Experimental Investigation of Acoustically Excited Cavity Turbulence in Channel Flow

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Measurements of turbulence intensity components were made downstream of the trailing edge of a high-aspect-ratio, two-dimensional rectangular slot cut into the base of a subsonic channel flow. The slot connected with a cavity and formed a Helmholtz resonator that could be excited from below. The presence of the slot can lead to either an increase or decrease in the axial component of turbulence intensity, depending on the distance from the wall; whereas the normal component of turbulence intensity is increased near the wall and is not affected in the outer region. The effect of applying acoustic excitation to the cavity, at a frequency that excites oscillatory air movement across the slot, is found to cause a large increase in the axial and normal components of turbulence intensity.

Nomenclature

B = sound pressure level (re: 20μ Pa, scale A)
d = half the channel gap
$\tilde{e}$ = hot-wire anemometer rms output voltage
f = frequency, Hz
I_x = axial turbulence intensity, $=\sqrt{\overline{u^2}}/U \times 100$
I_y = normal turbulence intensity, $=\sqrt{\overline{v^2}}/U \times 100$
l = slot dimension in the flow direction
L = level of the wave analyzer input signal,dB with respect to a reference voltage of $100\mu V$
Re = Reynolds number, $=U_m d/\nu$
u = axial turbulent velocity fluctutation
u_e = effective cooling velocity of the hot wire
U = local time mean velocity
U_m = fully developed value of U at $y=d$ in the fully developed region of the smooth channel
v = normal turbulent velocity fluctuation
x = axial coordinate measured from channel inlet
x_0 = axial coordinate measured from the slot centerline
y = wall distance
z = transverse coordinate (normal to x and y)
ν = kinematic viscosity

Subscripts

e = effective values (of B or L) due to power input to the loudspeaker and background noise
b = values (of B or L) due to background noise only

Introduction

DETAILS of fluid motion in an acoustically excited resonator has been the subject of study by numerous investigators. Ingard and his co-workers[1,2] studied an acoustically excited resonator with the cavity discharging into a stationary atmosphere. These studies revealed that the inflow into the cavity was essentially potential, while the outflow led to the formation of a distinct free jet out of the cavity.

Baumeister and Rice[3] conducted a visual study of the effect of grazing flow on the oscillatory flow through an orifice to a Helmholtz resonator at a frequency of 2 Hz. The orifice hole was 1.27×1.27 cm square and the resonator cavity $6 \times 6 \times 2.5$ cm. The Reynolds number was 4000, based on the effective hydraulic diameter of the orifice. The details of the fluid motions into and out of the orifice were obtained for both grazing and no grazing flows. Similar observations were obtained by Rogers and Hersh[4] with flow visualization tests on a square-edged wall orifice ($12.7 \times 20 \times 12.7$ mm). The cavity was 51 mm in diameter.

Cavity excitation was examined by Ronneberger[5] who conducted flow visualization studies for a two-dimensional rectangular cavity exposed to the laminar grazing flow of water. The back wall of the cavity was a piston that could be operated in small oscillations by means of an electromotor. With the piston oscillating, a wave was excited at the leading edge of the cavity and the wave was amplified on its way downstream. At the trailing edge of the cavity, the mean flow was directed alternatingly into and out of the cavity, depending on the deflection of the shear layer.

Employing a split film anemometer, Charwat and Walker[6] made detailed measurements of the time-dependent velocities induced inside and outside the opening of an acoustically excited two-dimensional rectangular cavity coupled to a turbulent flow in the test section through a high-aspect-ratio rectangular slot. A Helmholtz resonator was imbedded within the turbulent grazing flow through the wind tunnel. Excitation to the cavity was provided with a loudspeaker mounted in the roof of the tunnel above the slot. Charwat and Walker[6] obtained patterns of flow in and above the slot at an excitation frequency of 100 Hz. The resonator was tuned to this value with no grazing flow.

Models for the flow into and out of the orifice of a Holmholtz resonator were formulated by Rogers and Hersh[4] and Walker and Charwat.[8]

In spite of the extensive research work covering various aspects of cavity flow, no turbulence data appear to be available for the flow downstream of the slot in the main flow.

