ENGINEERING METHODS OF NOISE CONTROL FOR MODULAR BRIDGE EXPANSION JOINTS

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ABSTRACT Modular bridge expansion joints are widely used throughout the world for the provision of controlled pavement continuity during seismic, thermal expansion, contraction and long-term creep and shrinkage movements of bridge superstructures. It was known that an environmental noise nuisance occurred as motor vehicle wheels passed over the joint but the mechanism for the generation of the noise nuisance was not previously known. Noise abatement options were investigated before settling on a Helmholtz Absorber installation. The benefit is most obvious in the frequency range of 50 to 200 Hz. The noise reduction provided by the Helmholtz Absorber installation is of the order of 10 dBA.

1. INTRODUCTION

Whilst the use of expansion joints is common practice in bridge construction, modular bridge expansion joints are designed to accommodate large longitudinal expansion and contraction movements of bridge superstructures. In addition to supporting wheel loads, a properly designed modular joint will prevent rainwater and road debris from entering into the underlying superstructure and substructure. Modular bridge expansion joints are subjected to more load cycles than other superstructure elements, but the load types, magnitudes and fatigue-stress ranges that are applied to these joints are not well defined [1].

The basic modular joint design appears to have been patented around 1960 but the original patent has now expired and approximately a dozen manufacturers now exist throughout the world.

Modular bridge expansion joints are generally described as single or multiple support bar designs. In the single support bar design, the support bar (beam parallel to the direction of traffic) supports all the centre beams (beams transverse to the direction of traffic). In the multiple support bar design, multiple support bars individually support each centre beam. Figures 1 & 2 show typical single support bar and welded multiple support bar design MBEJ's respectively. In Figure 1, the term "blockout" refers to the recess provided in the bridge superstructure to accommodate the casting-in of an expansion joint.

The MBEJ installed into the Western abutment of Anzac Bridge is, in fact, a hybrid design having pairs of support bars in series across the full width of the joint. Each pair of support bars is attached to alternate groups of four centre beams (i.e. Centre beams 1, 3, 5 & 7 are attached to the odd numbered support bars and centre beams 2, 4, 6 & 8 attached to the even numbered support bars). The support bar pairs are spaced at 2.25m centres across the full width of the bridge resulting in a total of 24 support bars.

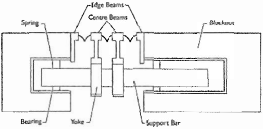

Figure 1 Typical Single Support Bar Design MBEJ

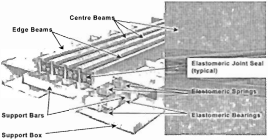

Figure 2 Typical Multiple Support Bar Design MBEJ

The MBEJ installed into the southbound carriageway of the bridge over the Georges River at Tom Ugly's Point is a typical welded multiple support bar design as shown in Figure 2.

It is known that an environmental noise nuisance occurs as motor vehicle wheels pass over the joint but the mechanism for the generation of the noise nuisance is not widely understood although Barnard & Cuninghame [2] do confirm the role of acoustic resonances.

A study was undertaken and the modular bridge expansion joints built into the Georges River (Tom Ugly's) Bridge and Anzac Bridge were selected for the study due to their proximity and ease of access. Engineering measurements were made under operational conditions to determine how the noise nuisance originated and was subsequently propagated into the surrounding environment [3].

2. NOISE GENERATION HYPOTHESIS

There was anecdotal evidence from environmental noise nuisance complaints received by the Roads & Traffic Authority of NSW (RTA) that the sound produced by the impact of a motor vehicle tyre with modular bridge expansion joints was audible at least 500 metres from the bridge in a semi-rural environment. Site inspection suggested that the noise generation mechanism involved possibly both parts of the bridge structure and the joint itself as there was distinct difference between the subjective character of the noise above and below the bridge deck.

