Monitoring ground-borne and structure-borne noise for management of construction impacts

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ABSTRACT

Construction activities such as demolition and excavation can generate significant structure-borne and ground-borne noise impacts on nearby receivers. Management of construction noise and vibration often includes the use of loggers equipped with communication capability to provide alerts and alarms when levels approach or exceed pre-determined thresholds. Suitable loggers are now widely available for monitoring airborne noise and providing real-time alerts. Similarly, several vibration loggers are available for monitoring ground or structural vibration. This paper deals with the issue of monitoring structure-borne and ground-borne noise from construction projects. Noise loggers are not well suited to this task because the affected location is within a building, where ambient noise from occupant activity often significantly exceeds the applicable criteria for ground-borne noise. Existing vibration loggers are not well suited to this task either, because they focus on assessment against criteria for structural damage and/or human comfort, both of which involve different frequency ranges, metrics and amplitudes of vibration than those that give rise to structure-borne and ground-borne noise. This paper presents a ground-borne noise monitoring method based on the "indirect measurement method", derived from the vibration velocity measured at (or near) the affected receiver, together with a transfer function to account for vibration transmission and radiation of noise within the receiver space.

1. INTRODUCTION

For many years, construction projects have needed careful management of airborne noise and ground-borne vibration impacts. However, for construction projects that involve underground construction and/or the demolition of buildings that adjoin other occupied premises, the issue of ground-borne noise is also significant. This is an increasingly important issue for a number of current and future infrastructure projects in Australia, such as Sydney Metro City and South West (Sydney Metro 2016); Melbourne Metro (Metro Tunnel 2016); WestConnex, Sydney (Sydney Motorway Corporation 2016); NorthConnex, Sydney (TransUrban 2016); Cross River Rail, Brisbane (Queensland Government 2016); and Forrestfield-Airport link, Perth (Public Transport Authority 2016).

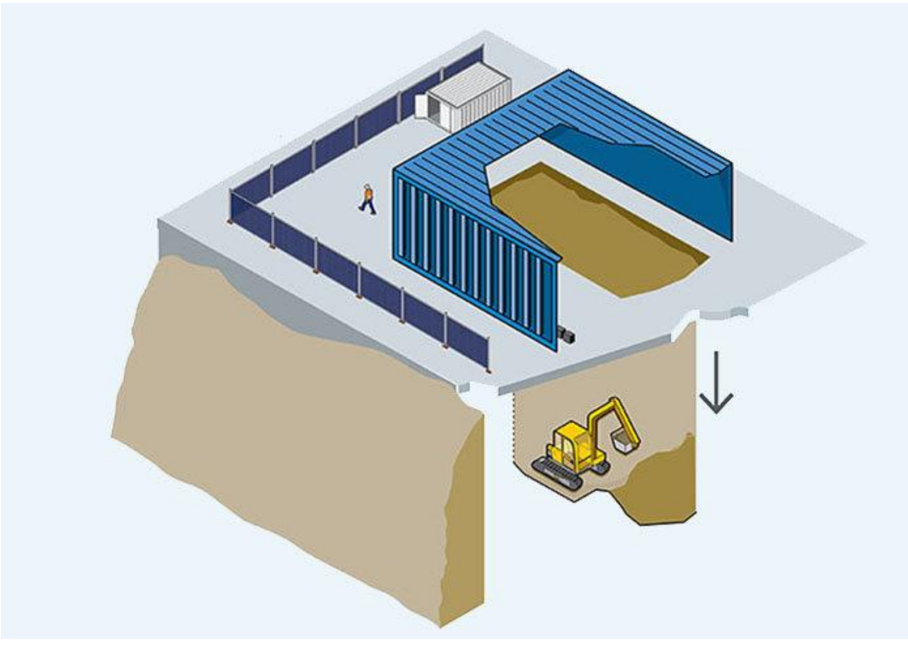

Figure 1: Left: Underground construction process in an urban area.