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The main object of the present work is to provide such measurements in the main flow downstream of a cavity coupled to the main flow through a high-aspect-ratio, two-dimensional rectangular slot cut in the base of a subsonic wind tunnel. The slot and cavity formed a Helmholtz resonator. Examined is the effect of applying acoustical oscillations into the cavity that are capable of exciting resonator frequency.

The initial work consisted of obtaining turbulence measurements in the fully developed region of the channel flow with no cavity (smooth wall). This was followed by turbulence measurements downstream of the open slot with no external excitation. The final stage was concerned with the effect of external excitation on the turbulence field downstream of the slot.

Experimental Work

Turbulence measurements were made in a rectangular channel of an aspect ratio of 9 (50.8×457.2 mm), using air. The filtered air was sucked into the channel through a bell-mouth entry. The bell mouth was followed by a honeycomb flow straightner and a wire gauze, beyond which was the channel. The axial coordinate x was measured from the channel inlet. A trip wire, with a diameter of 3.2 mm, was attached to the channel walls at $x \simeq 6.4$ mm. Formica sheets, 1.6 mm thick, were stuck to the blockboard top and bottom walls of the channel to ensure smooth interior surfaces, whereas the outside of these walls were stiffened by angle iron at regular intervals. Each side wall of the channel was provided with a Perspex window to allow visual observations in the working section, the rest of the side wall consisting of rectangular section aluminium bars.

The channel was connected to the 254 mm diam fan by means of sheet metal ducts. Honeycombs were provided at the fan inlet and outlet. The air discharged from the fan into a circular pipe 203.2 mm in diameter with an orifice plate 152.4 mm in diameter for airflow measurement.

Measurements of the axial turbulence intensity were made using DISA single hot-wire miniature probes (type 55F21), in conjunction with a DISA constant-temperature anemometer (type 55A01), with the axis of the wire set in the transverse (z) direction. The d.c. and rms voltages were read from a DISA d.c. voltmeter (type 55D30), and a DISA rms voltmeter (type 55D35), respectively. The normal component of turbulence intensity was measured using a DISA miniature X probe (type 55A38), in conjunction with two DISA constant-temperature anemometers (type 55A01), and a DISA random signal indicator and correlator (type 55A06).

Measurements of the local mean velocity were made using total head tube and wall static pressure tappings. Because the bore of the total head tube was only 0.33 mm, and because the end of the tube was chamfered, no displacement correction was applied. Fully established flow was obtained at $x/d = 102$. (d = half-channel width = 25.4 mm). The single and X-wire probes were caliberated against the total head tube, the results indicating very close agreement with King's law.

The slot was cut in the working section base. It was rectangular in shape, 1.59 mm long in the streamwise direction, 304.8 mm in the transverse direction (z), and 90.49 mm deep. See Fig. 1. The ratio of the slot length to width was chosen to be small to obtain a two-dimensional configuration. The slot centerline was situated at $x/d = 111.5$. Two concrete slabs, about 51 mm thick, were attached to the underside of the working section base with Araldite, one on each side of the slot, to reduce vibration. Fixed to each slab was a sheet of blockboard to which the loudspeaker was fixed. The whole working section base was supported from below by a large concrete box.

The loudspeaker volume and the rectangular slot formed a Helmholtz resonator when the slot was open to the flow. The resonator could be excited as required by means of an oscillator. The loudspeaker was a Goodman, type Axiom 301, 279.4 mm in diameter, 20 W, with an impedence of 15 Ω. It was driven by a 25 W Derritron power amplifier that had a built in sine wave generator capable of generating frequencies in the 0.0015–22 kHz range.