The hypothesis was developed by Ancich [3] that motor vehicle tyre impacts vibrationally excite modular bridge expansion joints thereby producing noise that is amplified within the bridge superstructure (due to acoustic resonances) and then propagated into the surrounding environment.

As Figures 1 & 2 show, each transverse centre beam is connected (at the tyre contact level) to the adjoining centre beam or edge beam by a thick rubber strip seal. It is this combination of the rubber strip seals with the steel beams that acts as a continuous membrane and affords MBJS their unique water proofing properties. However, when the MBEJ vibrates, this membrane behaves in much the same way as the skin of a drum or the diaphragm of a loudspeaker. Experimental modal analysis studies [4] [5] indicated that typical MBEJ's have both flexural and translational modes. The most significant translational mode was a vertical bounce/bending mode where all parts of the MBEJ were vibrating essentially in phase at the same frequency and in combination with some vertical bending of centre beams and support bars.

Ancich *et al* [6] confirmed with finite element modelling the measured natural modes and indicated that MBEJ's were very sensitive to damping and operational conditions where motor vehicle tyre impacts to successive centre beams were in-phase or notionally in-phase. In the worst combination of low damping (<5% of critical) and in-phase excitation, the modelled dynamic amplification factor was as high as 11.

3. MEASUREMENT PROCEDURE

To test the hypothesis, simultaneous noise and vibration measurements, at the Georges River (Tom Ugly's) and Anzac Bridges, were recorded and analysed. Vibration data were obtained from an accelerometer attached to a transverse beam (centre beam) of the MBEJ. Noise data were obtained from a precision Sound Level Meter located inside the void space within the bridge abutment directly beneath the MBEJ and at external locations.

The simultaneous noise and vibration data were recorded onto a Sony Model PC 208A DAT recorder using a Bruel & Kjaer Type 2260 (Investigator) Sound Level Meter, Type 4370 Accelerometer and Type 2635 Charge Amplifier and subsequently analysed using a OROS Type OR25 FFT analyser.

4. RESULTS & DISCUSSION

Measurements were initially made at the Georges River (Tom Ugly's) Bridge and the narrow band frequency analysis of the vibration data indicated the presence of a small number of discrete frequencies generally in the range 50-150 Hz.

It was believed that these frequencies were likely to be the vertical and/or horizontal bending frequencies for the transverse beams (tyre contacting) of the modular expansion joint. Figure 3 shows the vibration spectrum of a typical

Table 1 Calculated and Measured Natural Frequencies - Georges River (Tom Ugly's) Bridge

Measured Frequency, Hz	Calculated Frequency, Hz^2	Calculated Vibration Mode^1
70	67.11	Vertical (1)
82	80.1, 80.8, 81.7, 82.9, 83.4, 83.5, 87.8, 89	Horizontal (4), Horizontal (2), Horizontal (3), Horizontal (5), Vertical (2 & 6), Vertical (1 & 4), Horizontal (4), Vertical (2 & 5)
90	89, 91.2, 97.4	Vertical (2 & 5), Horizontal (3), Vertical (3, 5 & 7)

Notes: (1) As the precise boundary conditions for the Georges River (Tom Ugly's) Bridge joint are not known, some assumptions were made. The Mode numbers associated with the various frequencies reflect the range of assumptions. Numbers in brackets refer to the calculated mode number.

(2) Calculated frequencies are considered correct ± 10% due to assumption uncertainties.

(3) Bracketed numbers following mode type refer to the calculated mode number.

Table 2 Calculated Room Acoustic Modal Frequencies compared with Measured Vibration Frequencies - Georges River (Tom Ugly's) Bridge

Measured Frequency, Hz		Calculated Frequency, Hz[1]	Calculated Acoustic Mode
Noise	Vibration		
N.A	N.A	11.1	Transverse (1)
76	70	74.1	Vertical (1)
82	82	81.9	Vertical (1)
N.A	90	148.3; 163.8	Vertical (2)

Notes: (1) Calculation of multiple frequencies for some acoustic modes arises from varying dimensions within the void space.
(2) Bracketed numbers following mode type refer to the calculated mode number.
(3) N.A indicates that the calculated frequency was not identified in the measurements.

