Wind-induced sound on buildings and structures

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1 INTRODUCTION

Wind flow around buildings and structures has led to annoying noise levels at several occasions, especially in cases where tonal sound was produced. The human hearing is equipped to distinguish tonal or pulsating sound from random noise patterns, causing tonal or pulsating sound to be perceived as more annoying (ISO 1996-2). Tonality is often caused by the phenomenon that the wind flow forms regular wave or turbulence patterns between, in or behind parts of the building or structure.

For instance, two tall buildings in the Netherlands shortly after completion became notorious for the high sound levels resulting from wind at speeds above 12-15 m/s. Costly measures had to be taken afterwards to reduce the noise. Other recent examples are available, both in The Netherlands and worldwide. In a number of cases, the source was found to be steel grids that had been applied as an ornament or as a functional addition to the building. It was, however, neither clear under what conditions steel grids produce tonal sound, nor exactly what acoustic phenomenon causes this sound production.

Figure 1: Two examples of buildings where wind-induced sound caused problems: *Het Strijkijzer*, The Hague (130 m), completed in 2007 (left) and *De Hoftoren*, The Hague (110 m), completed 2003 (right).

In the master thesis reported in this paper, research was carried out to gain better insight in the 'whistling grids' problem (Ploemen, 2010). First a literature study was carried out in order to determine if any existing models could be found describing the phenomenon. Furthermore, a number of experts from Dutch consultancy firms in the field of acoustics were interviewed, to make an inventory of the state of the art in the advising practice.

1.1 *Literature review and state of the art in practice*

The interaction of flow and structure is a well known source of acoustical or structural problems (Blevins, 1990 and De Bruijn). The field of aero-acoustics comprises many researches of vibrations caused by airflow, originating from different domains, such as aerospace engineering, automobile design, duct design, etcetera. Several studies, among which Blevins (1990) is a quite comprehensive one, describe how the mechanism of vortex shedding leads to tonal sound: alternating vortices arise in the wake of an object. Early research (around 1878) by Strouhal already indicated that for a cylinder the frequency of the shedding was only dependent on the proportion of the flow speed and the characteristic size (diameter) of the cylinder. Similar results have been reported by various authors on an array of plates or strips, paying attention to the ratio between length (in direction of the flow) and thickness (perpendicular to the flow) (chord/thickness-ratio or c/t ratio).

This, however, does not explain that in some situations frequencies are measured that remain constant while modifying the wind speed. Parker (1966) and Parker and Griffith, (1968) found that in a setup of parallel thin plates within certain flow speed ranges constant frequencies can be heard that do not change with the flow speed. These resonance frequencies appeared to depend on the distance between the thin plates, and not primarily on the c/t-ratio. Spruyt (1972) did further research on sound caused by flows through grids perpendicular to the flow direction, elaborating on the work of Parker mentioned above. He states that the sound is originating from acoustical resonance between multiple periodically shedded vortices in phase, and that the grid size determines the possible resonance modes for certain speed range bandwidths. In many practical examples grids are involved emitting high sound levels when subject to wind, which makes the researches of Parker and Spruyt very relevant.

More recently, Granneman et al. (2009) performed relevant research, as a spinoff of the search for solutions for the Strijkijzer case in The Hague (see figure 1). In the wind tunnel, a series of parallel strips was mounted on a varying number of bearing bars, where both the distance between the strips and the amount of bearing bars could be modified. The distance between the bearing bars appeared to be crucial for the production of tonal sound. Furthermore the rounding of the strip edges by attaching a thicker edge appeared to significantly decrease the noise generation. The research of Granneman coincided in time with the research carried out in the MSc thesis, leading to some parallel research and findings. A comparison will be made in chapter 4 of this paper.

