Design and implementation of a masking system for tonal industrial noise emissions

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A noise source that exhibits tonal qualities is often deemed to be more annoying than one which is broadband in nature. As such, in environmental noise assessments, it is common to apply a decibel penalty (typically up to +5dB) to noise sources with tonality. Tonality is often objectively classified as a function of the spectrum shape described in narrow bands, where a prominent band relative to its adjacent bands indicates tonality. This paper outlines the practical implementation of a tonality masking system which was applied to a low-frequency industrial noise compliance issue. The system intended to remove the tonality penalty by introducing masking noise, altering the spectrum shape favourably. The added masking needed to be targeted to not only remove the tonality classification, but also minimise the increase in overall A-weighted level to less than one decibel. A feed-forward *Unity* software system was developed which accurately detected the tones in real-time and calculated the optimum masking signal in third octaves. The signal was then reproduced through a subwoofer within the industrial facility. After commissioning, the resultant noise levels were assessed and found to be non-tonal, with an overall A-weighted level increase of no more than 0.8dB. This case study was in Western Australia which has a legislated definition for tonality, although other local authorities have similar definitions for tonality, meaning the masking system developed here could have much broader tonality masking applications across Australia (and internationally).

1 INTRODUCTION TO INDUSTRIAL NOISE AND TONALITY

Industrial noise is a well-documented cause of complaint from residential properties nearby to industrial areas, and many local authorities (e.g., councils) legislate maximum noise emission levels to reduce the likelihood of complaint. Industrial noise can vary significantly in its nature due to amplitude, intermittency, impulsiveness, special audible characteristics, tonal qualities, etc., and each of these characteristics has a subjective effect on the annoyance caused by the noise. A noise source that exhibits tonal qualities is often deemed to be more annoying than one which is broadband in nature. As such, in environmental noise assessments, it is common to apply a decibel penalty (typically up to +5dB) to noise sources which exhibit tonality. Tonality is often objectively classified as a function of the spectrum shape described in narrow bands, where a prominent band relative to its adjacent bands indicates the presence of tonality, as depicted in Figure 1.

Controlling tonal noise from industry is often difficult because the tone or tones being generated may be inherent parts of the industrial equipment's operation and cannot be simply removed without completely disabling the equipment. As with many noise control problems, low frequency tones, in particular, are difficult to reduce with conventional acoustic treatment methods.