The intensity of pressure level inside the cavity was measured by means of a Bruel & Kjaer (B&K) 12.7 mm diam microphone (type M 4134). See Fig. 1. The microphone output was fed via a B&K cathode follower (type 2615) to a B&K power supply (type 2801). The output of the power supply was applied to a Muirhead-Pametrada wave analyzer (type D 489 EM), that gave the level of the input signal to the analyzer in decibels with respect to a reference voltage of 100 μV. The single level thus defined is denoted by L. The wave analyzer was capable of performing spectral analysis of the input signal on a one-third octave basis. Alternatively, narrow-band filtering was also possible. The analyzer was capable of dealing with frequencies in the range of 0.019–21 kHz. It is more customary, however, to carry out sound spectral analysis relative to a reference pressure of 20 μPa, but no such analyzer was available at the time. Nevertheless, the spectral analysis obtained in terms of L is adequate in identifying the most dominant frequencies. In order to obtain the absolute sound pressure level in the flow, a second microphone (B&K type 4145, 25.4 mm diam), in conjunction with a B&K precision sound level meter (type 2203), was placed flush with the upper wall of the channel directly opposite of the slot. The sound pressure level obtained with the latter arrangement is relative to a reference pressure of 20 μPa and is denoted here by B. The pressure oscillograms in the cavity were obtained using the 12.7 mm diam microphone, a Solartron oscilloscope (type CD 1400), and Shackman poloroid camera (type PL 1).

Results

Determination of Resonator Frequencies

An estimate of the resonant frequency in the cavity at no flow was made by conducting an experiment in which the loudspeaker was excited with various sinusoidal oscillations. A hot wire was placed just over the centerline of the slot, which was kept open, at $y/d = 0.039$. For zero velocity in the channel, the rms output voltage $\tilde{e}$ of a hot-wire anemometer, was measured as the applied frequency of the oscillation to the loudspeaker was varied very smoothly, keeping the acoustic power output L (as measured by the microphone) constant throughout the frequency range. This was considered important because a generated level might give the impression of be-

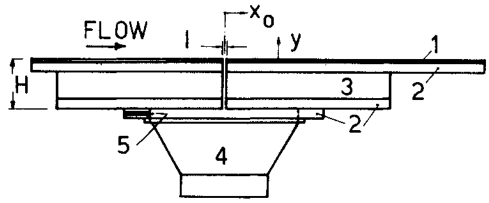

Fig. 1 Details of the cavity: 1) Formica, 2) blockboard (19 mm thick), 3) concrete, 4) loudspeaker, 5) microphone, $H = 90.49$ mm, $l = 1.59$ mm.

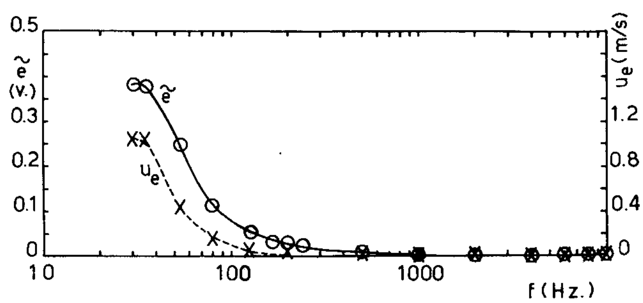

Fig. 2 Variation of $\tilde{e}$ and u_e with frequency at $x/l = 0$, $y = 1$ mm, $L = 39$ dB, $B = 75$ dB, slot open, no flow.

ing the resonant frequency. The results are shown in Fig. 2. They indicate that the rms voltage $\tilde{e}$ peaks at about 30 Hz. However, this peak is not very sharp. The experiment suggests that the cavity resonates at about 30 Hz with no flow.

When the test section roof was removed, the application of frequencies below 100 Hz at no flow gave rise to an oscillatory air movement across the slot (in the y direction) and the air movement became more intense as the frequency was lowered to about 30 Hz. This is indicated in Fig. 2, which shows the variation of u_e over the open slot at $y/d=0.039$ as a function of frequency. u_e is the effective cooling velocity of the hot wire and is obtained from the hot-wire calibration curve. It is a measure of the average jet velocity in the slot and gives a physical feel for the magnitude of the excitation applied.