As shown in Figure 1, it is now common practice in urban areas to minimize airborne noise from underground construction by the use of a decking slab and / or purpose-built acoustic shed. The residual effects on adjacent receivers include both ground-borne vibration and ground-borne noise, but the ground-borne noise component is generally more problematic than the vibration. For example, the Environmental Impact Statement for the Sydney Metro City & South West project (Sydney Metro 2016: Chapter 10) notes that "*People tend to hear vibration before they feel vibration".* This is explained further in Section 2.

The other feature of some major infrastructure projects is the need to demolish existing buildings, often in close proximity to (or sometimes adjoining) sensitive receivers. For example, the construction process for the Chatswood to Sydenham stage of the Sydney Metro project has been likened to key-hole surgery (Rodd Staples, quoted in the Sydney Morning Herald, 2015). Figure 2 shows one of the buildings to be demolished for Sydney Metro.

Figure 2: Left: A high-rise building (highlighted) to be demolished to make way for the new Martin Place metro station in Sydney. Right: An artist's impression of the new station (with over-station development above)

A range of mitigation and management strategies is used to address construction noise and vibration impacts, ranging from the timing of the works and the selection of plant and equipment through to the use of noise attenuating devices (shrouds, enclosures, barriers and so on).

Monitoring of noise and vibration often forms part of the overall management strategy used on large projects, including the use of unattended monitors that send alert messages to project staff if noise or vibration levels reach pre-determined thresholds. This allows the project team to ensure that much of the construction work can proceed without delay, but work can be slowed, stopped and/or supervised more closely when the risk of impacts increases.

However, remote monitoring of ground-borne and structure-borne noise is not common practice. The main reasons for this are:

1. That direct monitoring of noise within the affected space is generally ineffective because the criteria for internal levels of ground-borne or structure-borne noise are lower than typical occupant and activity noise levels.
2. The indirect method discussed in this paper requires real-time manipulation and processing of vibration signals, including user-defined frequency-dependent transfer functions. While instruments and analysers are available to perform this task, they are not well suited to functioning as a low-powered, secure, remotely accessible and relatively low cost remote monitoring system.

2. BACKGROUND

2.1 Structure-borne Noise and Ground-borne Noise

Ground-borne noise is sometimes also referred to as re-radiated noise, structure-borne noise and solid-borne noise (International Organization for Standardization, 2005) and, in Australia, is often collectively referred to as regenerated noise.

Regenerated noise in buildings is a result of the transmission of vibration energy from a vibration intensive source to a receiver room where structure-transmitted vibration causes the walls, floors, and ceiling to vibrate faintly and hence to radiate audible noise. Where the source of the vibration interfaces directly with the structure (for example, a piece of mechanical plant or a hammer drill), the resulting re-radiated noise is generally referred to as structure-borne noise. Where the source of the vibration is external to the receiver building (such as a railway tunnel or a nearby construction site), the vibration travels through the ground and into the receiver building via the building foundations and is generally referred to as ground-borne noise. The terms are used interchangeably in many relevant documents; this paper uses regenerated noise to describe the overall effects, but also refers specifically to ground-borne and structure-borne noise as they are subtly different effects.

An overview of the ground-borne and structure-borne noise phenomena is illustrated in Figure 3. The figure shows the ground-borne vibration source (S1) and structure-borne vibration source (S2), the vibration propagation between the ground-borne vibration source and nearby building foundations (2), the propagation of vibration within the building elements (3), and the radiation of vibration energy as noise (4).

