This paper explores the wind-induced tonal noise generated by slotted and perforated architectural building panels and assesses the potential of modifying the edges of the slots and perforations as a means for noise mitigation. The far-field noise spectra were gathered via microphone in the anechoic wind tunnel at the University of Toronto. Three slotted panel models were tested with varying slot gaps and thicknesses at a range of wind speeds up to 30 m/s and flow angles up to 30°. The results showed two distinct tones being generated for all slot geometries considered in this study at certain ranges of flow velocities and angles. This tonal noise generation was associated with the fluid-dynamic mechanism. Modifications made to the slotted panels were either a partial or full-depth bevel put on the edge of the slots, which could either be oriented to be on the flow-facing or leeward side. Only the ones with the edge modification on the flow-facing side reduced one or both of the tones (in some cases eliminating them completely). They had adverse effects on the leeward side. Also, no significant difference was observed between the effects of partial and full-depth bevels. The bevel was more effective in tone mitigation when the slot gap was smaller. Two perforated panels were tested with equal open area ratios and hole diameters of 6 mm and 3 mm, respectively. Only the panel with 6-mm-diameter perforations was found to produce tonal noise. The perforations have a natural roundedness on one side, and the tonal noise was eliminated when the rounded edge was oriented to be on the leeward side. These trends show promise in utilizing edge modifications on perforated or slotted panels for tonal noise mitigation.

Keywords: perforated panels, building façade noise, tonal noise

1. Introduction

Perforated panels are often used for their aesthetic appearance on the exterior façades of buildings. These perforations are usually circular, however, different geometries of perforations may also be employed. One major problem associated with these architectural elements is their tendency to produce loud noises when exposed to winds. While this noise is generally broadband in nature, for certain wind speeds and directions, some perforation dimensions produce strong tonal noise, described as howling and humming. Tonal noise is often found more irritant than broadband noise. Some famous examples where undesirable tonal noise generation from such panels were seen include One World Trade Center in New York City, USA, Beetham Tower in Manchester, UK and 8 Eglinton Avenue East in Toronto, Canada. Noise environment in Canada as well as many other countries is regulated to ensure that inhabited places are desirable for living. Therefore, the adverse impacts of architectural panels on the noise environment of communities is unacceptable. During the construction phase of buildings, architects and designers often overlook the possible noise problem for perforated panels, and the realization of this problem afterwards requires costly replacements of the panels with a different product (which is the only known...
solution at this point). Widespread use of these panels by building architects in recent years has made the associated tonal noise problem a prevalent environmental concern. Consequently, this study aims to explore the tonal noise generation problem by perforated panels (consisting of circular holes) as well as slotted plates (consisting of long rectangular bars) as their two-dimensional counterparts, and assess the viability of various geometric variations as noise mitigation measures.

Extensive work exists in the literature related to flow past perforated or slotted plates that are parallel or perpendicular to the flow [1-7]. However, for panels used in architectural applications, the wind direction can be oblique. Only a very limited number of studies have looked at perforated or slotted plates at oblique angles to the flow [8-10]. In these studies, acoustic tests showed that the tonal noise generation depends on the flow direction (relative to the plate), the geometry of the plate as well as the flow velocity. For a given plate geometry, tones were produced only for specific ranges of flow velocities and incidence angles. When a certain plate geometry and angle of incidence is concerned, there was an ideal flow velocity that produced the loudest tonal noise output. This ideal flow velocity was lower for plates with larger openings. Vanoostveen [10] is the only study in the literature that conducted flow visualization on two-dimensional slotted panels with oblique flow incidence. This study showed that tonal noise generation is produced when vortices forming in the shear layer separating from the leading corner of each slot impinges near the downstream edge of the slot opening, and tonal noise is not produced without such an impingement. The frequency of the resulting tones increased with flow velocity and decreased with the gap opening between perforations (i.e., the impingement distance). Such a dependence is typical of fluid-dynamic mechanism of flow-induced oscillations (as explained below in the next paragraph). Another interesting observation, which was first reported by Blinet et al. [9], was the large influence of the sharpness of the perforation edges on the tone production. Variation in hole edge profile is common in perforated architectural panels due to the punching process used to manufacture them. In this process, the holes on the side of the panel that the punching tool enters have a blunt edge, whereas the side where the tool exists is left with holes that have a sharp edge. Blinet et al. [9] showed that a perforated plate with blunt-edged holes facing the flow produced no tonal noise compared to a plate having the same hole diameter but sharp edges under the same wind velocity and angle of incidence.