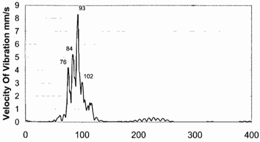

Figure 3 Centre Beam Vibration Spectrum – Tom Ugly's Bridge

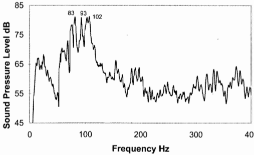

Figure 4 Acoustic Excitation Spectrum – Tom Ugly's Bridge

Georges River (Tom Ugly's) Bridge centre beam. Examination of Figure 3 reveals the presence of three dominant peaks in the frequency spectrum (70 Hz, 82 Hz & 90 Hz). Consequently, a grillage analysis of the joint was undertaken using Microstran® [7]. This analysis was used to calculate natural modal frequencies and **Table 1** shows the measured and calculated vibration frequencies.

Table 1 indicates a high degree of correlation between the calculated natural frequencies and the three dominant frequencies (70 Hz, 82 Hz & 90 Hz) measured at the Georges River (Tom Ugly's) Bridge.

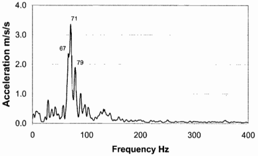

Figure 5 Centre Beam Vibration Spectrum – Anzac Bridge

A possible explanation for the high environmental noise nuisance is acoustic coupling between vibration of the modular joint and room acoustic modes inside the void space within the bridge abutment beneath the modular joint. This possible explanation was tested by calculating the frequencies of the various room acoustic modes encompassed by the vibration frequencies of interest [8]. This comparison is shown as Table 2.

Additional calculations were undertaken to determine the acoustic modal frequencies within the bridge box girders as these structures are acoustically connected to the void space within the bridge abutment beneath the modular joint. The calculated frequencies appear as Table 3.

Figure 4 shows the acoustic excitation spectrum from measurements undertaken inside the void space within the bridge abutment beneath the modular bridge expansion joint. Examination of Figure 4 reveals the presence of two dominant peaks in the noise frequency spectrum (76 Hz & 82 Hz) and similar or matching frequencies also appear in Figure 3 and Table 2.

Similar measurements to those undertaken at Georges River (Tom Ugly's) Bridge were repeated at the Anzac Bridge. Figure 5 shows the corresponding vibration spectrum of a

Table 3 Calculated Box Girder Acoustic Modal Frequencies compared with Measured Vibration Frequencies - Georges River (Tom Ugly's) Bridge

Measured Frequency, Hz	Calculated Frequency, Hz[1]	Calculated Acoustic Mode
70	59, 73	Transverse (1), Vertical (1)
82	73, 86	Vertical (1), Transverse (1)
90	86	Transverse (1)

Notes: (1) Calculation of multiple frequencies for some acoustic modes arises from varying dimensions within the box girder.
(2) Bracketed numbers following mode type refer to the calculated mode number.

Table 4 Calculated and Measured Natural Frequencies (Anzac Bridge)

Measured Frequency, Hz	Calculated Frequency, Hz[2]	Calculated Vibration Mode[1]
57	34.5	Horizontal (1)[3]
65	N.A[4]	N.A
70.5	N.A	N.A
84	91.3, 94.9, 99.4	Vertical (2 & 3), Horizontal (4)
122	103.4, 108.4, 111.2, 118.8, 119, 124.3	Horizontal (5), Vertical (6), Horizontal (7), Vertical (8), Horizontal (9), Vertical (10)
189	N.A	N.A

Notes: (1) As the precise boundary conditions for the Anzac Bridge joint are not known, some assumptions were made. The Mode numbers associated with the various frequencies reflect the range of assumptions.
(2) Calculated frequencies are considered correct ± 10% due to assumption uncertainties.
(3) Bracketed numbers following mode type refer to the calculated mode number.
(4) "N.A" indicates that no calculated frequency was found to correspond with the measured frequency.

typical Anzac Bridge centre beam. Examination of Figure 5 reveals the presence of six dominant peaks in the frequency spectrum (57 Hz, 65 Hz, 70.5 Hz, 84 Hz, 122 Hz & 189 Hz).

