow over the orifice is not well understood. The current investigation focuses on cylindrical Helmholtz resonators of various size excited by turbulent grazing flow with low subsonic Mach number, and subsequent evaluation of the aeroacoustic properties of the flow field within the vicinity of, and downstream of, the resonator orifice. The analysis provides information on the relationships between the pressure and velocity fluctuations within, and downstream of, the resonator and the characteristics of the grazing flow and the resonator geometry. The investigations are also relevant for the application of drag reduction.

Helmholtz resonators consist of a cavity with a fixed volume of compressible fluid coupled to the environment through a short neck (or orifice). The spring effect of the flow inside the cavity allows the volume of the air to compress and expand [1,35,38,40]. There exists a large number of publications which demonstrate that the flow instabilities within the shear layer which develop over the orifice are primarily responsible for excitation of the resonator [10–19]. There are, however, a number of different hypotheses for the shear layer behaviour over the orifice of a Helmholtz resonator. It has been shown that, depending on the characteristics of the resonator and the grazing flow, there are different shear layer developments [17,37,4,13]. Fig. 1 shows one example of the flow behaviour over the orifice in which the shear layer has a sheet-like motion until it reaches the mid point of the orifice and then breaks down into quasi-periodic vortices which travel to the trailing edge of the orifice. The pressure waves produced due to interaction of the vortices with the trailing edge of the orifice propagate back toward the orifice leading edge, which triggers the release of the next vortex. The pressure fluctuations inside the cavity are increased when the frequency of these
instabilities approaches the resonance frequency of the resonator. This process generates a highly forced response of the air flow within the cavity into the shear layer to relieve the pressure inside the resonator. The flow–excited resonator thus changes the characteristics of the flow over the orifice and downstream of the resonator.

Early experiments were carried out by Rossiter and Britain [36] who investigated the flow excited resonance and acoustic feedback of shallow cavities for the grazing flow of subsonic or transonic Mach numbers. They determined a semi-empirical relationship for the instability frequencies within the shear layer as:

\[ \text{St}_i = \frac{fi}{U} = \frac{i - \alpha}{M + 1/k} \quad \text{for} \quad i = 1, 2, 3, \ldots \]  

where St represents the Strouhal number, k is a coefficient based on the convection velocity of the vortices over the orifice and \( \alpha \) is experimentally determined and is a function of length to depth ratio of the cavity. A number of investigations have been undertaken to complement this relationship, both experimentally and analytically. For example, Bilanin and Covert [3] suggested a mathematical model to calculate the deflection of the vortex sheet over the orifice. They concluded that \( \alpha \) is the phase lag (typically 0.25). The effect of the shear layer thickness over the orifice has been considered by Tam and Block (1978). They developed a model based on experimental results from Michalke [27] and concluded that the ratio between the turbulent boundary layer thickness and the cavity depth plays an important role in determining the discrete frequencies of oscillation. Overall good agreement was observed between their model and experimental results at low Mach numbers.

There is an immense body of literature on the prediction of the flow behaviour around the resonator orifice using various models. In the study by Nelson et al. [29] the velocity fields within the shear layer were assumed to be a superposition of two parts, the first purely vortical flow and the second a potential flow. The vortical component was calculated assuming a constant circulation strength model and the potential component estimated from models of the frequency response of the resonator. The pressure fields inside and outside the cavity have been calculated by Howe [16] who used an appropriate Green’s function for a linear perturbation of instabilities over the opening of the resonator. It was assumed that there is a vortex sheet across the opening and the Strouhal number of the unstable motion of this sheet was estimated. It was concluded that the Strouhal number is weakly related to the aspect ratio of the cavity. Using a modified Lattice–Boltzmann equation the pressure field within the shear layer has also been calculated by Mallick et al. [23]. The predicted pressure spectra did not agree with experimental results due to the effects of boundary layer thickness on the convection velocity of the vortices passing over the orifice; therefore they multiplied the velocity of the grazing flow by a factor of 0.7 which allowed them to predict the pressure with good agreement. A practical analysis technique called feedback loop analysis has been developed to predict the