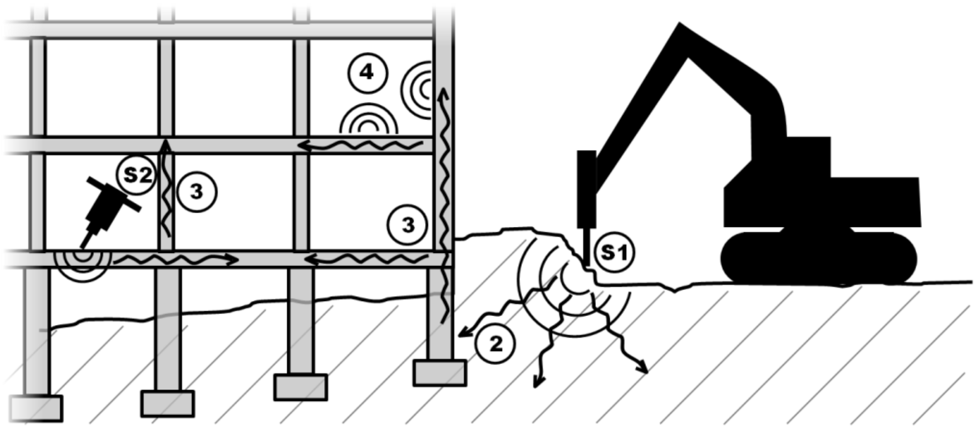

Figure 3: Schematic showing ground-borne and structure-borne noise from construction and demolition

Regenerated noise levels are directly related to vibration velocity levels of the radiating surfaces and are typically estimated using equation 1 (ANC, 2012), where Lp is sound pressure level (dB re 20µPa), Lv is spatially averaged vibration velocity level (dB re 1 x 10^{-6}mm/s), and k is a constant for the receiving space, generally between 27 and 32 dB.

$$Lp = Lv - k \quad (1)$$

2.2 Regenerated Noise Criteria for Construction Projects

Regenerated noise levels are relevant only where they are higher than the airborne noise component, such as when construction plant is located underground or isolated by a high performance acoustic enclosure. The NSW Interim Construction Noise Guideline (EPA, 2009) provides residential noise management levels for regenerated noise for evening (40 dBA) and night-time (35 dBA) periods. The Environmental Impact Statement for the Sydney Metro City & South West project (Sydney Metro 2016: Technical Paper 2) included ground-borne criteria for daytime impacts at residential properties (45 dBA) and commercial premises (50 dBA).

Regenerated noise is often a concern at lower levels of vibration than other effects, including human perception and potential damage to structures. For example, the threshold of human perception is generally taken to be approximately 0.1mm/s RMS, which is a vibration velocity level of 100dB (re 1 x 10^{-6}mm/s). This would result in a regenerated noise level in the region of 70dB based on equation 1. This, in turn, would represent an A-weighted level of regenerated noise of 45 dBA (if the energy is concentrated in the octave frequency band centred on 63Hz) and 61 dBA (if the energy is concentrated around 250Hz). This shows that vibration levels at or below the threshold of human perception can cause regenerated noise levels that significantly exceed regenerated noise management levels for residential and commercial premises.

2.3 Regenerated Noise Monitoring

The direct measurement and monitoring of regenerated noise is often impractical due interference from typical occupational noise levels within buildings. Figure 4 shows typical noise levels within a medium sized open-plan office over 15 minutes. It shows that transient noise levels from conversations and phone calls frequently exceed the regenerated noise criteria. This does not imply that the regenerated noise criteria are inappropriate; the low frequency content and character of regenerated noise means that it can still be intrusive at levels well below typical occupant noise levels. But it does mean that a simple regime of monitoring A-weighted noise levels would not be effective in identifying regenerated noise issues.