Self-sustaining flow oscillations in cavity-type geometries are generally categorized into three classes [11]: fluid-resonant, fluid-elastic and fluid-dynamic. The fluid-resonant oscillations are associated with the strong coupling of the fluid oscillations (typically in the shear layer) with either the compressibility or free-surface standing wave effects in the cavity. Fluid-elastic oscillations are associated with the interaction of the fluid with the elastic movement of one or more solid walls. The fluid-dynamic flow oscillations are associated with the selective amplification of the inherent instability of the shear layer along with an effective feedback mechanism, which involves further enhancement of the shear layer instability by the upstream propagating pressure perturbations emanating from the shear-layer impingement location. Rossiter [12] developed a semi-empirical formula for high subsonic/supersonic rectangular cavity flows exposed to grazing flow (i.e., cavity mouth parallel to the flow) to predict the frequency of fluid-dynamic oscillations in terms of Strouhal number $St$, as:

$$St = \frac{fD}{U} = \frac{n-\alpha}{1/K + M}$$

(1)

where $n$ is an integer representing the shear layer mode number, $\alpha$ is an empirical constant which depends on the length to depth ratio of the cavity, $K$ (commonly given a value of 0.57) is the vortex convection speed across the cavity mouth relative to the freestream velocity, $M$ is the Mach number and $D$ is the characteristic length of the cavity. A typical characteristic of the fluid-dynamic flow oscillations for a cavity under grazing flow is that the frequency of oscillations increases linearly with increasing flow velocity for a given impingement length and decreases linearly with increasing impingement length for a given flow velocity. Although this characteristic is observed for cavities with their mouth parallel to the flow, a review of the abovementioned past studies on flows over perforated or slotted plates under oblique flow angles suggests that the associated mechanism is fluid-dynamic. This mechanism may be
the only mechanism responsible from the self-sustained flow oscillations in perforated or slotted plates or may coexist simultaneously with fluid-resonant or elastic effects.

The aims of the present study are twofold: first, it builds onto the existing literature by investigating the acoustic response of slotted panels with various slot gaps, slot thicknesses, angles of incidence to the flow, and flow speeds. These tests can be compared to the findings of previous work and used as a baseline for measuring the effectiveness of design modifications in noise mitigation. Second, it expands the previous observation of Blinet et al. [9] related to the dependence of the tonal noise generation on the edge sharpness of circular perforations and applies various edge modifications onto the circular holes of perforated panels and slots of slotted panels to assess their effect on tonal noise generation.

2. Experimental Setup and Testing

The test facility used for far-field acoustic measurements was the open-jet anechoic wind tunnel located at the University of Toronto Institute for Aerospace Studies. The test section is a 600 mm x 600 mm x 2400 mm open jet with adjustable flow speed from 0 m/s to 74 m/s. This open-jet is enclosed within a 6 m x 6 m x 3 m chamber, which is anechoic above 170 Hz and has a reverberation time of 0.032 s. The microphone used for the far-field noise measurements was a PCB high-precision condenser microphone. It was positioned 750 mm downstream of the upstream edge of the model and 750 mm from the edge of the tunnel nozzle in the sideline direction on the leeward side of the model. 30-seconds of data was recorded at a rate of $2^{16}$ Hz and unweighted narrowband Sound Pressure Levels (SPLs) were calculated from the data.