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**Nomenclature**

- \( c \): speed of sound (m/s)
- \( c_f \): friction coefficient
- \( d \): orifice diameter (mm)
- \( f_i \): instability frequency (Hz)
- \( f_r \): resonance frequency of the resonator (Hz)
- \( H \): Shape factor
- \( i \): acoustic mode index
- \( k \): convection velocity coefficient
- \( K \): Launder acceleration term
- \( l \): length of the orifice (mm)
- \( l_e \): effective length of the orifice (mm)
- \( L \): cavity depth (mm)
- \( l_u \): streamwise turbulent length scale (mm)
- \( M \): Mach number
- \( \text{Re}_f = \frac{u_i}{v} \): Reynolds number based on friction velocity and boundary layer thickness
- \( \text{Re}_f(t) \): temporal autocorrelation function
- \( \text{Re}_\theta = \frac{U}{\theta} \): Reynolds number based on free stream velocity and momentum thickness
- \( S \): cross-sectional area of the orifice (m²)
- \( V_c \): cavity volume (m³)
- \( Sk \): skewness
- \( \text{St} \): vortex shedding Strouhal number
- \( t \): time (s)
- \( U \): free stream velocity (m/s)
- \( U^+ = \frac{U}{\nu} \): scaled velocity
- \( U^*, \text{rms} \): non-dimensional averaged turbulence intensity
- \( V \): flow velocity perpendicular to the grazing flow (m/s)
- \( y^+ = \frac{y}{\nu} \): scaled viscous length
- \( \alpha \): phase delay between vortices forcing and acoustic feedback
- \( \nu \): kinematic viscosity (m²/s)
- \( \delta \): boundary layer thickness (mm)
- \( \theta \): momentum thickness (mm)

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![Flow behaviour inside and outside a cylindrical Helmholtz resonator with a turbulent boundary layer grazing flow.](image)

**Fig. 1.** Flow behaviour inside and outside a cylindrical Helmholtz resonator with a turbulent boundary layer grazing flow.
resonance frequency and amplitude at resonance of the flow-excited Helmholtz resonator [6,26]. The feedback loop analysis, using describing functions for flow component and acoustic component, captured the interaction between the oscillatory flow and the resonator [20,22].

The flow behaviour around the Helmholtz resonator has also been investigated experimentally. For example, Panton and Miller [33] placed nine different Helmholtz resonators in the fuselage of a glider to excite the resonators with a turbulent boundary layer. To measure the velocity field hotwire anemometry was utilized within the resonator neck. The pressure fluctuations interior and exterior to the cavity were measured by surface mounted microphones placed on the wall surface and inside the cavity. It was observed that the convection velocity of vortices within the shear layer is related to the turbulent boundary layer thickness. They also concluded that the eddies within the shear layer impose a frequency close to the resonant frequency of the resonator when their size is around twice the orifice diameter. Flow measurements downstream of the resonator showed that the boundary layer is only changed in the vicinity of the orifice and the downstream surface pressure spectra were unaffected. The fluid dynamics of a laminar shear layer over a two-dimensional resonator was visualized by Ronneberger [35] who proved that the interaction of the shear layer with the trailing edge of the orifice has a smaller effect than the model which had been developed to explain the effect of grazing flow on the acoustic impedance of small orifices. The characteristics of the Helmholtz resonator were also varied by Panton [32] and it was observed that the ratio of the cavity depth to the boundary layer thickness is directly related to the peak value of the pressure inside the cavity. The effects of the neck geometry and the shape of the upstream, downstream and interior edges of the cavity on excitation of Helmholtz resonators were also investigated in detail by Dequand et al. [8]. It was observed that the pressure fluctuation amplitude is highly dependent on the profile of upstream edge of the orifice such that the vortex path remains far from the downstream edge for the chamfered upstream edges. However, the orifice with a sharp upstream edge causes the vortex path to enter the neck and pass close to the downstream edge. Flow excited Helmholtz resonators have also been investigated experimentally by Nelson et al. [30] who used Laser Doppler Velocimetry to measure the amplitude of the fundamental streamwise and transverse components of the velocity fluctuations within the shear layer. It was observed that the boundary layer rolled up into discrete vortices which convected to the downstream edge of the orifice. However, Chatellier et al. [5] using Particle Image Velocimetry (PIV) found that the self-sustained oscillations of the cavity flow arise from an unstable mixing layer and not from shedding vortices. The influence of the upstream turbulent boundary layer thickness on the resonator behaviour has also been demonstrated [2]. It was concluded that a thicker boundary layer is associated with a large decrease in the sound pressure level and a significant increase in the pressure loss. The flow-acoustic coupling within the unstable shear layer over six flow-excited Helmholtz resonators at low subsonic Mach number was investigated by Massenzo et al. [24]. It was observed that when strong excitation occurs, the power spectral density of the pressure inside the resonator, and the streamwise and wall normal velocity fluctuations over the orifice all have a fundamental peak around the resonance frequency of the resonator. A complete representation of the fluid dynamic behaviour of the shear layer over the orifice has been provided using PIV measurements [22] and it was shown that the hydrodynamic forcing of the vortices within the shear layer by flow inside the cavity increases for a specific range of grazing flow speed.