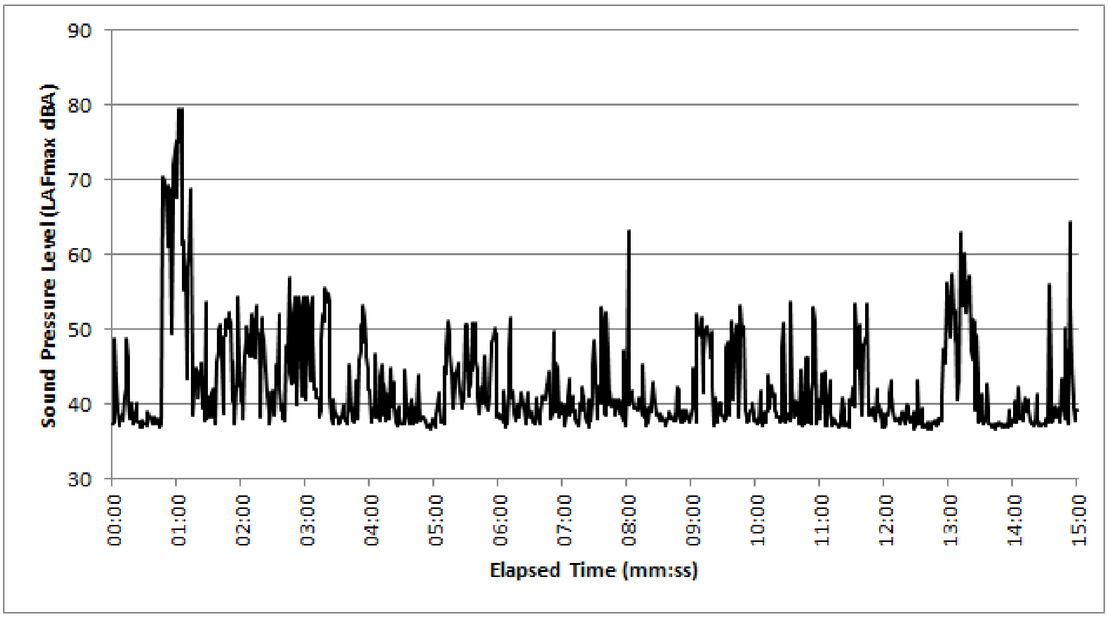

Figure 4: Example of typical open-plan office noise levels

3. PROPOSED APPROACH

As discussed in Section 2.1, the ground-borne (or structure-borne) vibration and resulting regenerated noise levels are directly related. This means that regenerated noise can be estimated, with reasonable accuracy, from measured vibration velocity. This is referred to as the “indirect method” (ANC, 2012).

Accuracy of the indirect method is improved if the transfer function between vibration (at the proposed monitoring location) and noise (in the affected sensitive space) can be verified in the field. The transfer function could be obtained through acquisition of empirical data involving short-term simultaneous measurements of construction regenerated noise and vibration at the proposed monitoring location and the receiver location. A comparison of the measured results would provide a suitable frequency domain transfer function per 1/3 octave band.

This transfer function would reflect the position and type of excitation signal present during the short-term measurements and may not be transferable for different plant or different work locations. In practice, it may be possible to check and update the transfer function on a regular basis (e.g. weekly) to account for changes in the location and type of construction activity.

The proposed approach for a real-time indirect measurement of regenerated noise involves applying adjustments to measured vibration spectra in real time to obtain estimated noise levels. The transducer sensitivity and frequency response requirements for indirect measurement of regenerated noise are suited to high sensitivity accelerometers. The vibration acceleration signal produced by the accelerometer must first be integrated to determine vibration velocity. The vibration velocity signal is processed to determine the 1/3 octave band spectra. The spectra would be time variant, and interpreted in a descriptor suitable for the applicable criteria. For example, construction regenerated noise assessment in accordance with the NSW Interim Construction Noise Guideline would require a 15 minute L_{Aeq} measurement.

The 1/3 octave band transfer function can then be applied to the measured velocity spectrum to determine estimated regenerated noise levels. This is a numerical spectral modification applied as discrete adjustments per 1/3 octave band. The resulting spectrum would then be A-weighted to determine the overall estimated regenerated noise levels for comparison against applicable criteria.

4. TRIAL APPLICATION

4.1 Methodology

A trial application of the proposed regenerated noise monitoring method was undertaken using a 600 W electric hammer drill to simulate construction vibration in the basement car park of a commercial multi-story building. The trial involved the simultaneous measurement of building vibration and regenerated noise at the measurement positions displayed in Figure 5. The construction vibration source (S) was located in the basement level between the building columns. The vibration level was measured in the same horizontal position on the three floors above (Ground Floor (V1), Level 1 (V2), and Level 2 (V3)). Regenerated noise was measured immediately adjacent the Level 1 and Level 2 vibration transducers (N1 and N2 respectively), which were each located near the center of a medium sized conference room.