This study was conducted in three parts with the results presented in the same order in the next section. The first was the testing of slotted panels with sharp (90°) edges. These panels consisted of two aluminum brackets, which were 320 mm in length, in which steel bars of 254 mm length and rectangular cross-section were attached. A horizontal plate at the exit of the wind tunnel nozzle was used to hold these panels, as shown in Figs. 1 and 2. The angle of incidence of the slotted panel being tested was changed in 5° increments from 0° to 30° with respect to the flow using the pre-drilled markings on the plate (which can be seen in the picture given in Fig. 2). Here, 0° defines grazing flow where the panel is parallel to the flow. The geometric features of the slotted panels are defined in Fig. 3, and the related values for the slotted panel models tested in this study are summarized in Table 1. The slot models in this study varied in slot gap $D$ and slot thickness $t$. Panels demarcated as 1 and 2 had the same $D/t$ ratio of 4, with the dimensions of panel 2 being the scaled-up version of panel 1 by a factor of 2. Panel 3 had a $D/t$ ratio of 2 and the same slot thickness as panel 2. These panels were tested at a variety of wind speeds from 10 m/s to 30 m/s over the range of angles of incidence indicated earlier.

![Figure 1: Model at exit section, looking upstream.](image1)

![Figure 2: Model at 30° angle of incidence, from above.](image2)

Preliminary studies were in fact performed on six different panel geometries, of which the three described above (and given in Table 1) is a subset. During the initial tests, the panel model was centred in the wind tunnel nozzle and an unexpected low-frequency tone dominated the data. With further tests, this tone was found to be related to the bluff body shedding from the first bar, with it acting as an inclined plate as in the studies of Knisely [13] and Chen et al. [14]. To mitigate this shedding, the model was
moved to the corner of the nozzle so that the first bar’s upstream edge was flush to the nozzle wall, as shown in Figs. 1 and 2.

![Flow direction](image)

**Figure 3**: Definition of the geometric features shown on a cross-sectional cut of a slotted panel.

<table>
<thead>
<tr>
<th>Panel #</th>
<th>t (mm)</th>
<th>D (mm)</th>
<th>D/t</th>
<th>S/t</th>
<th>Sketch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>6</td>
<td>4</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>12</td>
<td>4</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

The second part of the tests involved slotted panels with modifications made to their edges. In contrast to the previously described sharp edges, the modified models had either a partial or full bevel on the lengthwise edge with a bevel angle of 45°. These modifications were made only to the panels 2 and 3 of Table 1 as the bar thickness, being 3 mm, was sufficient to produce the two distinct bevel geometries on edges. Each modified panel was tested both having its sharp and beveled edges exposed to the flow by flipping the model in the wind tunnel. These tests are depicted in Figs. 4 and 5.

![Partial bevel edge modification](image)

**Figure 4**: Partial bevel edge modification on the flow-facing side (top) and leeward side (bottom).

![Full bevel edge modification](image)

**Figure 5**: Full bevel edge modification on the flow-facing side (top) and leeward side (bottom).

![A section of the perforated panel](image)

**Figure 6**: A section of the perforated panel.

![Blunt edge on flow-facing side](image)

**Figure 7**: Blunt edge on flow-facing side.

![Blunt edge on leeward side](image)

**Figure 8**: Blunt edge on leeward side.

The third part of the tests was executed on panels with circular perforations. Two panels were tested, each having an open area that was 40% of the total area, hole diameters of 6 mm and 3 mm respectively, and thicknesses of 1.5 mm. Figure 6 pictures a section of one of these perforated panels. Owing to the manufacturing process, these perforated panels had a side with blunt perforation edges (that had a radius of about 0.5 mm) and a side with sharp edges, and by simply flipping the panel in the tunnel, it was possible to assess the noise output of both sides exposed to the flow. This change during testing is pictured in Figs. 7 and 8, where a cross-sectional cut through the perforations is shown. Both panels were mounted to the same brackets used for the slotted models. The perforated panels had a height of 230 mm.
and a length of 320 mm, and tested across the same range of flow speeds and angles used for the earlier parts of this investigation.

3. Results and Discussion

This section presents results for the aforementioned three parts of testing involving slotted panels with sharp edges, slotted panels with one side having partially as well as fully beveled edges while having the other side sharp, and perforated panels with circular holes that have rounded edges on one side and sharp edges on the other. SPLs are presented and plotted against either frequency \( f \) in dimensional form or Strouhal number \( St \) in non-dimensional form. Herein, Strouhal number is computed as depicted in Eqn. 1, with \( f \) representing frequency, \( D \) representing the gap opening in the case of slots or hole diameter in the case of circular perforations, and \( U \) representing the flow velocity.