In the fall of 2008 five experts from the main Dutch consultancy firms have been interviewed. The following are the main findings resulting from these interviews:

- cavities, lamellas and steel grids are a well known origin of wind-induced sound; the sound levels produced can be very high. Locally higher wind speeds as a result of the flow around the building can bring forward the onset of problems as well as result in higher nuisance;
- the rounding of the elements' leading and trailing edges helps to reduce the risk of wind-induced sound;
- prediction in the design stage is still very difficult; the available acoustical models are to simple and course to cover the complex reality;
- wind tunnel testing is the only way to achieve a reasonable level of certainty, but this is limited to the specific case under investigation;
- CFD until now does not offer a workable alternative, due to the great difference in the large scale of the global flow pattern in an urban environment and the small scale of the occurring sound inducing mechanisms but is promising for the future; wind tunnel research is expensive; this results in the situation that most researches on wind-induced sound are directly related to advice for actual building projects.

From literature and expert interviews it became clear that many factors determining the risk of tonal noise annoyance as a result of wind induced sound remain still unknown, and no accurate prognosis can be made in advance. Therefore, a series of wind tunnel tests on various steel grids was performed, to try and indentify the parameters responsible for the tonal sound. Grid manufacturer DEJO kindly provided a number of steel grids with varying geometric parameters. The Faculty of Aerospace Engineering kindly offered the possibility to use the new 'Open Jet Facility' wind tunnel (Wassink, 2008). In the following sections the successive research steps and conclusions are described.

2 MEASUREMENT SETUP

2.1 *Wind tunnel facility*

From practice, it is known that wind-induced tones with grids typically require wind speeds of at least 12-15 m/s or higher. The Open Jet Facility (OJF) at the Faculty of Aerospace Engineering, TU Delft, capable of speeds to 30 m/s from a 2.85 x 2.85 m^2 opening, was used. It permits for full scale testing, avoiding issues associated with scaling. The flow of the jet is almost laminar, with a turbulence of less then 1%, and a constant wind speed (deviation < 0.5%) over the outlet of the jet, already constant within a few centimeters from the edges of the outlet.

2.2 *Grid specimen*

Twelve 1x1 m² galvanized steel DEJO grids with rectangular meshes were available for testing, all of commonly used standard sizes and types. Six of these grids (numbered 1-6 in the remainder of the paper) were sharp-edged, the other six (numbers 7-12) had a slightly rounded finish of the edges, with a radius of approximately 0.25 mm.

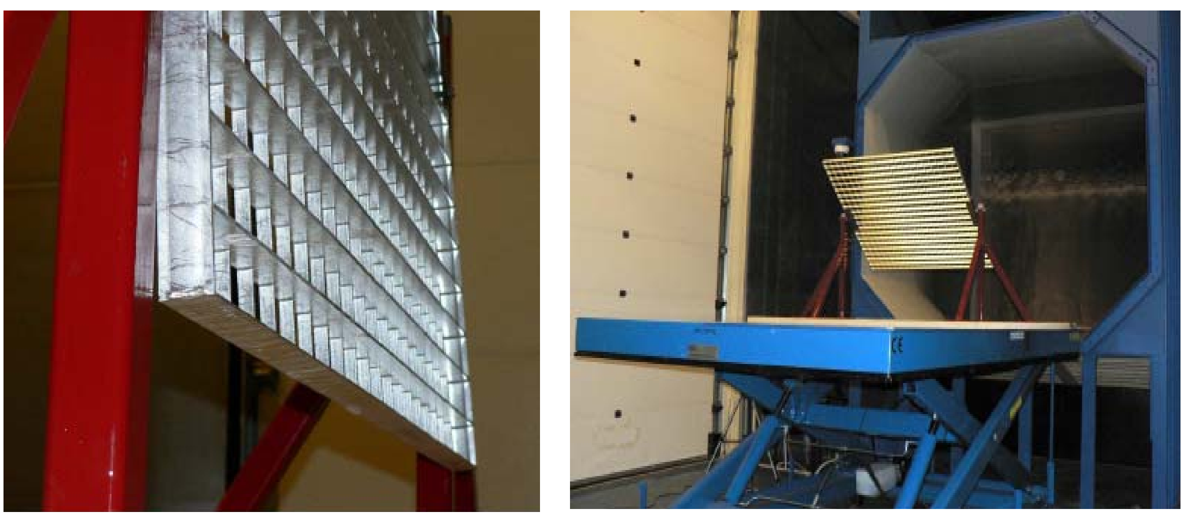

Figure 2: Test setup, with a close-up (left) of a grid mounted in the wind tunnel, ready for testing (right).

