Control of Aeolian Noise Generated by the Finned Balustrade of a Freeway Pedestrian Overpass

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Abstract

During construction of a new freeway in Melbourne, it was found that tonal wind-induced noise was being generated by the finned balustrades of architecturally designed pedestrian overpasses which had been installed at several locations along the route. As the level of wind-induced noise was unacceptable at residences in the vicinity of the over-passes, a solution to reduce or eliminate the noise had to be developed. The solution needed to be practical to retrofit to the existing structure, while satisfying strict project constraints in relation to urban design, design life, and safety in design rules. This paper outlines the investigation that was undertaken to determine the wind-conditions under which the noise occurred, discusses the noise-generation mechanisms that were established to be causing the noise, and presents a summary of the potential solutions that were identified through theoretical analysis, wind tunnel modelling and field trials.

Introduction

AECOM was engaged as the acoustic consultant on the development of Eastlink, a 40km toll road through Melbourne's eastern suburbs, undertaken as a Public Private Partnership between Connecteast and the Victorian Government. Six pedestrian overpasses were built as part of this project, and were fitted with balustrades that were designed to enhance the visual amenity of the project. Unfortunately, the balustrades of these overpasses were found to generate a significant level of wind-induced noise under certain wind conditions.

The balustrades consisted of a series of vertical fins spaced at 125mm centres, with cylindrical horizontal supports near the top and bottom. Each fin was constructed from 6mm thick steel plate, and was approximately 2m long and 125mm deep. A typical balustrade is shown in Figure 1.

Under the wind conditions where the noise was observed to occur, the tonal noise generated by the balustrades was measured to be up to 40 dB above the residual noise levels. This level of noise was unacceptable at residences neighbouring the overpasses, and was unlikely to be sufficiently masked by traffic noise once the freeway was operational. A solution to reduce the level of wind-induced noise was therefore required, for implementation with minimum possible delay to the project.

Figure 1 – Finned Balustrade of Pedestrian Overpass

Strict design rules associated with the freeway project dictated that the solution could not significantly change the appearance of the overpass, could not provide any hand or foot holds that would assist people in climbing over the balustrade, would need to be resistant to vandalism, and have a design life of nominally 20 years.

This paper presents a joint effort by Thiess John Holland (the company responsible for construction of the project), AECOM, and the University of Adelaide to understand and overcome this noise issue within tight design and time constraints. After a description of the noise problem, a model of the noise generation mechanism is presented. This model was used to produce a number of mitigation measures, which were tested in an anechoic wind tunnel. These tests led to the selection of the most appropriate measure, which was implemented on the

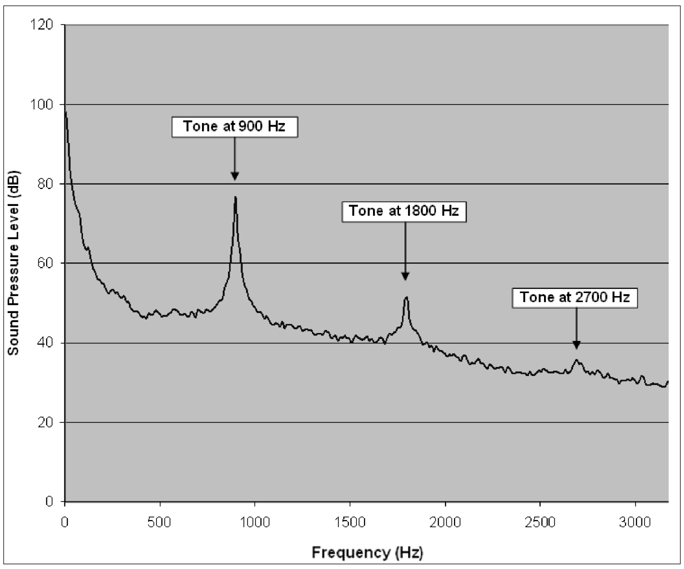
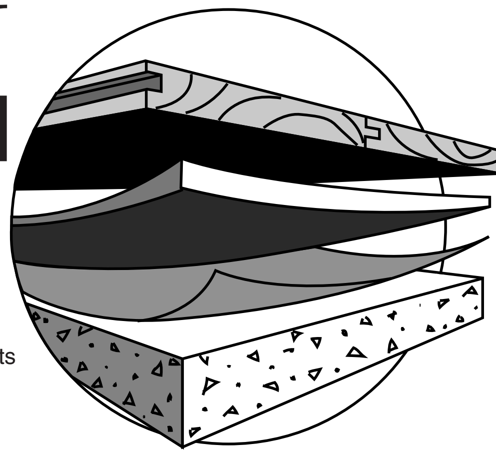


Figure 2 – FFT of the Wind-Induced Noise

EMBELTON
IMPACTAMAT



FLOOR ISOLATION

TYPICAL PERFORMANCE CHARACTERISTICS
The table below gives IIC ratings based on tests of various surface treatments Ref. ASTM E989 using an Impactamat resilient interface on a 100mm thick concrete structural floor.