The effect of the flow on the resonator frequency was then investigated. Spectral analysis of the cavity pressure at a Reynolds number $Re=1.52\times10^4$ was determined with no power input to the speaker. The results are shown in Fig. 3. The figure presents two pressure spectra. Spectrum (i) was obtained with a tape covering the slot mouth in the working section, so that only the background noise in the cavity was recorded. This spectrum analysis was carried out on a third-octave basis. Spectrum (ii) was of the open slot (tape removed) and shows the combined effect of the flow and the background noise. Spectrum (ii) was obtained on a third-octave basis for frequencies greater than 50 Hz; for frequencies below 50 Hz, the bandwidth was 1 Hz.

Spectrum (i) in Fig. 3 is characterized by the dominant frequencies of 50 and 250 Hz. Spectrum ii shows that, as the frequency is lowered below about 50 Hz, a sharp increase in the decibel level is obtained. There is evidence of peaks at about 20, 25, and 38 Hz. Clearly, these frequencies are not associated with the background noise.

Pressure oscillograms obtained in the cavity were obtained for a number of Reynolds number values, with no power supplied to the loudspeaker. The background noise, which was obtained with the slot mouth closed, is presented in Fig. 4 for $Re=1.52\times10^4$. This oscillogram and that obtained at $Re=6.16\times10^4$ (not shown) show a predominant frequency of about 250 Hz characterizing the background noise. When the tape was removed, the pressure oscillograms showed that the cavity pressure was dominated by low frequency values that varied with the Reynolds number. Typical oscillograms are shown in Fig. 5 for $Re=1.52\times10^4$. Predominant frequencies may be calculated from these oscillograms as approximately 20 and 25 Hz. These values are in agreement with those obtained from the spectral analysis.

Spectral analysis of the axial turbulent velocity fluctuation u just downstream of the trailing edge of the cavity at $x_0/l=4$ and $y=1$ mm (see nomenclature) did not display any peak (Fig. 3), indicating that vortices are being shed from the slot mouth over a broad band of frequencies. It is reasonable to conclude, therefore, that the predominant frequencies observed in Figs. 3 [Spectrum (ii)] and 5 are not related to vortex shedding phenomenon at the slot mouth, but that they represent cavity resonant frequencies.

Cavity Excitation

Having identified the cavity resonant frequencies, the next step was to study the effect on the turbulence downstream of the trailing edge of the slot of exciting these resonant frequencies. At $x_0/l=4$, $y/d=0.039$, and $Re=1.52\times10^4$, the axial turbulence intensity I_X was measured as the frequency of excitation to the loudspeaker was varied very smoothly at a constant loudspeaker effective power level L_e throughout the frequency range. L_e is the power level due to the loudspeaker input power as well as the background noise. The results are presented in Fig. 6. They show that I_X tends to a peak value at about 30 Hz. The values of I_X are seen to increase as the excitation frequency is lowered below about 100 Hz, which was the frequency at which oscillatory air movement across the slot became observable at no flow. This oscillatory air movement could be picked up by the hot-wire anemometer as shown in Fig.7. This figure represents an oscillogram of the axial turbulence fluctuation u at $x_0/l=4$, $y/d=0.039$, and $Re=1.52\times10^4$, when an excitation frequency of 50 Hz was applied to the loudspeaker. The oscillogram demonstrates a frequency of 50 Hz superimposed on the turbulence fluctuations.

It seems reasonable to conclude that the increase in I_X at a frequency below about 100 Hz is attributed to the oscillatory air movement between the cavity and the main flow. This movement intensifies as the excitation frequency approaches about 30 Hz, which is close to the value of the resonant frequencies. However, because the loudspeaker could not be operated below 30 Hz, because the resonant frequencies at $Re=1.52\times10^4$ were found to have similar values (20, 25, and 38 Hz), and since the peaks observed in Figs. 2 and 6 are not very sharp, it was difficult to determine which of these resonant frequencies was the one actually being excited.