Within a set of six grids, three parameters were varied: mesh size, steel strip thickness, and the ratio of the height and width of the individual strips that make up the grid (c/t-ratio, see subsection 1.1). Each grid had a differed combination of those parameters, as shown in table 1.

Table 1. Dimension of the grids (see Figure 3 for definitions)

grid #	Mesh size (mm)	Bearing strip (c x t in mm)	Helper strip (c x t in mm)
1, 7	33.33 x 33.33	30 x 2	10 x 2
2, 8		30 x 3	
3, 9		40 x 2	
4, 10	49.99 x 49.99	30 x 2	10 x 2
5, 11		30 x 3	
6, 12		40 x 2	

In addition, a second round of testing was performed in 2010, which included a grid with a mesh size of 66x66 mm, as well as more fully rounded specimen. Also, the use of expanded metal mesh, applied onto grid, was evaluated as a possible countermeasure.

2.3 *Test setup and procedure*

Each grid was mounted between two tripods of welded steel tubes fitted to a thick laminated plywood base plate (see Figure 2), in turn bolted to the wind tunnel's testing platform. The bearing strips were in horizontal orientation (see Figure 3), parallel to the tilting axis, the helper strips were in vertical orientation. In all experiments with different grids, the wind tunnel was first started at a wind speed of 15 m/s, and the grid slowly tilted around a horizontal axis until a tone could be heard. Then sound recordings were taken at wind speeds of successively 10, 15, 20 and 25 m/s.

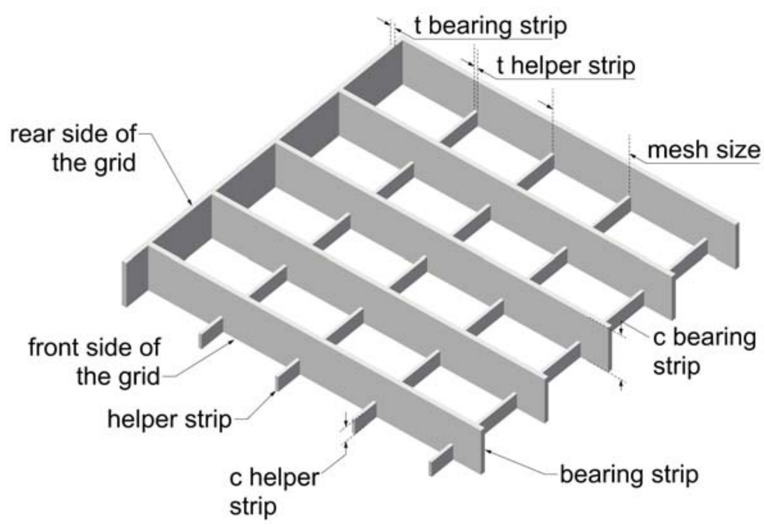

Figure 3: example grid with definition of the geometrical parameters

This procedure was repeated until the grid had made a full circle tilt around the axis. The sound meter was positioned directly outside the contours of the tunnel exhaust flow at a distance of circa 1.5 m from the edge of the grid. Every recording was about 30 seconds in length, and saved as a wav-file in a Norsonic NOR-140 sound meter. Subsequent data post-processing of the sound files was done in Matlab. The post-processing consisted a.o. of Fourier frequency analysis, making the results dimensionless in several different ways, and plotting in different graph layouts.

3 MEASUREMENT RESULTS

3.1 *Sound pressure level related to wind speed*

All tested grids produced tones that were clearly audible above background noise levels, with sound pressure levels reaching up to 112 dB (re. 20 µPa). Tones were usually found at two to four very specific angles. In some cases tones were found at wind speeds as low as 8 m/s, although typically the onset of tonal sound occurred between 10 and 15 m/s. As expected, the sound pressure level of both the tones and the background noise increased with higher wind speed. The highest sound pressure level measured was 112 dB with a frequency around 2586 Hz, at 25 m/s.