Consequently, a grillage analysis of the joint was undertaken using Microstran®. This analysis was used to calculate natural modal frequencies and Table 4 shows the measured and calculated vibration frequencies. The possibility of acoustic coupling to room modes in the Anzac Bridge abutment void space was also tested by calculating the frequencies of the various room acoustic modes encompassed by the vibration frequencies of interest. This comparison is shown as Table 5.

5.0 NOISE ABATEMENT OPTIONS

The analysis of measurements supported the hypothesis that an environmental noise nuisance resulted from the interaction of vibration of the modular bridge expansion joint with acoustic resonances produced inside the abutment void space below the joint.

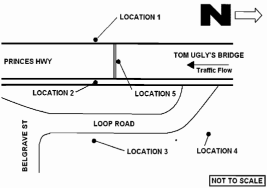

Figure 6 Site Plan Showing Noise Measurement Locations

Table 5 Calculated Room Acoustic Modal Frequencies compared with Measured Vibration Frequencies (Anzac Bridge)

Measured Frequency, Hz	Calculated Frequency, Hz[1]	Calculated Acoustic Mode
N.A	19.0	Transverse (3)
57	45.3, 47.8, 53.8	Axial (1), Vertical (1), Axial (1)
65	63.7	Vertical (1)
70.5	71.7	Vertical (1)
84	86.0	Vertical (1)
122	127.4, 135.8, 143.3	Vertical (2), Axial (3), Vertical (3)
189	172.0, 191.1	Vertical (2), Axial (2) & Vertical (3)

Notes: (1) Calculation of multiple frequencies for some acoustic modes arises from varying dimensions within the void space.
(2) Bracketed numbers following mode type refer to the calculated mode number.
(3) N.A indicates that the calculated frequency was not identified in the measurements.

Table 6 Helmholtz Absorber Modules Target Frequencies

Segment	Design Centre Frequency of Helmholtz Absorber, Hz					
	1	2	3	4	5	6
Frequency (Hz)	64	80	90	105	110	120

The reverberant nature of the void space was considered to be the reason for the apparent amplification of the low frequency sound pressure within the void space. As true standing waves do not propagate, this highly reactive (long reverberation time characteristic) of the void is not apparent in the far field. Due to the small amount of acoustic absorption in the void, some of this sound energy is absorbed within the void and some is radiated to the environment through openings. The build-up of acoustic energy is then radiated into the environment.

Martner [9] reports the results of noise measurements of a number of different types of bridge expansion joints, including modular bridge expansion joints. Whilst he indicates that the installation of an acoustic enclosure beneath the expansion joint was very effective, it is not clear whether the enclosure was used with the modular design. Rhombic plates welded onto the top surface of the edge and centre beams are reported to offer noise reductions of up to 9 dBA below the bridge deck [10]. However, these engineering methods of noise control were considered to be either too expensive or, in the case of the rhombic plates, largely developed for a particular proprietary design MBEJ. In addition, whilst these noise control measures are undoubtedly effective, their use may have an adverse impact on the ability of the asset owner to routinely inspect and maintain the joint.

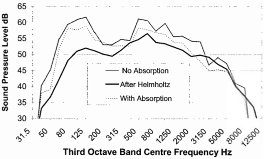

Figure 7 RMS Average Third Octave Band Noise Spectra at Location 4

It was considered that cost-effective noise abatement could be undertaken by:

1. Modifying the dynamic behaviour of the joint to shift the natural frequencies so that they no longer co-incide with acoustic resonances.