The present study details the pressure fluctuations inside the resonator and within the boundary layer within the upstream and downstream vicinity of the resonator when excitation occurs. This is followed by an investigation of the vertical velocity fluctuations of the turbulent grazing flow passing across the orifice, for various resonator sizes. Moreover, the streamwise velocity distributions downstream of the resonators are analysed. The analysis provides the ability to investigate the potential of Helmholtz resonators to amplify the flow instabilities which is useful for flow control purposes.

2. Experimental arrangement

In the present investigation the resonator was placed underneath a flat plate which was installed in a closed-return-type wind tunnel with a rectangular test section of 50 cm × 50 cm and a length of 2 m. The test section side walls diverge with respect to the centreline to maintain zero streamwise pressure gradient along the working section. However, owing to the parallel installation of the ceiling wall and the flat plate, there was a less than 9 Pa pressure drop over the test section. The Launder acceleration term (K) is considered to be a suitable measure of the influence of the pressure drop on the results obtained at the measurement section [25], is going by:

\[
K = \frac{\gamma}{U^2} \frac{dU}{dx},
\]

where \( K \) is the kinematic viscosity, \( U \) is the streamwise velocity. The small value of \( K \) (less than \( 7.68 \times 10^{-9} \)) indicates that the flow acceleration does not have a considerable effect on the results. The walls and ceiling were made of Plexiglas and the plate was made of fibreboard to allow easy adjustment for different models and probes. As shown in the schematic of the experimental arrangement in Fig. 2, the flat plate has a super-elliptical leading edge to eliminate possible separation. It has also an adjustable angle trailing edge flap of 0.20 m in length which can be positioned to ensure that

![Fig. 2. Schematic of the experimental setup.](image-url)
the stagnation point is on the measurement side of the plate and the boundary layer is developed smoothly. The tunnel inlet has screens to manage the flow and a contraction at its outlet to provide a uniform flow upstream of the test section. The free stream velocity was in the range of 2–30 m/s with a low level of turbulence, between 0.3% and 0.7%. A delay of 20 s was applied between measurements at different speed increments to ensure the wind tunnel maintained a constant free stream velocity. The boundary layer was tripped by a wire of 3 mm in diameter located 14 cm from the leading edge to establish a low Reynolds number fully developed turbulent boundary layer flow. The flush mounted cylindrical resonator was positioned 35 cm from the leading edge. It has a cavity with an adjustable floor such that the volume of the resonator can be varied over the range of 0.01–0.05 m³ for a cavity diameter of 25 mm. Four circular orifices with various lengths and diameters were also used to investigate the sensitivity of the results to the orifice geometry.

To investigate the flow behaviour inside and outside the resonators, both instantaneous pressure and velocity fields have been determined and the repeatability of each measurement was tested. The pressure fluctuations around the orifice and inside the resonator were measured by four 1/8" G.R.A.S type 46DD microphones. These low sensitivity microphones can obtain data at high sound pressure levels and high frequencies up to 174 dB (P_ref = 20 µPa) and 140 kHz, respectively. The microphones have been arranged as shown in Fig. 3 to identify the effects of the resonator on the pressure fields within the boundary layer, very close to the orifice edge and inside the cavity. As indicated in Fig. 3 the characteristics of the incoming boundary layer and the velocity fluctuations in the vicinity of the orifice were also measured using an IFA 300 constant temperature hot-wire anemometer. This type of probe has a single platinum-plated tungsten wire which has a diameter of 5 µm and has an active length of 1.25 mm. The probe was operated in constant current mode at 0.2 mA with an overheat ratio of 1.8 and an operating temperature around 230 °C. This minimises the sensitivity of the probe to ambient temperature changes and the thermal conductivity of the surface. The sampling rate of up to 10 kHz and recording time of 10 s was applied for obtaining hotwire data to ensure suitable temporal resolution for the measurements. The probe was calibrated using the wind tunnel and the nonlinear fitting curve showed an error less than 7% for low velocities.

Details of the experiments including a description of the measurements of resonance frequency of the resonators are discussed in the next section. This is followed by analysis of the pressure and velocity spectra to determine the characteristics of the flow around the flow-excited resonator. In the subsequent sections the effect of resonators on the turbulent boundary layer are also highlighted.