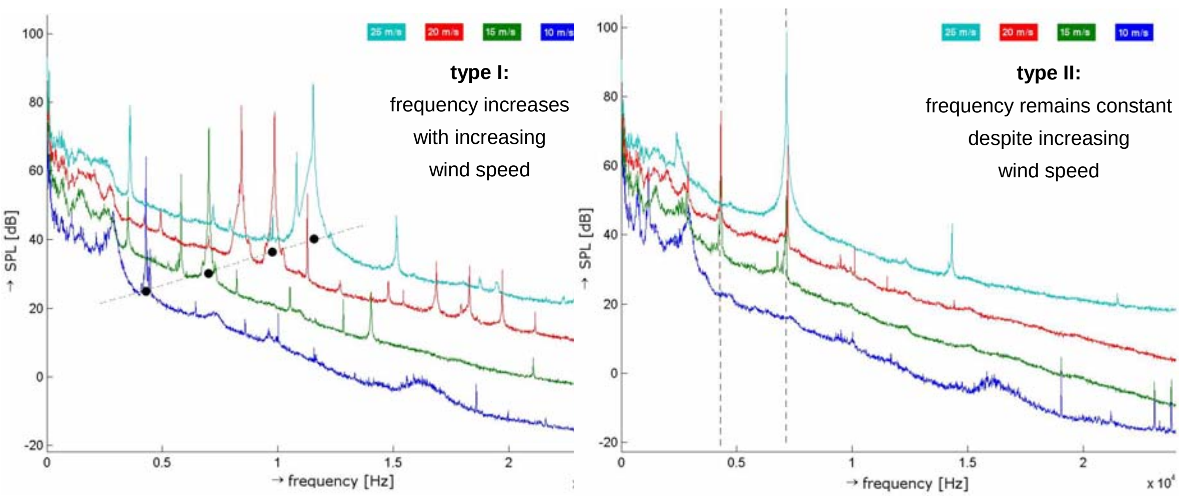

Figure 4: example of increasing frequency and sound level with increasing wind speed (type I, left), and tones with constant frequencies (type II, right).

Above the minimum wind speed, tones could often be heard without interruption while increasing the wind speed to 25 m/s. This implies that there is no practical “safe zone” in terms of wind speed once the minimum speed needed for the onset of problems has been reached.

3.2 *Frequency related to wind speed*

The typical frequencies of the tones found in this research are above 1500 Hz. Turning off the wind tunnel engine from top speed caused a gradual decrease of the wind speed from 25 m/s to zero. During this period it was observed that many tones stayed audible at a constant frequency over a range of wind speeds. However, during the same procedure, sudden changes in frequency were also noted, indicating that more than one mechanism is responsible for the induction of sound. Subsection 3.5 will deal with these two types of tones in more detail.

3.3 *Sound pressure level related to the angle between grid and flow*

The angle between flow and grid influences the production of tonal noise. This result was also found by Knisely (1990). In figure 5 an overview is given of the produced sound pressure level (SPL) for all different angles that were tested. For example: the circles within the ellipse show a SPL from 45 to 75 dB for grids #4 and #10 with a 30x2 bearing strip, under an angle of 130 degrees, which more or less matches the setup as shown in the small icon top left of the diagram in figure 5. From the graph it can be concluded that it is not possible to identify a range of angles between flow and grid that will exclude tonal noise. A similar SPL-angle graph was made with the two mesh sizes as variable instead of the strip's c/t dimensions. This also led to a quite scattered picture and the conclusion that of the tested set of grids both mesh sizes 33x33 and 49x49 mm produce whistling tones.