FLOOR SURFACE TREATMENT (Floating Floor Construction)	Impactamat			Overall IIC Rating	IIC Improvement over bare slab	Ref.fig.
	Construction	Type	Thickness			
Loose lay timber veneer flooring with thin foam bedding layer	full cover	750	5mm	47-50	18-20	1
Direct bond 19mm block parquetry	full cover	900	5mm	45-49	18-20	2
Direct bond 10mm ceramic tiles	full cover	750	5mm	44-46	13-15	2
Particle board or strip timber battens supported at nom. 450 x 450 centres with acoustic absorption	pads 75 x 50mm	750	10mm	52-60	21-30	3
Double layer bonded 12mm ply with bonded parquetry, supported at nom. 300 x 300 centres (sports floor)	pads 75 x 50mm	750	10mm	52-57	21-27	4
50mm reinforced concrete slab or 25 mm slab with 20mm bonded marble/slate/ceramic tile	full cover	750	10mm	58-63	27-32	6
50mm reinforced concrete slab	full cover	750	15mm	59-64	28-33	5
100mm reinforced concrete slab	full cover	750	15mm	60-65	29-34	5

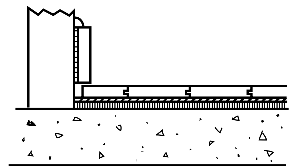


Fig. 1 Timber loose lay floating floor

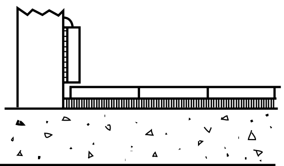


Fig. 2 Direct bond parquetry or ceramic tiles

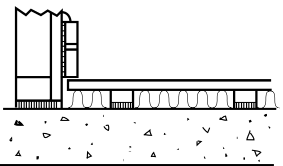


Fig. 3 Timber strip floor on battens with isolated frame wall

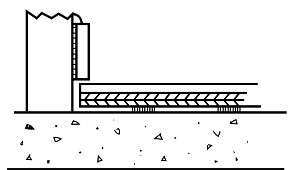


Fig. 4 Sports floor

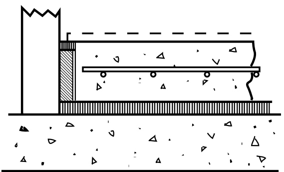


Fig. 5 Concrete slab

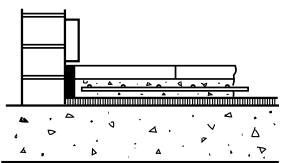


Fig. 6 Marble/slate ceramic tiles with thin reinforced slab

IMPACTAMAT by EMBELTON features two main environmental properties: it is recycled and it reduces noise pollution.
Indeed, it is made from 100% recycled natural rubber recovered from tyres, granulated and reconstituted as a solid mat (various sizes are available upon request).

IMPACTAMAT is a flexible material manufactured as a preformed sheet bound together with a flexible binder.
It is a low cost impact absorbing layer for covering hard earth or concrete in outdoor applications or as an underlay for in-situ cast or pre-cast concrete floors where noise isolation is required (rubber underlay, acoustic insulation, door mats, playground and sports surfaces, industrial floor tiles etc.).

footbridges. Preliminary results are discussed.

Characterisation of the Noise

In order to determine the cause of the aeolian noise, and to develop solutions, it was first necessary to establish the characteristics of the noise, and the wind conditions under which it occurred.

Initial data provided to the consulting team, in the form a recording of the noise that was taken by a site worker using a digital camera, provided preliminary information in relation to the characteristics of the noise. A Fast Fourier Transform (FFT) performed on this recording showed that the predominant frequency of noise was about 900Hz, with harmonics at 1800Hz and 2700Hz, as shown in Figure 2.

The wind speed and direction at the time when the recording was made was not noted, but the frequency of the noise generated was not observed to vary with wind speed.

To better establish the wind conditions under which the noise occurred it was proposed to perform wind speed and direction measurements in the vicinity of one of the pedestrian overpasses at a time when the noise was observed to be occurring. However, due to the variable nature of the wind and the distance of the nearest affected overpass from the engineering offices, it proved difficult from a logistical perspective to perform manned measurements to characterise wind conditions at the time when the noise was occurring.

On several occasions the consulting team were telephoned by site staff to notify them that the noise was occurring, but they were either unable to travel to site immediately, or they travelled to site only to find that the wind had died down and the noise had stopped by the time they arrived. After several unsuccessful attempts to perform manned measurements it was decided to attempt to use an unattended one-third octave environmental noise logger installed near to one of the overpasses, together with a portable weather station, to determine the typical wind speed and direction when the noise was occurring. The logger was set up so that it could be remotely accessed via telephone, to listen to the sounds at site and confirm if the noise was occurring at any particular time.