3. Characteristics of the resonator and the grazing flow

To measure the value of the resonance frequency of the resonators a loudspeaker with a 100 mm diameter was placed at the inlet of the test section to generate a white noise signal. Fig. 4a displays the transfer function between the reference microphone, which was positioned close to the loudspeaker, and the microphone located inside the cavity in absence of the grazing flow. The frequency of the resonance, 605 Hz, is indicated by the peak in the magnitude of the transfer function and the 180° change in phase.

The measured resonance frequencies are in relatively good agreement with the expected values obtained using the empirical formula [15,33]:

\[ f_r = \frac{c}{2\pi} \sqrt{\frac{S}{L (V_c + 0.33L^2)}} \]  

(3)

where \( c \) is the speed of sound, \( l_e \) is the effective length of the orifice, \( L \) is the cavity depth, \( S \) cross-section area of the orifice and \( V_c \) is the cavity volume. Four different orifices were employed with three different cavity depths to yield a total of twelve Helmholtz resonator configurations. Table 1 presents the geometric parameters of the resonators, theoretical results for \( f_r \) which were calculated using Eq. (3) and measured resonance frequency. The resonator dimensions have been chosen to achieve a resonance frequency in the range of 400–2200 Hz.

To characterize the grazing flow in vicinity of the resonator, the velocity distribution within the incoming turbulent boundary layer was measured using the hotwire. As illustrated in Fig. 5 the instantaneous velocity field was acquired near the orifice for four profiles: three profiles for the characterization of the turbulent boundary layer upstream (P1) and downstream of the orifice (P3 and P4), and one profile (P2) for the \( y \) component of the velocity within the shear layer that develops over the resonator orifice.

To verify that the incoming flow near the surface is a fully developed turbulent boundary layer, the mean and fluctuating velocity profiles scaled by friction velocity at P1 have been compared with the experimental data of Harun et al. [14].
shown in Fig. 6 the profiles are comparable in the logarithmic region of the boundary layer which demonstrates that a fully developed turbulent boundary layer with zero pressure gradient exists within the flow upstream of the resonator orifice.

The velocity fields around the resonator have been measured for three different free stream velocities; 16, 21 and 28 m/s. The upstream flow parameters at P1 are summarized in Table 2.

To observe the features of the flow fields inside and outside of the flow-excited resonator, the pressure and velocity fluctuations were measured and investigated as described in Sections 4 and 5, respectively.

4. Pressure fluctuations in presence of grazing flow

The measured instantaneous pressure fluctuations inside and in the vicinity of the resonator in the presence of grazing flow are described in this section. The power spectral density (PSD) of the pressure was obtained using a Hanning window and a 29 point FFT and 50% overlap when averaging. Pressure spectra were measured for a range of free stream velocities, however no peak was observed in the spectra when the velocity was in the range of 2–15 m/s. Therefore all investigations in the present study are for a grazing flow velocity of greater than 16 m/s. The PSD difference between the internal and external pressure fluctuations obtained using Mic 1 and Mic 2 was investigated rather than measurement of the frequency response function because there is almost no coherence between these two pressure measurements. In the first step, the sensitivity of the pressure fluctuations to the cavity depth was examined at a flow speed of $U = 23$ m/s. It can be seen from the results shown in Fig. 7 that the maximum pressure level occurs for all resonators when $L/D \approx 4$ and the peak value decreases for other cavity depths. The values of the peak frequencies are in all cases very close to the resonance frequency of each resonator. It was also observed that the pressure fluctuations inside the HR3 resonator are very sensitive to the cavity depth because there is a considerable difference of 18 dB between the measured maximum and minimum peak values for the three cavity depths investigated.

The characteristics of the orifice also have a considerable impact on the pressure fluctuations inside the resonator. To understand these effects, the free stream velocity was fixed at 18 m/s and four different orifice configurations were examined. As discussed, for all
of the resonators considered the maximum pressure fluctuation occurs when $L/D = 4$, and hence further measurements were carried out with this fixed cavity depth. Fig. 8(a) shows a comparison of the PSD pressure difference for a fixed resonator cavity and orifice length, and indicates that the maximum value of PSD pressure difference is obtained with the larger orifice diameter. The difference of 5 dB between the magnitude of the peaks indicates that the sensitivity of the pressure fluctuations to the orifice diameter is not significant. Fig. 8(b) shows a comparison of the PSD pressure difference for a fixed resonator cavity depth and orifice diameter, and shows that the length of the orifice is another parameter which alters the resonator pressure oscillations. As can be seen in Fig. 8(b), increasing the orifice length reduces the pressure fluctuations inside the resonator. The gap of 19 dB between the peaks indicates that orifice length has a significant effect on pressure fluctuations inside the resonator.