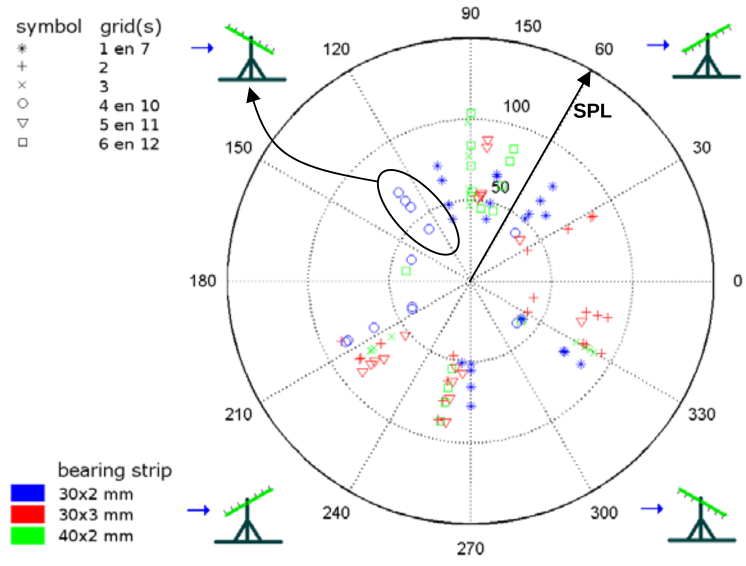

Figure 5: plot of the angle between grid and flow and sound pressure level on radial scale ranging from 0 to 150 dB, for all measurements.

3.4 *Wind flow through grid*

Disrupting the flow just upstream of the grid with a small object canceled or significantly reduced the tones in loudness. This effect was best noticeable with small objects (e.g. a ruler) held near the center of the grid, indicating that this area is the most productive source of noise. The disturbance was minimal when the object was positioned nearer to the edges. A plausible explanation is that due to the aerodynamic flow resistance of the grid, the wind flow tends to bend around the grid edges, resulting in lower flow speeds through the edge zones than through the centre of the grid.

3.5 *Parameter based comparison: two types of tones*

A comparison of the measurements of various grids has been performed for a number of parameters, such as their material's finish and geometry (mesh size, dimensions of the strips). Comparing various series of measurements of grids at different speeds revealed the existence of two distinctly different types of tones. With the first type, the frequency of the tones increases with wind speeds (see figure 4, left), whilst the second type is characterized by peak frequencies being constant over various wind speeds (figure 4, right). The former (type I) is mostly found at angles between 20 and 60° from horizontal (see figure 6), while the latter (type II) is common when the grid is within 20° from a vertical position (i.e., 70-90° from horizontal).

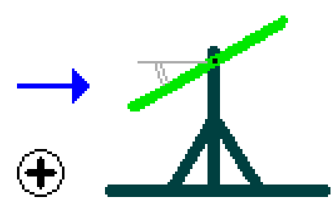

Figure 6: Small positive angle to the (horizontal) flow

In the case of type II tones, the wavelengths are determined by the geometry of the grid. The wavelengths are found to be either once or twice the dimension of the mesh openings. With mesh openings measuring 33 and 50 mm and a grid thickness of 30 or 40 mm, common wavelengths were 48-51 (equal to mesh sides; ~6.8 kHz), 59-61 (~5.7 kHz), and 80-83 mm (equal to twice the grid thickness in both cases; ~4.2 kHz). A tone with a wavelength close to 30 mm (~11.4 kHz) was found only once, although that size was present both in the mesh sides and the grid thickness. This suggests the occurrence of that type II is subject to a minimum required mesh sizes. Below such a limit, the effects of the flow around neighboring strips would be such that no regular pattern emerges. Similarly, with increasing mesh size, the strips of the grid would be situated to far apart to form a repetitive structure, i.e. the flow around the next bearing strip wouldn't influence or interact with that around a previous strip anymore. In the tests performed with 66 x 66 mm grids, tones still occur, hence a maximum size must be larger than this.