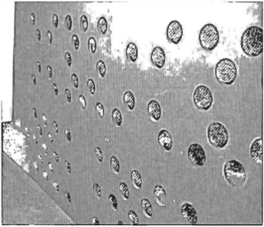

Figure 8 Helmholtz Absorber

2. Reducing the overall dynamic response by additional modal damping. This option included the trial use of tuned mass dampers.
3. Providing acoustic absorption and limited screening, adjacent to the joint, to reduce noise propagation.
4. Modifying the acoustic absorption properties of the void space to eliminate or reduce the incidence of acoustic resonances.

The above strategies represent both "new construction" and "retro-fit" options. However, their efficacy and cost-effectiveness was still to be established by engineering measurement

There were initial plans to design and test Option 2. However, this option was ultimately not pursued. Although tuned mass dampers (TMD) would likely provide an effective noise reduction, these devices were not strongly advocated due to the high number of natural modes present and hence a high number of TMD's needing to be fitted and tuned [11]. An alternative to the TMD concept would be the use of broadband damping coupled mass absorbers.

The perceived disadvantage of this approach being the requirement for a significant mass attachment to each centre beam. An array of damping coupled mass absorbers was subsequently trialled at Anzac Bridge to reduce the risk of fatigue failure but elaboration of that work is beyond the present discussion.

Due to resonances within the void space, the use of acoustic absorption and limited screening, adjacent to the joint was not considered practical. Consequently, only Option 4 was investigated. This investigation was undertaken using two different approaches. Firstly, the simple addition of acoustic absorption into the void space was tested.

Noise measurements were conducted on 4 May 2001 at which time trial acoustical absorption material had been installed over the floor of the void below the expansion joint. The absorption was arranged in a 100 mm thick layer over the floor area of the void and raised 75 mm (nominally) above the floor surface (to optimise low frequency sound absorption). Noise measurement locations are shown as Figure 6.

Whilst the above deck (Locations 1 and 2) and the side (Location 3) measurements show no significant change in the noise spectra, the below deck Locations 4 and 5 show a significant increase in the low frequency bands when the trial absorption was removed.

As the measurements at Location 5 (from within the void space) are the result of sound pressure due to both propagating sound energy as well as non-propagating standing waves, the results at Location 4 provide a better indication of the effect on the emitted (propagating) noise.

The second approach involved the construction of a Helmholtz Absorber within the void space. The internal dimensions of the Helmholtz chambers were calculated to co-incide with the dominant acoustic frequencies. The Helmholtz Absorber panels were designed to target the critical frequencies shown in Table 6.

Figure 7 shows a comparison of RMS average one-third octave band noise spectra at Location 4 before and after the Helmholtz absorber installation. Also shown are the one-third octave band noise spectra with floor absorption only, for comparison.

These results clearly demonstrate the effectiveness of the Helmholtz absorber modules in the target range of 60 Hz to 160 Hz.

Figure 8 shows the installed absorber modules.

6.0 CONCLUSION

Noise and vibration measurements have been undertaken at Anzac and Georges River (Tom Ugly's) Bridges. The analysis of these measurements supported the hypothesis that an environmental noise nuisance results from the interaction of vibration of the modular bridge expansion joint with acoustic resonances produced inside the void space below the joint.

The trial addition of acoustic absorption batts into the void space of Tom Ugly's Bridge was considered to be only marginally effective for noise control and was not pursued. However, the installed Helmholtz Absorber at Tom Ugly's Bridge has reduced the modular expansion joint induced low frequency "booming" noise emissions by up to 10 dB. The character of the noise emission from the underside of the bridge deck would no longer be classified as tonal and hence the likelihood of modular expansion joint related noise complaints has been significantly reduced.

The use of Helmholtz Absorbers at other bridges with modular expansion joints is considered to be viable as an engineering method of noise control.

ACKNOWLEDGEMENT

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