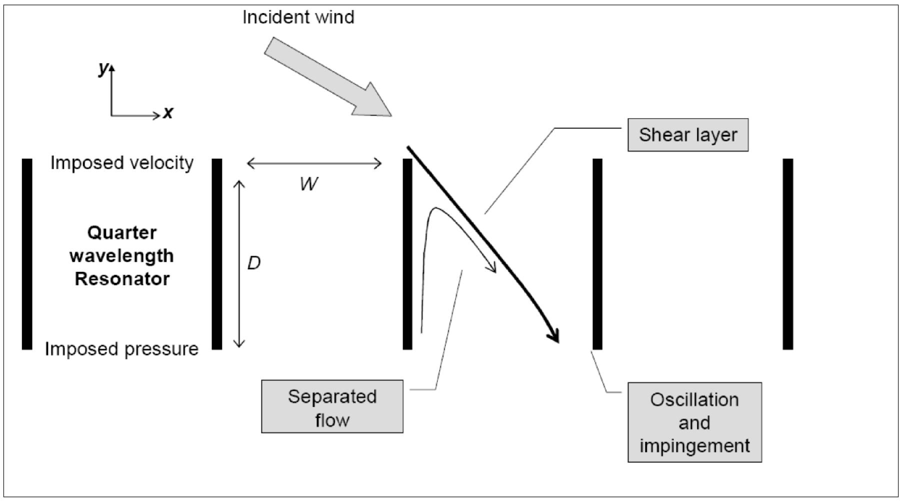


Figure 3 - Detailed Cross-section in Plan View Illustrating the Physical Parameters of the Balustrade and the Proposed Model for the Noise Generation Mechanism (from [4]).

This proved successful, and time periods where the noise monitoring results showed tonal peaks in the 800 Hz/1 kHz and 1.6 kHz/ 2 kHz one-third octave bands were able to be correlated with wind speed and direction data from the weather station. Based on this analysis it was established that the noise was occurring during periods when the wind direction was approximately 25 to 30 degrees to the balustrade and the 10-minute average wind speed was 6 to 7 m/s, gusting to approximately 10 m/s.

The University of Adelaide was then engaged to undertake an investigation of the physical phenomena responsible for this tonal noise, and develop mitigation measures that could be retrofitted to the existing balustrades. This work was detailed in a number of consulting reports [3],[4], and is summarised in the present paper.

Potential Noise Generating Mechanisms

The most recognised source of aerodynamic noise is often associated with vortex shedding, the frequency of which is largely determined by a characteristic Strouhal number, which is typically around 0.2 for bluff bodies [1]. The Strouhal number, denoted St, is the vortex shedding frequency f (Hz) normalised by the flow speed U (m/s) divided by a characteristic dimension D (m) of the structure, which in the present case is the thickness of the fins:

$$St = f.D/U \qquad (1)$$

This equation implies that the tone associated with vortex shedding has a frequency that is proportional to the wind speed. In the present case, however, the frequency of the tone was found to be independent of the wind speed. Furthermore, an unrealistic Strouhal number was obtained when the typical wind speeds and fin thickness were used in Eq. (1). Vortex shedding was therefore ruled out as the noise generation mechanism of interest.

Another potential noise source mechanism was structural coupling between the balustrade and the flow, resulting in vibration that would cause the observed tones. A preliminary analysis proved inconclusive, and the high modal density of the structure in the frequency range of interest did not support the existence of a well defined, isolated 900 Hz tone and its first harmonic.

Additional modelling subsequently indicated that the noise was generated by a more complex aerodynamic phenomenon, which is detailed in the next section.

Proposed Model for the Noise Generating Mechanisms

Based on a two-dimensional analysis of the flow around a balustrade panel as illustrated in Figure 3, it was assumed that a coupling was occurring between the shear layers originating from the sharp corner at the upstream edges of the balustrade fins, and the acoustic behaviour of the space delimited by two consecutive fins. For the purpose of the two-dimensional analysis, the width W is the distance between two fins, and the depth D corresponds to the thickness of the balustrade panels, which in the present case is equal to the width of the fins.

At low Reynolds numbers, the shear layers undergo transition from laminar to turbulent flow over the distance separating two fins. This transition mechanism is extremely sensitive to, and a powerful amplification mechanism for, external disturbances in a certain frequency range that is determined by the velocity profile of the shear layer [3],[4].

In the present case, it is argued that the disturbance that leads to an unstable response of the shear layer is caused by an acoustic resonance of the air volume separating pairs of adjacent fins. This volume is delimited by 1) the two fins, which impose a velocity condition; 2) the open faces of the balustrade, which can be approximated as imposing a pressure condition; and 3) the shear layer, which imposes a velocity condition through the development of flow instabilities.

Based on the frequencies of sound measured on site, it was concluded that resonance along the depth of the cavity was supporting the feedback mechanism. The approximate frequency of these resonances is determined by the following equation

$$D = \left(\frac{n}{2} + \frac{1}{4}\right)\lambda \qquad (2)$$

Where n = 0,1,2,... and λ (m) is the acoustic wavelength at the frequency of interest. Based on this equation, the first two modes are expected to occur at 0.7 and 2 kHz, which is approximately consistent with the field observations.

The feedback loop responsible for the observed tones is sketched in Figure 4.

It should also be noted that this phenomenon is only expected to occur at low Reynolds numbers, and in conditions such that the shear layer flow couples well with the acoustic resonances of the cavities.