Figure 6 shows an increase of turbulence intensity only at the cavity resonant frequencies. In contrast, work on the excitation of unheated free jet mixing regions shows that a broadband amplification of turbulence can be acheived by a pure tone acoustic excitation. In the case of such a jet, the mechanism of turbulence amplification is related to changes in the large- and small-scale jet flow properties associated with the acoustic excitation.[12]

Turbulence Profiles Downstream of the Slot

Profiles of the axial and normal components of turbulence intensity corresponding to smooth channel flow (no slot) were obtained at a number of Reynolds numbers in the fully

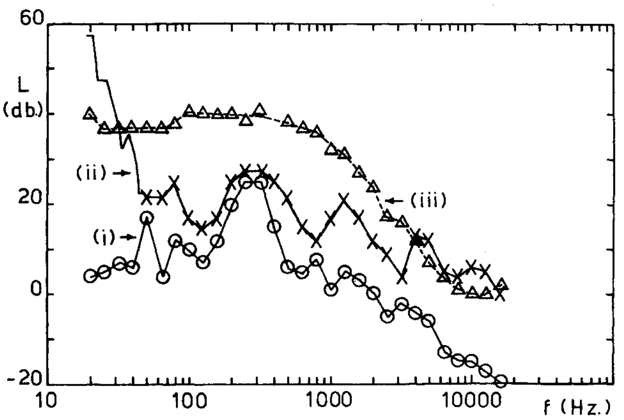

Fig. 3 Spectra at $Re=1.52\times10^4$: (i) background noise spectrum (slot mouth blocked); (ii) cavity pressure spectrum, slot mouth open, actual data points for $f<50$ Hz are not shown for clarity, but the bandwidth = 1 Hz; (iii) spectrum of the u fluctuation at $x_0/l=4$, $y=1$ mm.

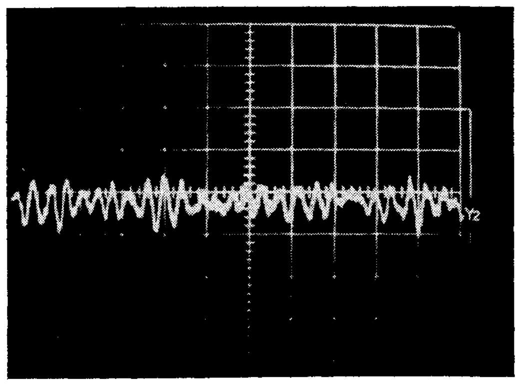

Fig. 4 Oscillogram of the background noise in the cavity (slot mouth blocked); time scale = 10 ms/cm, $Re=1.52\times10^4$.

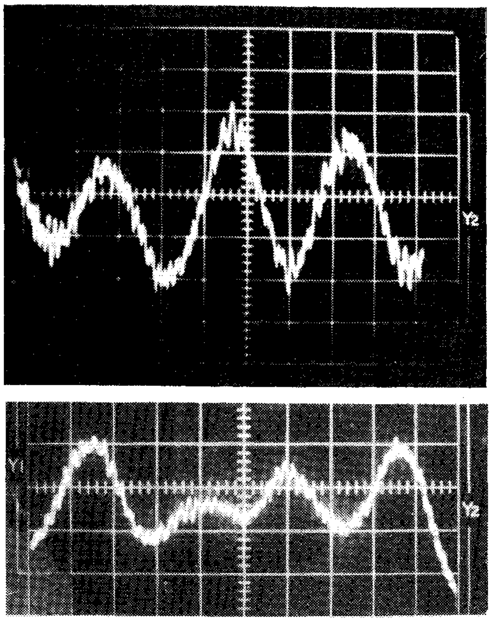

Fig. 5 Alternative oscillograms inside the cavity at $Re = 1.52 \times 10^4$: slot mouth open, time scale = 20 ms/cm.

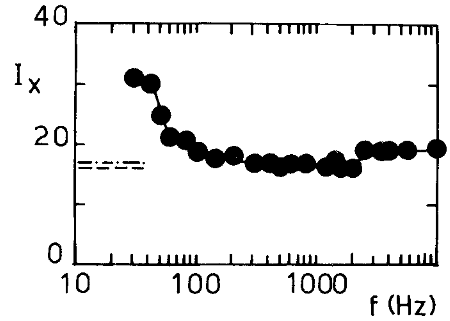

Fig. 6 Variation of I_X at $x_0/l = 4$, $y = 1$ mm with frequency: $Re = 1.52 \times 10^4$, $L_e = 54$ dB, ... smooth channel value, and —.—. value corresponding to open slot, but no power input to the loudspeaker.