The influence of the boundary layer thickness on the self-excitation phenomenon was investigated for a range of velocities. It should be noted that at resonance, the air flow inside the cavity is significant resulting in a high pressure amplitude very close to the natural frequency of the resonator. At resonance, the instabilities within the shear layer force the shear layer into the cavity thus increasing the pressure. To relieve this high-amplitude pressure, the flow within the cavity forces the shear layer out of the orifice. This process changes the characteristics of the boundary layer in the vicinity of the orifice. In the present study the effects of the resonators on the grazing flow were considered when the high-amplitude pressure fluctuations inside the resonator occur. Therefore all pressure and velocity measurements in this study have been carried out when $L/D = 4$. To investigate the pressure changes inside the resonator, the difference between the PSD of the pressure inside the cavity and the PSD of the pressure within the incoming turbulent boundary layer has been investigated. It was found that the maximum amplitude of the pressure fluctuation occurs when the boundary layer thickness is very close to the orifice diameter (Fig. 9a). As shown in the figure the maximum value of the PSD at a boundary layer ratio of $d/d = 0.98$ is 5 dB higher than of $d/d = 0.85$. Fig. 9b reveals that when the boundary layer thickness is greater than the orifice diameter, its impact on the pressure fluctuations within the cavity is reduced. The orifice length has also considerable impact on the maximum value of the pressure fluctuations. As shown in Fig. 9c, when the orifice length is reduced to 0.1

![Fig. 7. PSD difference between pressure fluctuations internal and external to Helmholtz resonator for a range of cavity lengths; (a) HR1, (b) HR2, (c) HR3 and (d) HR4.](image)

![Fig. 8. Effects of the orifice diameter and length on the resonator pressure spectrum; (a) sensitivity to the orifice diameter and (b) sensitivity to the orifice length.](image)
of the boundary layer thickness, the maximum value of the pressure fluctuations occurs, which is around 34 dB. As the boundary layer thickness is close to the orifice length the pressure fluctuations are reduced (Fig. 9d).

5. Velocity field within the boundary layer around the orifice

To better understand the interaction of the turbulent boundary layer with the flow inside the cavity and orifice edges, turbulent length scale and $y$ component of the instantaneous streamwise velocity over the orifice has been investigated. It follows by analysis of the instabilities within the boundary layer downstream of the resonators.

5.1. Characteristics of the shear layer

The flow behaviour at location P2 was characterized using the hotwire. In the first step the streamwise turbulent length scale at the mid-point of the orifice was measured. Considering Taylor's
frozen turbulence hypothesis, the length scale is the longest correlation distance between two points within the shear layer and it was shown that this length can be determined by using autocorrelation function as \[ l_u = \frac{U}{R_{uu}} \frac{\int R_{uu}(0) \, dt}{\int R_{uu}(0) \, dt} \] where \( l_u \) is the streamwise turbulent length scale and \( R_{uu} \) is the temporal autocorrelation function. In the present study the turbulent length scale also has been measured using the autocorrelation function at P2. In order to integrate in a finite domain, the integration time is from \( t = 0 \) to the first zero crossing of the autocorrelation function. As can be seen in Fig. 10, the sensitivity of the length scale to the free stream velocity is higher for HR2 and HR4 than other the configurations. The results indicate that with increasing orifice diameter the turbulent length scale is reduced significantly. It was also observed that the relationship between the turbulent length scale and orifice diameter for HR3, which was strongly excited by the flow, is the opposite of the other cases. A significant difference between the length scales for HR3 and HR4 at \( Re_s = 1140 \) indicates that the value of the length scale is a function of the orifice length and free stream velocity.

In order to understand the effects of the resonators on the behaviour of the shear layer, the flow velocity in the y direction was also considered. Fig. 11 shows the maximum and minimum mean y component of the velocity at the mid-point of the orifice. It can be seen that at \( Re_s = 1568 \), the resonator with highest orifice diameter, HR1, imposes more force on the air flow inside the cavity to inject it into the grazing flow. Therefore the injection of the flow occurs over the HR1 with \( V_{\text{max}} = 4.6 \, \text{m/s} \). Conversely, in the resonator with higher orifice length, HR4, the suction value is higher than the injection throughout the velocity range.