3.6 *Expanded metal mesh as a countermeasure*

During a second round of wind tunnel tests, two types of expended mesh (see figure 7) were evaluated as a possible countermeasure. Such a setup is sometimes used to create a less slippery walking surface. Steel wire was used to firmly attach the expanded metal to the grids, at either the front or rear side of the grid. The expanded metal would cover the complete surface of the grid. This resulted in a significant decrease of the occurrence of tones, although they were not completely eliminated. Typically, the tones would occur only at higher wind speeds (25 m/s), and at fewer angles than without the countermeasure. The expanded metal proved most effective when attached to the front side of the grid. Grids with expanded metal produced significantly higher levels of broad spectrum noise, but not to such a degree it would present noise hindrance problems in practice.

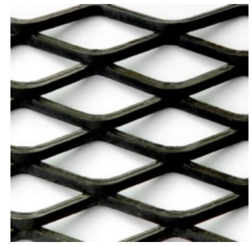

Figure 7: 'Expanded metal' mesh. Sized used would have openings smaller that the grid mesh.

3.7 *Effects of rounding the strips*

In the second session, some of the grids had strips rounded as much as possible, i.e. a radius of 3 mm. Contrary to what was expected based on the findings from the interviews mentioned in subsection 1.1, such rounded strips didn't behave differently in the wind tunnel test. The number of angles at which tones could be heard, their loudness, and the onset speed appeared unchanged. A possible cause is the limited degree of rounding that can be achieved with a strip thickness of just 3 mm.

4 COMPARISON OF RESULTS BY GRANNEMAN ET AL.

Granneman et al. (2009) performed similar tests in a wind tunnel with a setup that allows for varying the number of and the distance between steel bearing bars, resembling a grid. The results confirm a number of observations made in this research, including the existence of a minimum wind speed for the tonal sound to occur, the persistence of such sounds over a range of wind speeds, and the notion of specific angles of attack at which the sound levels are much louder. Interestingly, while Granneman identifies the peaks as aeolian tones defined by the Strouhal number in his paper, its plots of the frequency against the sound level show peaks that do not increase in frequency as wind speeds increase, as one would expect in case of Strouhal. Those would appear to match the principle of the tones previously designated as "type II" in this research. Unfortunately, the graphs' horizontal axis is only in 1/3rd octave bands, thereby providing insufficient detail to be able to determine the wave lengths and hence a possible relation to the geometry of the test grating as found with our grids.

The requirement of repetitiveness in terms of a minimum number of equally spaced elements (found to be 9 by Granneman et al.) provides an interesting perspective at a possible way of eliminating tones, and may well be at the core of why grids produce very high sound levels. This concept could also provide an explanation for the source of the tones being located only near the centre of our 1x1 meter grids, as suggested by our attempts to influence the tones by (partially) disrupting the flow upstream of the test grid. While attempting to replicate the findings by partially covering the tested grids we did find a similar minimum number of strips needed in order to produce tones of about ten, although our setup with fixed size grids was less suitable for this particular purposes than the fully modular design deployed by Granneman.

Contrary to the results obtained by Granneman we were able to find tones at a mesh size of 50mm (and in a later session in October 2010 also – albeit at less angles – with a 66x66mm). Nevertheless, the existence of an upper limit to the spacing of the strips is likely to exist, above which the structure acts as individual strips and feels to meet the typical repetitive character identified by Granneman (and also suggested by practice) as a apparent prerequisite.

5 CONCLUSIONS

The OJF of TU Delft offers a good facility to test the acoustical phenomena as described.

Grids of the types tested always produce sound when exposed to wind speeds higher than 8 m/s. Without prior testing or countermeasures these grids cannot be recommended for building practice due to the risk of loud tones. Two distinctly different types can be easily distinguished by whether or not the frequency changes with the speed of the flow.

Sounds levels well in excess of 100 dB are possible with a surface area as small as one square meter and plenty of room for the flow to divert around the grid. The potential problems with any facade or roof having hundreds square meters is evident. The only circumstance that keeps these problems from occurring more often is the strong dependence on the angle of attack, which must be within narrow bands for tonal noise to occur at all.

Further work should be done on visualizing the flow in or near the mesh openings, for example by means of particle image velocimetry (PIV). This kind of approach could also be useful to evaluate the influence of turbulence, and whether the flow in the wind tunnel is a realistic enough substitute for the more turbulent profile of the wind outdoors.

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