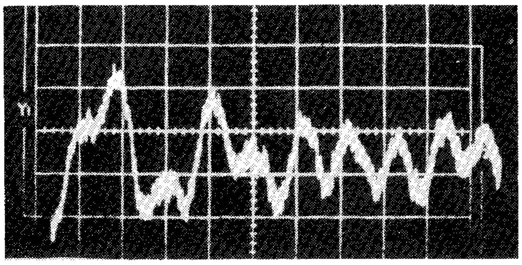

Fig. 7 Oscillogram of the axial turbulent velocity fluctuation u at $x_0/l = 4$, $y = 1$ mm with a 50 Hz oscillation applied to the loudspeaker ($Re = 1.52 \times 10^4$, time scale = 20 ms/cm).

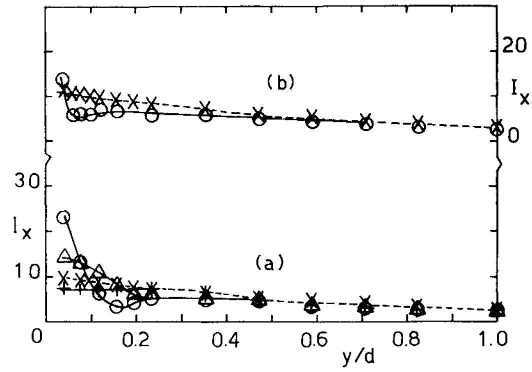

Fig. 8 Profiles of turbulence intensity I_X downstream of the slot (no acoustic excitation): a) $Re = 6.16 \times 10^4$; b) $Re = 3.08 \times 10^4$. Symbols: ○ $x_0/l = 4$, △ = 18, + = 66, and × undisturbed smooth channel.

developed section of the channel. The results indicated good agreement with previously published data, e.g. Laufer,[7] (comparison not shown). The smooth channel profiles are presented by the dotted lines in Figs. 8-11.

Figure 8 shows profiles of I_X downstream of the trailing edge of the open slot, with no acoustic oscillations. At $Re = 6.16 \times 10^4$, and immediately downstream of the slot at $x_0/l = 4$, the presence of the slot leads to an increase in the values of I_X near the wall, at $0.04 < y/d < 0.1$. In the region 0.1 $y/d < 0.47$, the values of I_X are smaller than those of the undisturbed values. There is evidence of a kink in the profile of I_X at $x_0/l = 4$ and $y/d = 0.15$. As the flow proceeds downstream of the slot trailing edge, at $x_0/l = 18$, the increase in I_X is found to occur over the region $0.04 < y/d < 0.175$ and the decrease in I_X over the region $0.175 < y/d < 0.47$. At $x_0/l = 66$, the effect of the slot is still evident. At $Re = 3.08 \times 10^4$, the behavior of I_X at $x_0/l = 4$ is similar to the corresponding one at $Re = 6.16 \times 10^4$. The values of I_X over the region $0.04 < y/d < 0.47$ are lower than the corresponding smooth channel flow values. The kink in the profile of I_X referred to above is also observed at $Re = 3.08 \times 10^4$.

The effect of exciting the cavity with a periodic oscillation of 50 Hz applied to the loudspeaker is presented in Figs. 9-11 at $Re = 1.52 \times 10^4$. This frequency was chosen to be in the region where the turbulence was clearly affected, but at the same time it was sufficiently high to avoid operating the loudspeaker at its minimum frequency range for long periods of time. Figure 9 presents the profile of I_X at $x_0/l = 4$ for three situations: smooth channel, open slot with no excitation, and open slot with a 50 Hz excitation. The figure shows that the presence of the slot results in an increase in I_X in the region $0.04 < y/d < 0.075$ and a decrease in I_X in the region $0.075 < y/d < 0.47$. This behavior is similar to that observed in Fig. 8 for $Re = 3.08 \times 10^4$ and 6.16×10^4. The effect of the acoustic excitation is found to cause a very high increase in I_X in the region $0.04 < y/d < 0.35$. Figure 10, which is similar to Fig. 9, presents the normal component of turbulence intensity I_y. The slot is seen to raise the level of I_y over the values of the smooth channel flow for $0.118 < y/d < 0.22$. The acoustic excitation is seen to cause even a higher increase in the values of I_y in the region $0.118 < y/d < 0.47$.