Spectral analysis of the velocity fluctuation perpendicular to the grazing flow at P2 was also considered. To this end the power spectral density (PSD) of V for all the resonators has been calculated. In the calculation a Hanning window was used along with \( 2^{10} \) FFT points with 50% overlap when averaging. As shown in Fig. 12, there is a considerable peak for the HR3 configuration, at \( Re_s = 1140 \), whilst no significant peak was observed in the PSD of the velocity fluctuations for the other configurations. The frequency of the maximum peak in HR3, 625 Hz, is close to the resonance frequency of the resonator. Interestingly, as mentioned previously, for HR3 the maximum peak in pressure fluctuations

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**Fig. 12.** Power spectral density (PSD) of the y component of the instantaneous velocity at the mid-point of the orifice; (a) \( Re_s = 873 \), (b) \( Re_s = 1140 \) and (c) \( Re_s = 1568 \).
also occurs at \( \text{Re}_c = 1140 \). The results show that the resonator with the lowest orifice length in a specific free stream velocity range can excite both the pressure and velocity fields.

5.2. Momentum boundary layer

The streamwise velocity fluctuations within the near wall flow downstream of the orifice demonstrate the effect of the resonator on the structure of the turbulent boundary layer. The streamwise averaged turbulence intensity, \( u'_{\text{rms}} \), at three different free stream velocities with and without the resonator present have been measured. As demonstrated in Fig. 13, HR1 and HR2 have opposite effects on the velocity fluctuations over the majority of the logarithmic region, \( 30 < y^+ < 150 \). It was observed that for HR1 at \( \text{Re}_c = 873 \) the intensity is increased, whilst HR2 reduces the amplitude of the velocity fluctuations in the logarithmic region. This is due to that the flow injection in HR1 is greater than the suction and the boundary layer is destabilized downstream of the resonator, whilst in HR2 the suction is almost equal to the injection. Fig. 13c shows that HR3 does not change the structure of the

![Fig. 14. Turbulence intensity profile at \( \text{Re}_c = 1140 \); (a) HR1, (b) HR2, (c) HR3 and (d) HR4.](image)

![Fig. 15. Turbulent intensity profile at \( \text{Re}_c = 1568 \); (a) HR1, (b) HR2, (c) HR3 and (d) HR4.](image)
turbulent boundary layer significantly. Although the pressure fluctuations within HR3 are the same as HR1 at \( \text{Re}_s = 873 \), the flow within HR3 cannot change the structure of the grazing flow because the thickness of the boundary layer is larger than the orifice diameter. Moreover, the suction in HR3 is higher than HR1 and thus the grazing flow is more stable downstream of the resonator. As mentioned before, when \( \delta \approx 1 \), slight pressure fluctuations occur inside HR4 which causes a reduction in the turbulence intensity within the boundary layer up to \( y^+ = 450 \). The results prove that at \( \text{Re}_s = 873 \) the resonator with minimum orifice diameter decreases the turbulence intensity, whereas flow downstream of the resonator with the largest orifice diameter has the highest amplitude velocity fluctuations. It should be noted that at \( \text{Re}_s = 873 \) the turbulent length scale for configuration HR2 is higher than the other cases. Therefore it can be concluded that a higher length scale over the orifice modifies turbulence structures downstream of the resonator to a greater degree.

The turbulence intensity of the \( u \) component of the velocity fluctuations at \( \text{Re}_s = 1140 \) due to presence of the Helmholtz resonators has also been analysed. As can be seen in Fig. 14, at \( \text{Re}_s = 1140 \) the effects of HR1 and HR2 on the boundary layer structure are similar to their influence at \( \text{Re}_s = 873 \). As mentioned before, the pressure fluctuations within both resonators are increased at \( \text{Re}_s = 1140 \) which in turn increases the flow injection and the turbulence intensity in vicinity of the orifice. Fig. 14c shows that for HR3 the velocity fluctuations at P3 have higher amplitude than at P1 in the near wall region, \( y^+ < 60 \). This increase is due to two reasons, firstly that the air pressure inside the resonator has its maximum value and to relieve this pressure a significant force has to be induced on the boundary layer in the near wall region which increases the instabilities. The second reason is the lowest value of the turbulent length scale over the orifice of HR3 at \( \text{Re}_s = 1140 \). It has also been observed that stabilization of the fluctuations in the vicinity of HR4 is decreased. This is due to that flow suction in HR3 and HR4 at \( \text{Re}_s = 1140 \) is decreased and the boundary layer is destabilized to a greater degree compared with \( \text{Re}_s = 873 \).