3.1 Slotted Panels with Sharp Edges

The narrowband acoustic spectra for panel 1 (specified in Table 1) when exposed to a constant flow speed of \( U = 20 \text{ m/s} \) is presented for varying flow incidence angles in Fig. 9. In this figure, the data is presented in non-dimensionalized form. The results clearly depict two dominant tones, marked with lines, at approximately \( St = 0.5 \) and 1. The \( St \) values of these tones match with those corresponding to the first two modes that the Rossiter formula (Eqn. 1) identifies for fluid-dynamic type oscillations. For purely grazing flow at 0°, such tones are not discernible in Fig. 9. However, for 5° incidence angle, tones appear, with their SPL increasing to a maximum between the incidence angles of 10° to 15°, followed by a decrease at larger angles. Similar trends were also observed for varying angles of incidence in the study of Vanoostveen [10] on slotted models of the same geometry.

![Figure 9: Acoustic response of slotted panel 1 with slot gap of \( D = 6 \text{ mm} \) and thickness \( t = 1.5 \text{ mm} \) at 20 m/s flow velocity and varying angle of incidence.](image)

![Figure 10: Acoustic response of slotted panel 1 with slot gap of \( D = 6 \text{ mm} \) and thickness \( t = 1.5 \text{ mm} \) at 10° angle of incidence and varying flow velocity.](image)

Figure 9 presents the data for the same panel geometry (panel 1) for varying flow velocities from 10 m/s to 30 m/s at a constant flow incidence angle of 10°. The Strouhal numbers corresponding to the tonal peaks remain constant, showing that the corresponding frequencies increase linearly with the flow velocity (which is typical of fluid-dynamic mechanism as noted by earlier studies [10]). It is, therefore, apparent that the mechanism for flow oscillations is fluid-dynamic for the slotted panel in oblique angles of flow incidence. The data for panels 2 and 3 is not shown in this paper as they also yielded similar trends, with tonal peaks appearing at approximately \( St = 0.5 \) and 1.
3.2 Slotted Panels with Modified Edges

To evaluate the effect of edge modifications on the acoustic response of the slotted panels, results are presented in Fig. 11 for three different flow velocities at 10° angle of incidence, which is where the two tonal peaks, previously discussed, were most prominent. The top row in this figure compares the SPL results of panel 2 having the partially beveled edge facing the flow side with those of the same plate with no edge modifications (i.e., having sharp edges) and the bottom row provides the same comparison for panel 3. Orange lines are used to provide SPL variations for the partially bevelled panels, whereas the blue lines indicate those for panels with no edge modifications.

![Figure 11](image)

Figure 11: Comparison of the SPLs of panel 2 (top row) and panel 3 (bottom row) with the partial bevel edge modification on the flow-facing side (orange line) and without any modifications (sharp edges) (blue line) for 10° angle of incidence and varying flow velocity from 10 m/s to 30 m/s.

![Figure 12](image)

Figure 12: Comparison of the unmodified slotted panel (blue line) and the partial bevel edge modification when oriented such that the bevel is on the flow-facing side (orange line) or on the leeward side (yellow line), for panel 3 at 10° angle of incidence and 20 m/s flow velocity.

In general, the data presented in Fig. 11 suggests that modifying the flow-facing edge of the slotted panels yields promising effect. For both panels, one or both of the prominent tones appear to be attenuated to some extent for all flow velocities, with the exception of panel 3 at the particular velocity of 10 m/s (where a larger tonal peak appears). The tone mitigation appears to be more significant with partial bevel application for the panel with smaller D/t (i.e., panel 3) especially at higher flow velocities. It is expected that the relative size of the vortical structures at the impingement location is a factor. Panel 2 with its larger slot gap of 12 mm would allow the vortical structures to grow to a larger size, possibly making the acoustic feedback mechanism more difficult to disrupt with an edge modification. It was observed that...
orienting the slotted model with the beveled edge placed on the leeward side of the tunnel had an adverse effect on tonal noise mitigation. As can be seen in Fig. 12 for panel 3, the partially beveled edge on the leeward side increases the SPL of the first tonal peak by over 10 dB compared to the unmodified case with sharp edges on both sides. This result is substantially more significant when compared to the partial bevels placed on the flow facing side, where the tone is more than 35 dB lower in amplitude. Nevertheless, SPL of the second subsequent tone is reduced by having the partial bevel on the leeward side compared to the panel with sharp edges, as well as the lower frequency content below 600 Hz.