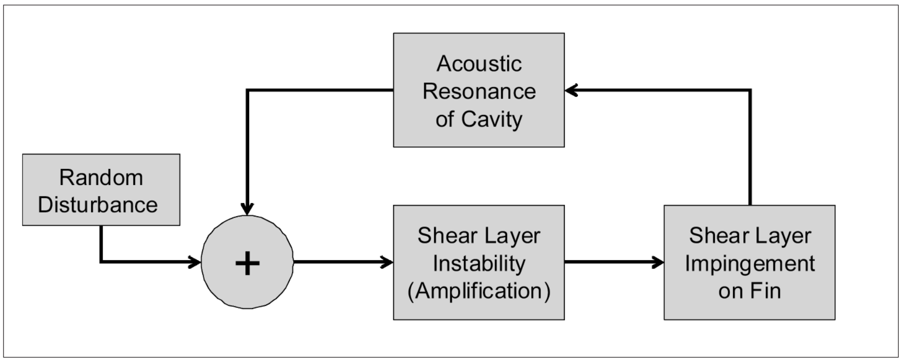


Figure 4 Block Diagram of Feedback Mechanism for Noise Generation

As the flow speed increases, the shear layers become turbulent and can no longer supply the strong amplification to the tonal disturbances, and the feedback mechanism stops, which is also consistent with site measurements.

Theoretical Solutions

Based on the noise generating mechanism suggested above, it was evident that the acoustic behaviour of each cavity was determined largely by the geometry of the balustrade. However, since the balustrades of most

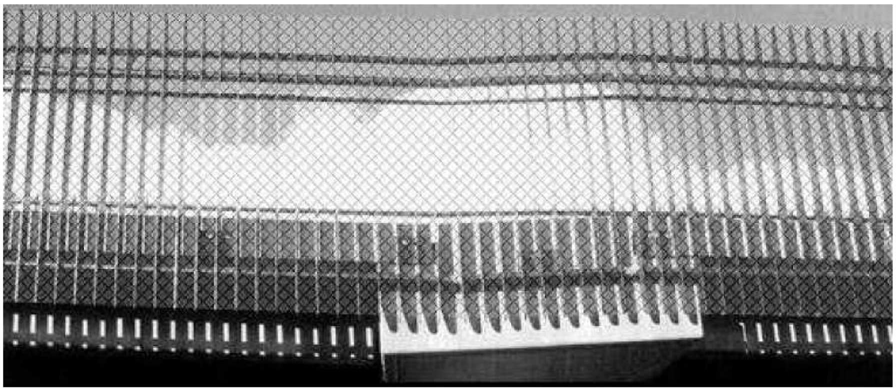


Figure 5 – Diagonal Wire Mesh Applied to Balustrade (Mock Illustration from [3])

of the pedestrian overpasses had already been constructed, it was not possible to significantly influence the noise generation through modification of the basic geometry of the balustrade. Rather, the only viable option was to reduce the sensitivity of the shear layers to the external excitations that were causing the acoustic resonance.

It was proposed that this could be achieved by introducing strong random fluctuations in the shear layer and surrounding region of the flow, using an irregular fin edge to assist the transition of the shear layer into turbulence, therefore ensuring that no organised vorticity pattern would be sustained and amplified in the shear layer.

A number of possible approaches to create irregular edges to the fins were identified:

Option 1 was to grind an irregular pattern in the edges of the fins. However, as the balustrade panels had already been painted and fitted to the overpasses, grinding and repainting the fins would have been a labour intensive and costly operation, when it was considered that there were over 12,000 balustrade fins across the entire project.

Option 2 was to add material to the fin to create a toothed, serrated or otherwise irregular edge, rather than remove material as with Option 1. It was anticipated that this would reduce the labour costs, and eliminate the risks associated with on-site grinding. It was suggested that this option could be trialled by applying an irregular bead (nominally 5mm in diameter) of a colour-matched silicone sealant or similar material to the edge of the fin. As a more permanent solution, it was suggested that this option could be implemented by way of irregular rubber or plastic extrusion the same length as the fin, which could be fixed to the edge of the fin with permanent adhesive.

Option 3 would simply involve modifying the profile of the fin edge e.g. rounding-off the square edges. A round edge was expected to cause the location of flow separation from the fin surface to be very sensitive to incoming turbulence as well as surface irregularities. It was expected that this would result in an irregular line of separation along the fin edge which would to be sufficient to disturb the shear layer that was thought to be developing from it. In practice, rounding of the fin edge could be easily achieved by fixing a plastic or rubber extrusion to the edges of the fins using a permanent adhesive.

Option 4 was a more global approach. It was proposed that wire mesh could be attached to the balustrade panel as illustrated in Figure 5. A diagonal woven wire mesh of nominally 50mm x 50mm with a wire diameter of 2-3 mm was recommended, based on the characteristics of the flow and the frequency of noise generated.

It was expected that this would eliminate the existing noise problem, but it introduced the risk that the mesh may then create vortex shedding noise when the wind was perpendicular to the balustrade and the mesh.