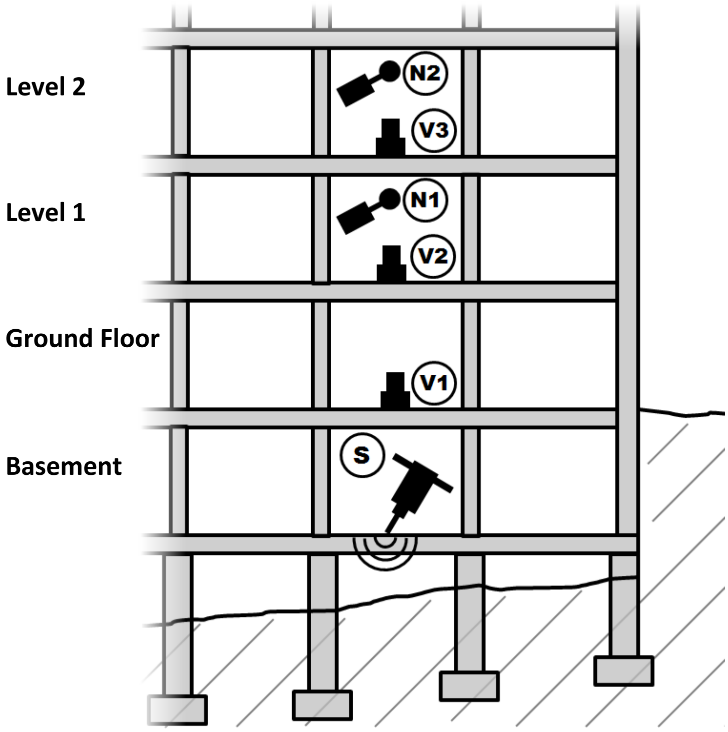

Figure 5: Trial Measurement Positions

All measurement devices were time synchronized to facilitate the direct comparison of measurement results. The building construction incorporates several partitions between the basement and the receiver rooms with no significant airborne noise flanking paths; noise levels measured within the receiver rooms were dominated by regenerated noise.

4.2 Proof of Concept

The vibration levels at measurement positions on Level 1 and Level 2 are compared against the corresponding measured regenerated noise levels in Figure 6.