The turbulence production has been reduced in the near wall region yet increased significantly further out from the wall for HR1 at \( \text{Re}_s = 1568 \) (Fig. 15a). At this velocity, injection of the cavity flow in HR1 is greater than \( \text{Re}_s = 1140 \) which leads to the generation of increased turbulence intensity within the logarithmic region downstream of the resonator. It is interesting to note that the flow behaviour downstream of HR2 at this free stream velocity

![Fig. 16. Energy spectra of \( u' \) upstream and downstream of the orifice of HR1: (a) \( y^+ = 40 \), (b) \( y^+ = 100 \), (c) \( y^+ = 40 \), (d) \( y^+ = 120 \), (e) \( y^+ = 60 \) and (f) \( y^+ = 120 \).]
is completely different to the other resonators investigated. As shown in Fig. 15b, the turbulence intensity has been increased over a small part of the logarithmic region by as much as 25%. As mentioned before, the value of the maximum pressure fluctuations within HR3 is decreased at $Re_s = 1568$ and the enhancement of the turbulence intensity is reduced. A reduction in the pressure fluctuations inside HR4 causes greater suction which stabilizes the instabilities within the boundary layer downstream of the resonator (Fig. 15d).

5.3. Energy spectra

In order to gain a deeper understanding of how the resonator modifies the turbulence structure, this section is focused on several important spatial locations within the boundary layer. To show the energy spectra of the streamwise velocity within all regions of the turbulent boundary layer the power spectral density (PSD) of the velocity was calculated using a $2^9$ FFT, with a Hanning window and 50% when averaging. As presented in the previous section, for all free stream velocities HR1 and HR2 have a greater impact on the flow structures downstream of the orifice than HR3 and HR4. Therefore in the following analysis attention has been centred on the changes in the underlying turbulence structure caused by HR1 and HR2. Figs. 16 and 17 show the PSDs of free stream velocity for the three different $Re_s$ at two locations within the logarithmic region. Fig. 16(a) and (c) illustrates that there is almost no change in energy over the frequency range examined. The increase in the power spectral densities shown in Fig. 16(b–f) over the full range of frequencies demonstrates that there is an increase in the velocity fluctuations of these locations. At $Re_s = 1568$ a shift in the energy spectrum over the low frequencies reveals that the energy in the large scale structures is slightly reduced.

As presented in Fig. 17, the flow structures downstream of HR2 have been changed considerably. It was observed that there is a significant reduction in the energy for $f < 600$ Hz at $Re_s = 873$ and $Re_s = 1140$, which shows that the large eddies transfer their energy to the small scale eddies (Fig. 17a–d). It should be also noted that there exists a shift in the power spectral density of the velocity at $P3$ at higher frequencies. Moving further away from the surface up to $y' = 120$ at $Re_s = 1568$, the energy is dramatically increased over the low frequencies, where increased turbulence intensity was also observed.

Fig. 17. Energy spectra of $u'$ upstream and downstream of the orifice of HR2. (a) $y' = 60$, (b) $y' = 100$, (c) $y' = 100$, (d) $y' = 200$, (e) $y' = 80$ and (f) $y' = 160$. 
The changes in the average skewness profile, shown in Fig. 18, are an indication that the turbulence structures in the logarithmic region have been modified. It was observed that there is a decrease in skewness for 150 < y* < 400 which is in agreement with flows for other drag reduction devices, such as the travelling wave technique [9,18]. Therefore the Helmholtz resonator can be used as a passive device to stabilize the fluctuations within the boundary layer. Post-processing of the present experimental results and analysis of the numerical data has demonstrated that the Helmholtz resonator can suppress the turbulent events. In our future work the effects of the generated vortices by the Helmholtz resonator on the instabilities and the intensity/duration of sweep event will be analysed.

6. Conclusion

The experimental results presented in this paper provide a detailed description of the turbulent boundary layer behaviour around the orifice and inside 12 different cylindrical Helmholtz resonators. The flush mounted resonators were installed within a flat plate in a low speed wind tunnel with low turbulence level (Tu% = 0.5). It was observed that there is almost no excitation of the pressure field when the free stream velocity was less than 15 m/s. Therefore all measurements have been carried out in the range of 16 m/s < U < 30 m/s.