This option was also not ideal in terms of urban design, as it would significantly alter the appearance of the overpass. However, the urban designer was prepared to accept it if it was found to be the only viable solution.

Option 5 was to grow a vine along the balustrade. The complex vegetal structure would offer flow disturbances of various length scales, therefore maximising turbulence in the flow. However, this was not a practical solution for a number of reasons; most notably that no provision had been made for plantings in the design of the overpasses, and that the vines would have significantly altered the appearance and character of the balustrades, which were a key urban design feature of the freeway project.

A final option, **Option 6**, which was suggested by the construction team, was to construct a series of deeper fins, spread along the length of the balustrade, to screen the incident wind from the unmodified fins in between (See Figure 6).

Wind Tunnel Modelling and Practical Trials

Trialling each potential solution in the 'real world' at full scale would

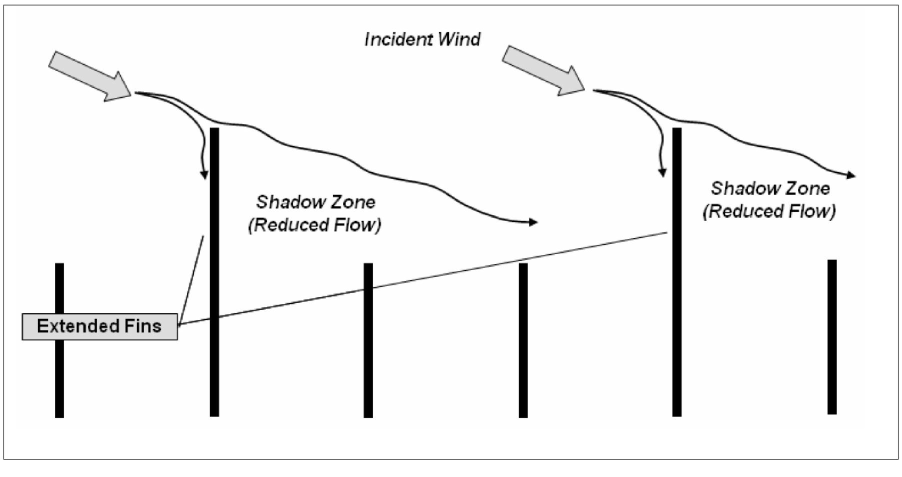


Figure 6 – Option 6: A Series of Deeper Fins Spaced Along the Balustrade

have required the solution under consideration to be installed to the full length of the balustrade of the overpass where it was to be tested. This was because the noise tended to be generated by small groups of fins, and would move around various sections of the balustrade depending on the exact wind conditions, rather than the noise being generated by all the fins on the balustrade simultaneously. This meant that if the solution was only installed to a small section of the balustrade it would have been difficult to establish if the solution was effective or not, as there would be no way of knowing whether the exact wind conditions at that particular section of the balustrade had been the conditions that would normally have resulted in the noise being generated, even if other parts of the bridge were generating the noise. To install each solution to a full balustrade would have been a very costly exercise.

Additionally, 'real world' testing would have been reliant on the correct wind conditions occurring to generate the noise. As time was a factor in finding a solution to this issue, it was not practical to wait for the correct wind conditions to occur randomly. Therefore, it was determined that the potential solutions, with the exception of Option 6, should be first tested in the wind tunnel to establish their effectiveness, and to identify any new issues that the solutions may potentially create.

Option 6 was relatively cheap and easy to test at full scale, so this option was installed and tested on one of the affected overpasses rather than in the wind tunnel.

Test Methodology

A half-scale model of a six-fin section of balustrade was tested in the small anechoic wind tunnel at the University of Adelaide as shown in Figure 7.

The specifications of the wind tunnel can be found in a previous publication [5]. Initial testing demonstrated that it was possible to reproduce the tones observed on site, with the emergence of the fundamental tone and first harmonic being most significant at a flow speed of nominally 17.5m/s at 26 degrees to the balustrade panel. When the scale was taken into account, this corresponded to a wind speed of 8.75 m/s and a direction of 26 degrees at full scale, which was consistent with the range of wind speeds and directions where the noise had been observed to occur on site.

Figure 8 presents the noise levels that were measured at each of four microphone positions around the model. Note that the tones occur at twice the frequency to those observed on site due to the wind tunnel model being at half scale.