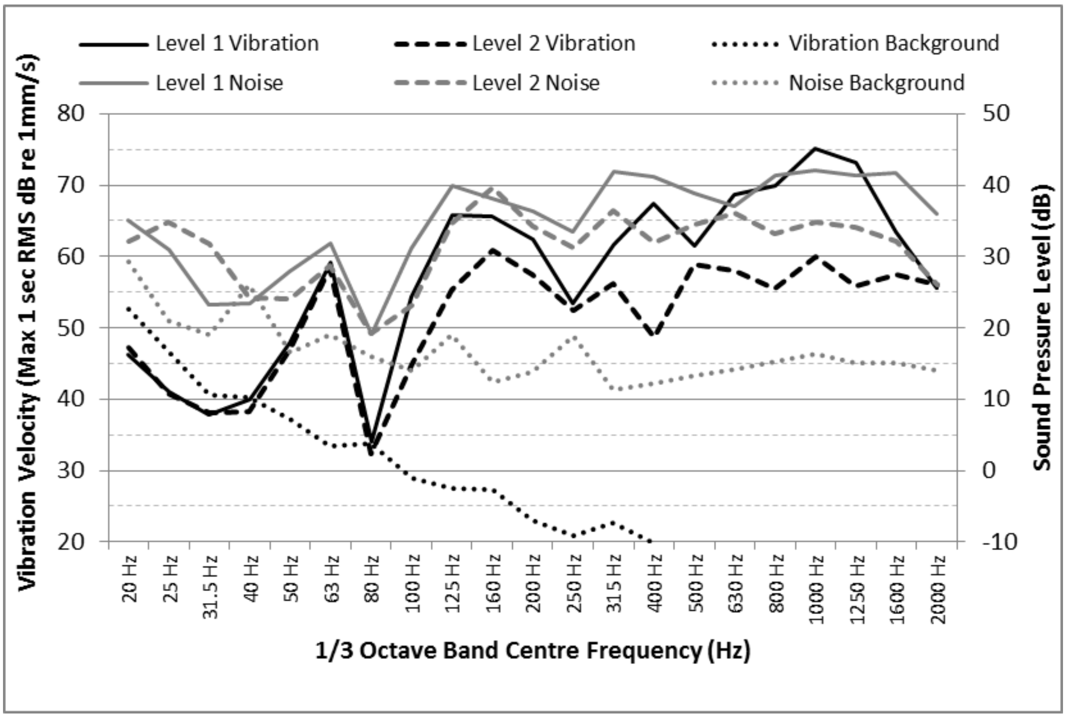

Figure 6: Measured Vibration and Regenerated Noise

From the results in Figure 6 it can be seen that the fundamental frequency of the excitation signal is located within the 50 Hz and 63 Hz 1/3 octave bands and most of the vibration energy emitted by the hammer drill is located between 100 Hz and 2000 Hz. It is also notable that the background vibration levels are much lower than the background noise levels, suggesting that vibration from external sources of regenerated noise (like construction) will have a higher signal to noise ratio and hence will be easier to detect than the noise itself.

The vibration velocity levels measured on level 1 and 2 can be used to estimate regenerated noise levels using equation 1. Figure 7 shows the calculated regenerated noise levels compared against the measured regenerated noise levels. The results show that the estimated regenerated noise levels are within 3 dB(A) of the measured levels.

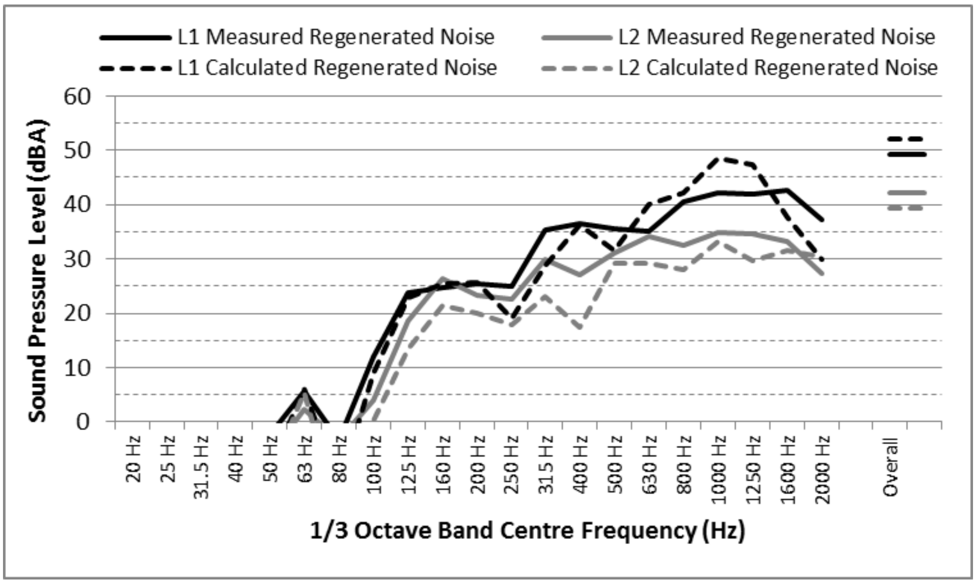

Figure 7: Measured and Estimated Regenerated Noise

4.3 Field Testing Real-Time Indirect Ground-Borne Monitoring System

A vibration logger with a communications port was connected to a computer. An accelerometer was connected to the logger and the vibration level was streamed from the vibration logger to the computer every 1 second. An application on the computer took the 1-second vibration spectra and applied a transfer function to determine the estimated regenerated noise level.

The transfer function was applied as discrete adjustments per 1/3 octave band. This processing could theoretically be performed within a vibration meter or logger. However, as this functionality is not readily available, for the purpose of this trial, the 1/3 octave band calculations were performed by an external computer.

The same construction vibration source was used in the basement to perform a similar task while the monitoring system measured structure-borne noise and vibration in the same locations shown in Figure 5. The regenerated noise levels calculated from the real-time structure-borne vibration data are shown in Figure 8.