The profiles of I_X downstream of the slot with an applied acoustic oscillation of 50 Hz is presented in Fig. 11. The figure shows that the profile becomes nearly coincident with that of the smooth channel at $x_0/l = 66$. Obviously, the axial extent over which the effect of the oscillation is felt will depend on the value of the effective power level of the oscillation L_e, the higher L_e, the greater the jet speed. The ratio of the jet speed to flow velocity has been found to be an important parameter in determining the type of interaction between the jet and the main flow. When this ratio is high, the interaction is similar to a situation in which there is no grazing velocity (jet issuing into an atmosphere).[3] It should be noted that results obtained for another slot geometry (not presented) having the same width (304.8 mm), but 6.35 mm long, indicated a similar jet movement when the cavity was excited at its natural frequency with a subsequent increase in the turbulence level.

The increase in turbulence level associated with cavity excitation is related to the fact that the sound transmitted through the openings can be partially converted into fluctuating vorticity that is shed from the edge of the opening. This is the case both with and without flow. This phenomenon is particularly dominant at low frequencies.[9-11] When there is

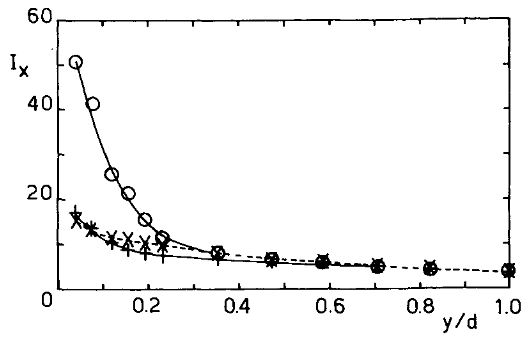

Fig. 9 Profiles of turbulence intensity I_X downstream of the slot ($Re = 1.52 \times 10^4$, $x_0/l = 4$). Legend: × undisturbed smooth channel; + slot open, no acoustic excitation; ○ slot open with a 50 Hz acoustic excitation ($L_e = 55$ dB, $L_b = 52.7$ dB, $B_e = 105$ dB, $B_b = 101$ dB).

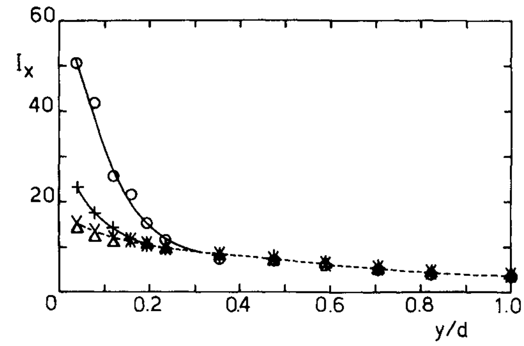

Fig. 11 Profiles of turbulence intensity I_X downstream of the slot with a 50 Hz acoustic excitation (values of L_e, L_b, B_e, B_b, and Re as in Fig. 9; ○ $x_0/l = 4$, + $= 18$, △ $= 66$, and × undisturbed smooth channel).

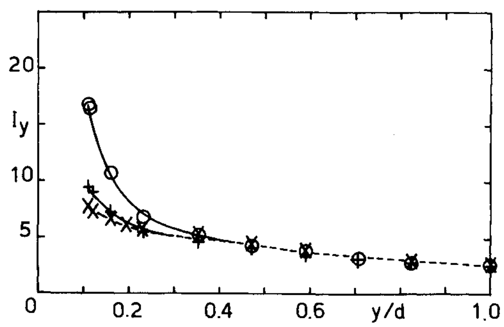

Fig. 10 Profiles of turbulence intensity I_y downstream of the slot. Legend as in Fig. 9.

flow, the mean flow convects away the vorticity into regions where it can no longer continue to interact significantly with the acoustic field and where its kinetic energy is ultimately dissipated as heat. Similar acoustic power dissipation is also possible at sharp solid boundaries in the absence of mean flow, provided that the particle velocity amplitude is high enough to cause flow separation and the associated convection of vortical energy.