For the edge modifications involving the full-depth bevel, there were no significant deviations from the abovementioned trends observed for the partial-depth bevel.

3.3 Perforated Panels

Figure 13: Comparisons of the acoustic response for the perforated panel with a hole diameter of $D = 6$ mm and blunt side facing flow (blue line), the perforated panel with a hole diameter of $D = 6$ mm and sharp side facing flow (orange line), and the perforated panel with a hole diameter of $D = 3$ mm and blunt side facing flow, at an angle of incidence of 10° and a flow velocity of 15 m/s.

The perforated plate with a hole diameter of $D = 6$ mm produced a distinct tone at 2,600 Hz when oriented such that the side with blunt hole edges was facing the flow (the blue line in Fig. 13). This was observed for flow velocities of 10 m/s, 15 m/s, and 20 m/s with Fig. 13 showing it for 15 m/s. This frequency is close to that observed by Feng [9] for a similar hole geometry (which was 2,500 Hz). The tone in Fig. 13 was eliminated when the sharp side of the panel was oriented to face the flow in parallel with what was observed by numerous previous studies [8-10]. It should be noted that in the case of the slotted panels, an edge modification on the non-flow-facing side exaggerated the tone whereas it mitigated the tone on the flow-facing side. This is opposite to what is observed in the case of the perforated panels as seen with the blue and orange lines in Fig. 13 above. The insight into this opposite observation is not known at this point to the authors and requires detailed investigation of the flow behaviour.

Reducing the hole diameter to $D = 3$ mm for the perforated plate was also successful at removing the tone (as can be seen from Fig. 13). This tone removal occurred regardless of the orientation of the blunt hole edge (although the result not shown here for brevity). Furthermore, the perforated plate with reduced hole diameter is associated with a significant broadband noise reduction at frequencies above 600 Hz, as shown by the yellow line in Fig. 13.

4. Conclusions

For the slotted panels with sharp edges, two distinct tones were identified for flow angles of incidence above 5°, reaching a maximum amplitude between 10° to 15°. The corresponding values of Strouhal number were consistent between different slot geometries and flow velocities, and are related to a Rossiter type fluid-dynamic feedback mechanism. Edge modifications in the form of a partial bevel and full
bevel were made to the slotted panel models to assess their effect on the two identified tones. For both types of slot edge modifications, having it on the leeward side further amplified the first tone whereas bevels on the flow-facing side were effective at reducing the SLPs associated with one or both tones.

The perforated panel with a hole diameter of \( D = 6 \) mm generated strong tones at 10 m/s, 15 m/s, and 20 m/s, which were all mitigated when the plate was oriented such that the side with sharp hole edges was facing the flow. This observation agrees with the previous work available in the literature on perforated plates but is contrary to the abovementioned observations made for modifying the edges of the two-dimensional slotted models. The panel with smaller holes, \( D = 3 \) mm, did not generate any distinct tones at any angle of incidence or flow velocity.

It is evident from the presented acoustic data that edge modifications to slotted and perforated panels have effects on the tonal noise generated, which are promising for noise control and mitigation. However, the results have also shown that improper application of certain modification is also liable for an increase in tonal noise, and therefore, a detailed understanding of the flow physics associated with each modification method is required for further elucidation. Future work is planned to include Particle Image Velocimetry (PIV) studies to gain understanding and insight into the flow mechanisms responsible for the unexpected trends observed in the acoustic data. With such knowledge, the design, manufacturing, and use of perforated and slotted panels for architectural applications can be done better for noise control.

5. Acknowledgments

This paper is supported by an NSERC Engage grant and Aercoustics Engineering Limited. A big thank you to Prof. Alis Ekmekci, who supervised this project, as well as Ryan Tam and Philip McCarthy, whose contributions to the project were invaluable. From Aercoustics, a big thank you goes to Nicholas Sylvestre-Williams, Principal, and Dr. Eric Salt, for their industry expertise and consultation.

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