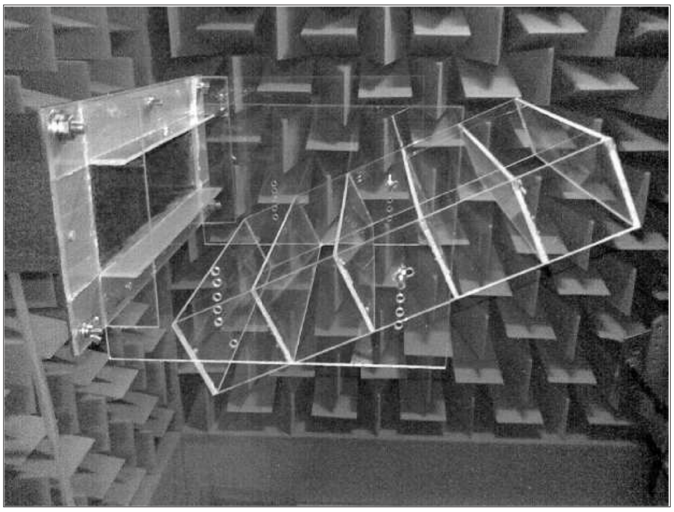


Figure 7 – Half Scale Model of the Balustrade in the Anechoic Wind Tunnel at the University of Adelaide [4]

Having reproduced the tones at half scale in the wind tunnel, similar settings were used to test the reduction achieved by the preferred mitigation options - Option 2 (irregular material added to edge of fin), Option 3 (rounded fin edges), and Option 4 (wire mesh applied to balustrade).

Additionally, the construction team opted to perform full scale tests of Option 6 (a series of deeper fins spaced along the balustrade) in parallel to the wind tunnel testing, as temporary fin extensions could be easily fabricated from plywood and attached to particular fins along the length of the balustrade.

Options 1 and 5 were not tested as they were not considered to be practical solutions.

The results of the testing are presented below.

Option 2 – Toothed or Irregular Fin Edge

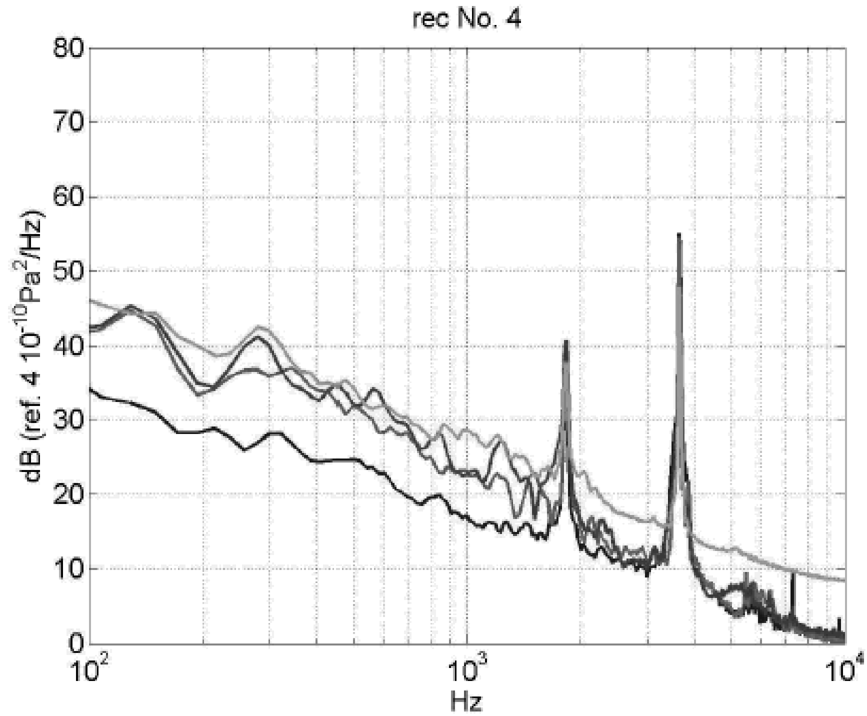


Figure 8 – Noise Spectra Measured at 17.5m/s, 26 degrees. Each colour corresponds to one of four microphone locations (from [4])

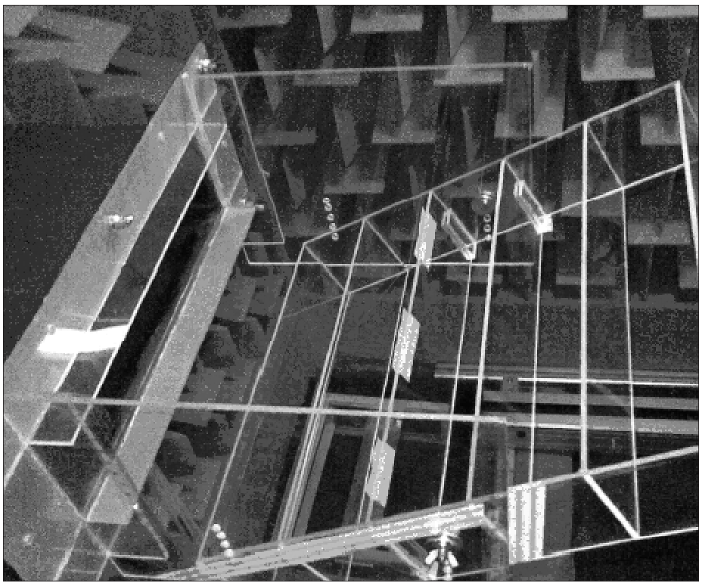


Figure 9 –Testing of Toothed Fin Edge with 50mm Pattern Length [4]

In this test, the possibility of applying a material, such as a serrated, toothed, or otherwise irregular extrusion to the fin edge was investigated. Tabs of adhesive tape 50mm long at 50mm spacing, extending 5mm beyond the edge of the fin, were used to represent the added material in the half scale case.