This is consistent with the flow visualization studies conducted with low-frequency oscillations introduced into the flow through a Helmholtz resonator.[3] These studies showed considerable turbulence activity in the main flow downstream of the slot when these oscillations are applied. Baumeister and Rice[3] found that, with no flow and large-amplitude displacements, separation of jet flow occurred upon discharge in either direction. Large eddies with high turbulence dissipated the kinetic head of the jet in the resonator cavity. With grazing flow, during the inflow portion of the cycle, the axial momentum of the grazing flow makes it difficult for the fluid to negotiate the turn into the orifice, resulting in a large separation or dead flow region at the upstream side of the orifice. On the outflow portion of the cycle, the orifice flow was seen to encounter the large axial momentum of the grazing flow, which had to be displaced before the orifice flow could emerge.

Rogers and Hersh[4] formulated an inviscid interaction "lid" model based on a simplified configuration of the interface (or lid) between the orifice and the grazing flow. The lid closes off the opening of the orifice when there is no orifice flow and deflects upward as though hinged about the upstream lip when there is orifice outflow. Conversely, during orifice inflow, the lid is deflected away from the opening, but this time as though hinged about the downstream edge of the orifice. Another "hinged lid" model was formulated by Walker and Charwat,[8] with the dividing "lid" oscillating about a hinge point that was not fixed a priori.

It follows from the above discussion that the flow into and out of the orifice may be looked upon as an unsteady jet in crossflow. This is supported by the measurements obtained by Charwat and Walker[6] of the time-dependent velocities induced inside and outside the opening of an acoustically excited Helmholtz resonator. However, the visual studies of Baumeister and Rice[3] have revealed certain features pertaining to this jet: 1) the inflow and outflow portions of the cycle are asymmetric; 2) the jet has a nonuniform cross-sectional area during both the inflow and outflow due to the formation of the vena contracta in the slot; and 3) the jet cross-sectional area varies with time and the amplitude of the oscillation. While turbulence intensity data downstream of a steady jet in a cross flow are published in the literature, no such data for the acoustically excited (unsteady) jet considered in the present study appear to be available. This precludes possible comparison of present turbulence data with similar results of other workers.

Summary and Conclusions

Measurements of turbulence intensity are obtained in the main flow downstream of the trailing edge of a high-aspect-ratio, two-dimensional rectangular slot cut in the base of a subsonic channel. One side of the slot faces the main flow and the other is enclosed with a loudspeaker. The cavity of the loudspeaker and the slot constitute a Helmholtz resonator.

Profiles of the axial turbulence intensity I_X immediately downstream of the trailing edge of the slot, at $x_0/l = 4$, show that I_X is increased near the wall and is not affected near the centerline. The corresponding profile of the normal turbulence intensity I_y at $x_0/l = 4$ revealed that I_y is increased in the region $0.119 < y/d < 0.22$. As the flow proceeds downstream, the effect of the slot diffuses to regions further away from the wall.

The effect of applying acoustical oscillations which are capable of exciting the resonator, into the cavity is examined. At zero flow in the channel, oscillatory air movement between the slot and the ambient air is found to occur when the resonator is excited with frequencies below about 100 Hz. The air movement becomes more intense as the frequency is lowered to about 30 Hz. This is considered to be the resonator frequency at no flow.

The effect of the acoustic excitation of the cavity, at a frequency that excites oscillatory air movement across the slot, is found to cause a large increase in I_X in the region $0.04 < y/d < 0.35$. Large increases are also encountered in I_y in the region $0.118 < y/d < 0.47$. Frequencies not associated with oscillatory air movement are found to have a negligible effect on the turbulence downstream of the slot.

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