It was concluded from the pressure fluctuation measurements that the resonators which have the highest cavity depth (L/D = 4) generate the greatest pressure fluctuations inside the resonator, which occur very close to the natural frequency of the resonator. The resonator response forces the shear layer out of the orifice, relieving the high-amplitude pressure. This process can stabilize or destabilize the turbulent boundary layer fluctuations. Therefore, in the present study the effects of the resonator on the grazing flow were considered when the high-amplitude pressure fluctuations inside the resonator occur. The results showed that the orifice length has significant effects on the pressure fluctuations within the cavity such that the difference between the maximum values of the PSD of the pressure within the resonator with l/D = 0.08 was 19 dB higher than when l/D = 0.6. It was concluded that the vortices within the shear layer over the orifice with l/D < 0.2 can easily penetrate the cavity, and thus the induced force from the cavity flow is increased. It was also observed that the resonator with the largest orifice diameter, d/D = 0.8, induces higher pressure fluctuations inside the cavity. The effects of the boundary layer thickness on the pressure fluctuations inside the resonator were also investigated. The free stream velocity was altered such that the turbulent boundary layer thickness, \( \delta \), in the vicinity of the orifice was in the range of 17–21 mm. It was found that when \( \delta \) is very close to the orifice diameter the pressure inside the resonator is increased. This is due to the fact that eddies within the smaller boundary layer, \( \delta < 0.8d \), cannot transfer their force to the cavity flow and that the eddies inside the larger boundary layer, \( \delta > 1.1d \), are too long to penetrate the cavity. Interestingly, it was also found that when the boundary layer thickness is around 0.1 of the orifice length the maximum value of the PSD of the pressure fluctuations are increased considerably by 19 dB.

Experiments have also been carried out to measure the velocity field around the orifice of the resonators. The streamwise velocity measurements upstream of the orifice indicated that the incoming grazing flow is a fully developed turbulent boundary layer with zero pressure gradient. Initially, the characteristics of the shear layer were considered at the mid-point of the orifice. It was observed that with increasing orifice size there is a dramatic shift in the turbulent length scale over the orifice. Comparing results for HR2 and HR4 shows that by increasing the orifice size by 5 mm, the turbulent length scale is reduced by 4.5 mm. However, it must be noted that unlike the other resonators when l/D = 0.08, the length scale has minimum value at ReC = 1140. The y-component of the velocity fluctuations over the orifice was also measured and it was shown that the resonator with longest orifice length, HR4, induces greater suction on the grazing flow than other resonators throughout the range of free stream velocities investigated. Interestingly, when d/D was increased from 0.2 to 0.8 the injection value is increased for ReC = 1568. This higher flow injection causes that the flow downstream of the orifice is more unstable. The results also show that the resonator with the shortest orifice length generates a strong excitation of the velocity fluctuations perpendicular to the grazing flow at ReC = 1140. This is thought to be due to the small discrete vortices which are generated over the orifice.

The turbulence intensity of the streamwise velocity fluctuations within the turbulent boundary layer downstream of the resonators was also analysed. A reduction in turbulence intensity demonstrates the potential of the resonator to stabilize the fluctuations within the boundary layer. It was shown that unlike the HR2, for the HR1 resonator the velocity fluctuations in the logarithmic region are increased by a maximum of 17% at ReC = 873 and 1140. Therefore, decreasing the orifice diameter causes a significant reduction in the turbulence intensity within the turbulent boundary layer downstream of the resonator. Interestingly when the free stream velocity was increased to ReC = 1546, the effect of HR1 on the grazing flow was changed such that the velocity fluctuations are increased by a maximum of 19% in the logarithmic region. It should be noted that the strong excitation of both the velocity and pressure fields of HR3 causes an increase in the turbulence intensity in the near wall region downstream of the resonator. It must be noted that in HR1, HR2 and HR3 with increasing flow suction, the instabilities within the boundary layer are reduced. Inasmuch as the orifice length in HR4 is near to the boundary layer thickness, the suction and injection strength should be equal to stabilize the fluctuations within the grazing flow. The changes in the turbulence structures caused by the resonators were also considered through the energy spectra of the velocity fluctuations within the boundary layer. It was concluded that in the near wall region (y* < 80) downstream of the resonator with the largest orifice diameter the energy contained in the large scale structures is significantly reduced. This flow behaviour is thought to be due to longitudinal vortices created by the resonator, and detailed investigation of this phenomenon is the subject of further work.

References