The test results, presented in Figure 10, showed that the tabs were quite effective in removing the tone, when compared to the original spectra presented in Figure 8.

Each colour corresponds to one of four microphone locations (from [4])

A brief investigation of the effect of reducing the tab length was carried out with tabs of 25mm and 13mm.

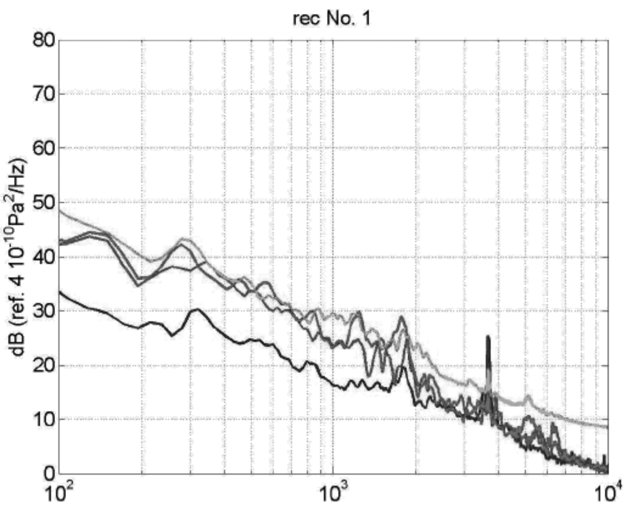


Figure 10 – Spectra Measured with Toothed Edge Fin with 50mm Pattern Length

The corresponding acoustic data showed an equally good reduction of the tones of interest if the flow configuration remained unchanged.

In the case of the 13mm tab, however, the tones reappeared when the angle of incidence was slightly reduced. This is thought to be because the spacing between disturbances of the shear layer was too large.

It was therefore suggested that an appropriate design rule would be to ensure that the characteristic length of the bead pattern (length and spacing) remains less than the distance separating two fins.

As such, it was concluded that a 100mm pattern length at full scale would provide adequate disturbance to the shear layer.

Option 3 – Rounded Fin Edge

In this test a half-round profile was added to the fin edge.

This modification proved to be very effective in reducing the tone, as demonstrated by the spectra presented in Figure 11.

However, while these results were very promising, it was noted that they might be adversely affected by environmental conditions on site, where a film of water, for example, could increase the edge surface smoothness and make the flow separation line more regular.

Option 4 – Wire Mesh

Testing of the wire mesh was performed with the mesh in two orientations – 1) diagonally relative to the balustrade fins and 2) aligned with the balustrade fins.

Both configurations were found to be effective in reducing the level of the tones observed. However, it was also noted that the mesh created an increase in broadband noise above 1 kHz.

Figure 12 and Figure 13 present the measured spectra for each mesh configuration.

Option 6 – A Series of Deeper Fins

In a parallel effort to the wind tunnel tests and modelling carried out by the University of Adelaide, a series of temporary 400mm wide fin extensions were manufactured from plywood and installed on one of the affected pedestrian overpasses at a spacing of approximately one extended fin every 5m (40 fins) as shown in Figure 14

Re-occurrences of the noise under the same wind conditions following the installation of the fin extensions indicated that the fin extensions were not having any significant effect on the airflow across the majority of the balustrade.

It is possible that decreasing the spacing of the extended fins to one every 0.4 to 0.5m (every 3 to 4 balustrade fins) may have made this approach more successful, as increased sheltering of the unmodified fins from the wind would have resulted.

However, this closer spacing was not deemed acceptable in terms of the urban design or the labour and cost that would be involved to complete the modification, so the idea was abandoned.

Current Status

At the time of writing, a variant of Option 2 has been implemented on the balustrades of the affected pedestrian overpasses. Construction of the freeway has also been completed and the freeway has opened.

Option 2 was selected as it was shown to be effective, was relatively straightforward to retrofit, could be made vandalism resistant, and had minimal impact on the appearance of

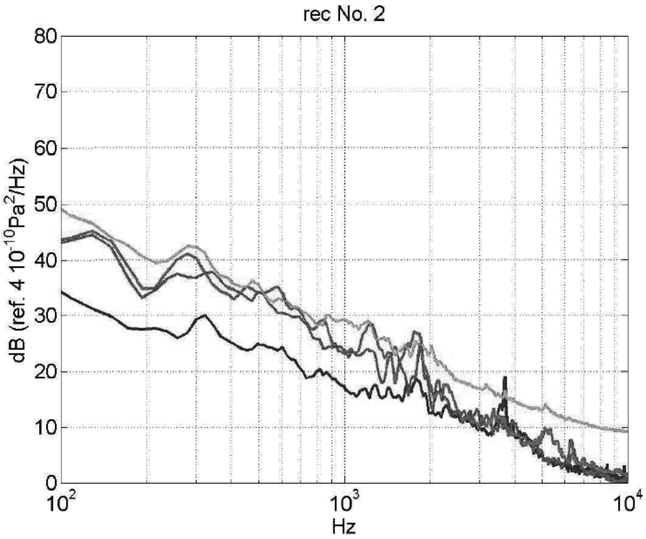


Figure 11 –Spectra Measured with Rounded Fin Edge. Each colour corresponds to one of four microphone locations (from [4])