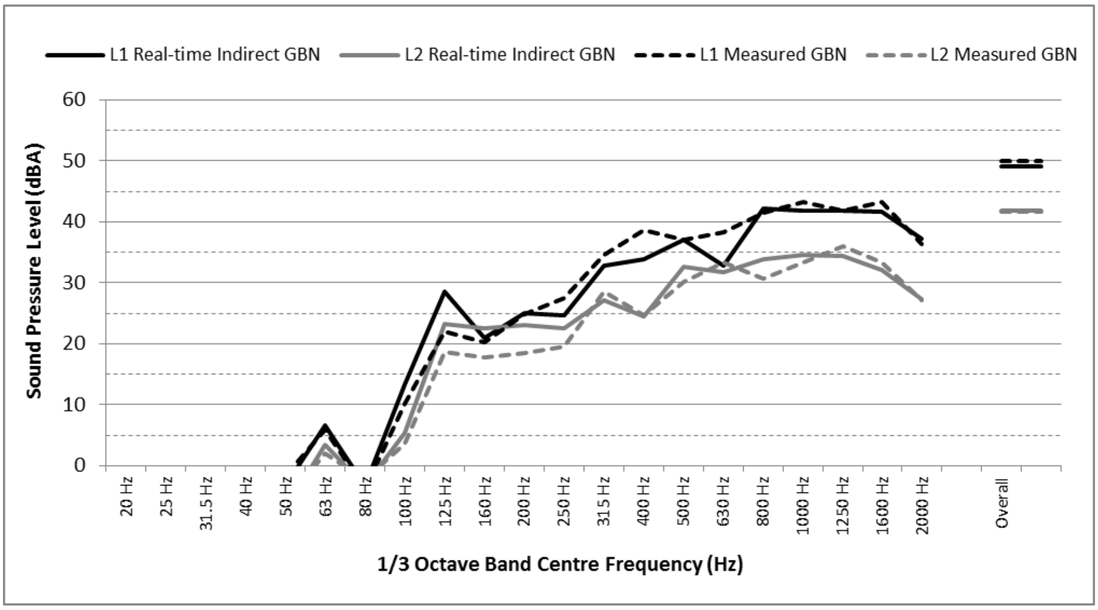

Figure 8: Direct (measured) and Indirect (real-time) Measurement of Regenerated Noise

The results show that the direct and indirect measurements of regenerated noise are within 1 dBA. The indirect estimate of regenerated noise spectra also matches the direct measurement results reasonably well, with 1/3 octave band levels within approximately 5 dB.

4.4 Practical Application

The field test described in Section 4.3 shows promising results, but involves an equipment set-up that is not suitable for long-term deployment on a remote site. In particular, the use of an external computer to apply transfer functions requires considerable power (necessitating mains power) and makes the equipment difficult to install in a small secure enclosure, as is the case for popular models of battery powered noise and vibration loggers.

There are several alternatives to PC computer processing systems that would be capable of applying the necessary transfer functions. The most practical solution would be for this functionality to be added to vibration logging equipment. If this can be achieved, battery-powered self-contained logging systems could be made available for implementing the indirect regenerated noise measurement method described in this paper.

In the absence of commercially available loggers for indirect regenerated noise measurement, the only viable alternative is to custom make a system using available instruments combined with an off-the-shelf microcontroller system (such as the Arduino, Raspberry Pi, etc). Such systems are cheap, use very little power, and are extremely compact (credit card sized footprint) and could easily be integrated into an existing noise logger's case. However, the disadvantage of such as system is that it would not be a self-contained instrument with manufacturer warranty, calibration, user manual, technical support etc.

5. DISCUSSION AND CONCLUSIONS

This paper has established that construction activities such as demolition and excavation can generate significant structure-borne and ground-borne noise impacts on nearby receivers and that this issue is likely to be increasingly significant during numerous large infrastructure projects underway or planned in Australia.

It follows that monitoring of structure-borne and ground-borne noise will be important as part of a range of mitigation and management measures. However, direct measurement of structure-borne and ground-borne noise is generally not practical and existing vibration loggers are not suitable for the task.

This paper has described a regenerated noise monitoring method based on the “indirect measurement method”, derived from the vibration velocity measured at (or near) the affected receiver, together with a transfer function to account for vibration transmission and radiation of noise within the receiver space. This approach is not new and a trial application confirmed that it is effective. The paper concludes that the technique would provide an effective way to assist in managing structure-borne and ground-borne noise impacts on major infrastructure projects, but that suitable remote logging equipment is not currently available to implement it.

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