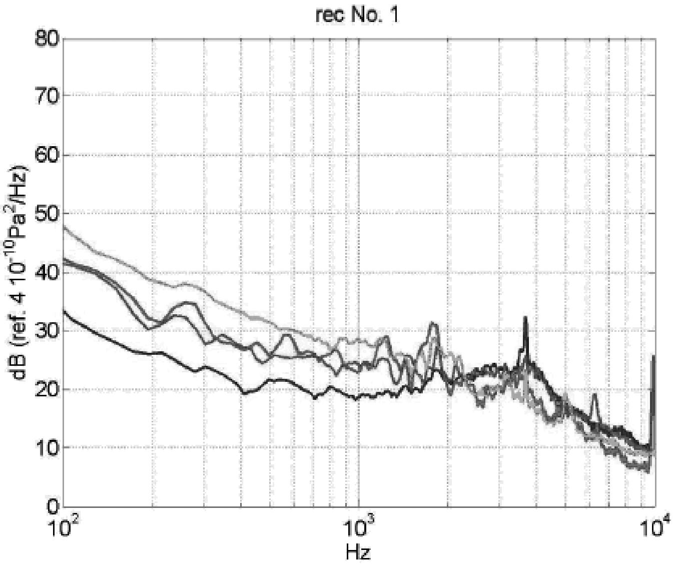


Figure 12 – Spectra Measured with Wire Mesh Aligned Diagonally. Each colour corresponds to one of four microphone locations (from [4])

the bridge from a distance.

Anecdotal evidence, supported by the fact that no further complaints have been received from residents living near to the overpasses, suggests that the modification to the balustrade fins has eliminated the aeolian noise issue.

No formal monitoring has yet been performed to confirm that the noise has been eliminated.

Conclusions

Wind-induced tonal noise was observed to be generated by the finned balustrades of pedestrian overpasses that had been constructed as part of a new freeway in Melbourne. Simultaneous unattended monitoring of one-third octave band noise levels, wind speed, and wind direction, was used to establish the wind conditions under which the noise was occurring.

Using the information gathered from the monitoring, a theoretical aero-acoustic model was developed to explain the noise generating mechanism. It was concluded that acoustic coupling effects between flow around the fins and the volume of air delimited by adjacent fins was effectively creating a quarter-wave

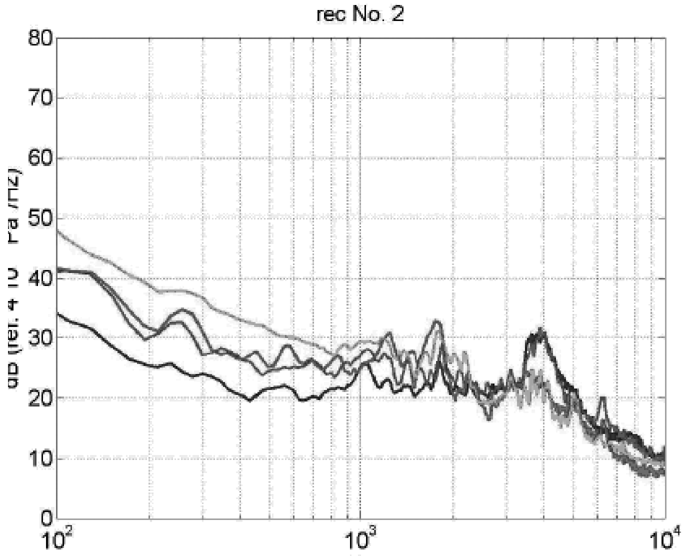


Figure 13 – Spectra Measured with Wire Mesh Aligned with Fins. Each colour corresponds to one of four microphone locations (from [4])

Figure 14 –Balustrade Fin Depth Extensions Installed on a Pedestrian Overpass

acoustic resonator. The frequencies of the tones predicted from this idealised model showed agreement with site observations.

Based on the model, it was determined that this tonal noise could be eliminated by inhibiting the amplification process in the shear layers by introducing strong perturbations (turbulence) into the flow.

Several modification options to provide the necessary flow perturbations were identified and tested at half scale in an anechoic wind tunnel. The results showed a range of modifications to be effective.

Based on the results of the wind tunnel experiments, a solution involving the addition of material to create an irregular fin edge was implemented at the full scale on the affected pedestrian overpasses.

It is believed that this modification has eliminated the occurrence of the wind-induced tonal noise, but further monitoring is required to ascertain this.

Future Work

An interesting area of further work would be to measure and map the sound field in the air volume between the fins when the noise is occurring. The results of this noise mapping could be used to refine the aero-acoustic model proposed in this paper.

Acknowledgements

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Their permission to use the data and reproduce the figures presented in these reports is gratefully acknowledged.

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