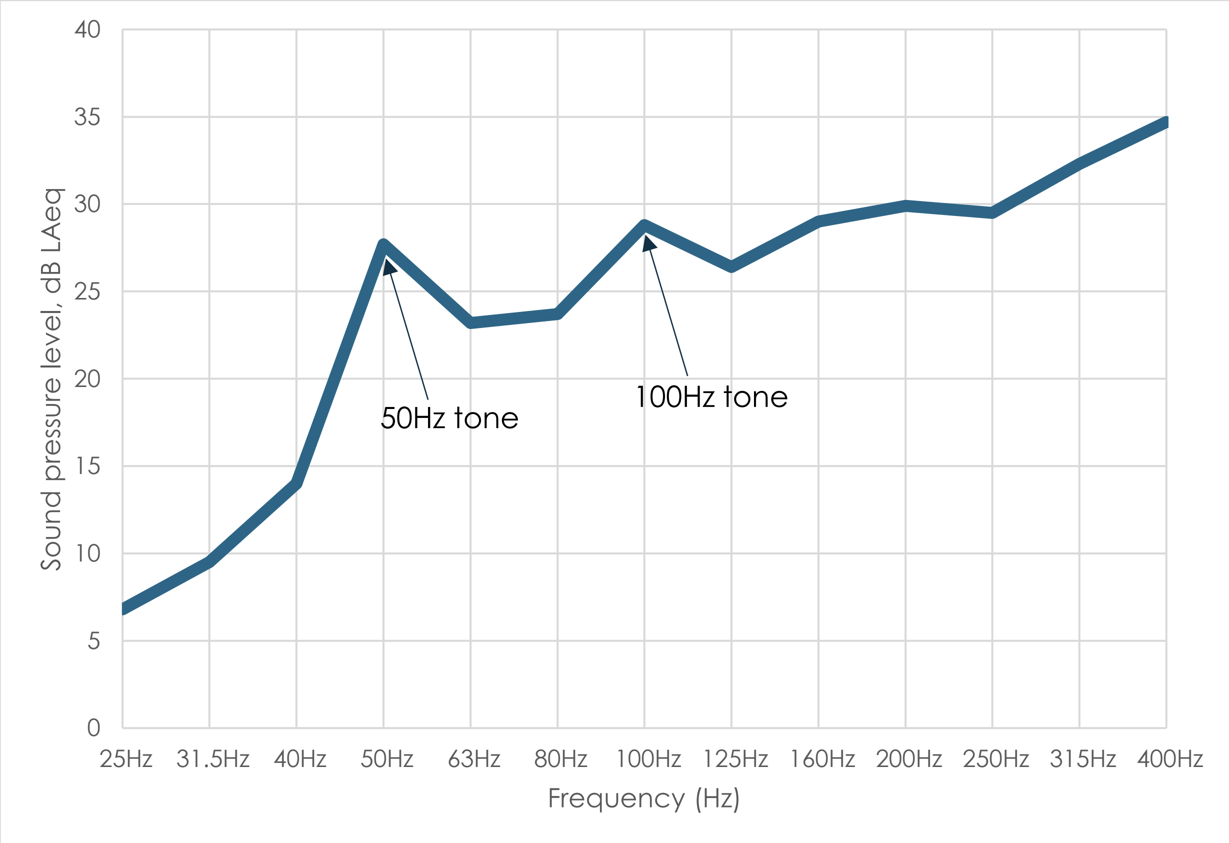

Figure 1 – An example of a sound pressure spectrum exhibiting tonality at 50Hz and 100Hz.

2 TONALITY CRITERIA

When determining the tonal quality of a noise source, it is important to understand the various ways in which tonality is identified according to local guidelines and regulations. Specific to the location of the case study in Western Australia, environmental noise limits are dictated by the WA EPNR 1997 (Western Australia Environmental Protection (Noise) Regulations, 1997), which is the legal framework that sets out the standards for acceptable noise levels within Western Australia. The purpose of the document is to establish maximum allowable noise levels for respective types of premises (e.g. residential, commercial and industrial) and avoid excessive noise pollution at neighbouring properties.

Section 7 of the WA EPNR 1997 states that noise emitted from any premises must be free of tonality, defined as follows:

> ***tonality*** means the presence in the noise emission of tonal characteristics where the difference between —
>
> (a) the A-weighted sound pressure level in any one-third octave band; and
>
> (b) the arithmetic average of the A-weighted sound pressure levels in the 2 adjacent one-third octave bands,
>
> is greater than 3 dB when the sound pressure levels are determined as $L_{Aeq,T}$ levels.

2.1 Comparison to Tonality in Other States of Australia

Similar environmental protection authority regulations are also available in other states within Australia with the same intent of limiting noise levels for sensitive noise receivers. A comparison of how tonality is determined by the respective policies or guidelines is summarised below:

- **Victoria** (Victoria State Environment Protection Policy (Control of Noise from Commerce, Industry and Trade) No. N-1, 2001)
    - Tonality is present where adjacent 1/3 octave bands have a difference greater than 3dB
- **Tasmania** (Tasmania Noise Measurement Procedures Manual, 2nd Edition, 2008)
    - Tonality is present where adjacent 1/3 octave bands have a difference greater than 3dB
- **Queensland** (Queensland Department of Environment and Heritage Protection "Noise Measurement Manual", 2020)
    - Tonality is present where adjacent 1/3 octave bands have a difference greater than 5dB
- **South Australia** (South Australia Environment Protection (Noise) Policy 2007, 2007)
    - Tonality is present where adjacent 1/3 octave bands have a difference greater than 5dB
- **New South Wales** (New South Wales Industrial Noise Policy, 2000) states tonality assessment criteria referencing ISO 1996-2 (ISO 1996-2:2007 Acoustics - Description, measurement and assessment of environmental noise - Part 2: Determination of environmental noise levels, 2007)
    - Tonality is determined where the A-weighted band exceeds each adjacent band by:
        - 5dB or more if the centre frequency of the tonal band is higher than 400Hz
        - 8dB or more if the centre frequency of the tonal band is between 160 and 400Hz
        - 15dB or more if the centre frequency of the tonal band is below 160Hz
    - 5dB penalty shall be applied to the measured A-weighted noise levels where an objectionable tone is defined.

As seen in the various states' legislations in Australia, the method in which a sound is determined as being tonal is comparably similar, with variances in terms of the values between the 1/3 octave bands as well as some of the legislations going into further detail of specific frequency band ranges.

This indicates that although there are some specific differences in terms of what is defined as tonality, there is a common approach in Australia that tonality is defined where there is a significant difference between the adjacent 1/3 octave band levels.

3 TONAL NOISE CASE STUDY

A 24-hour industrial facility in Western Australia was identified as producing non-compliant tonal noise at neighbouring residential properties during the night-time period. The facility owner had implemented various control measures over several years to reduce noise emissions using standard passive attenuation methods (e.g., noise barriers, absorption, sealing gaps, changing to quieter ancillary equipment, etc.). Whilst the upgrades reduced the overall A-weighted sound pressure to compliant levels, the persistence of low-frequency tones meant that the facility's noise output attracted a +5dB penalty to the overall A-weighted level, pushing the rated sound level consistently over the night-time noise limit.

Removing the tonal noise from the industrial facility was deemed to be extremely difficult and costly due to it being generated by one of the primary machines in the facility. The idea of creating an electro-acoustic system was proposed as a cost-effective control method to mask, rather than eliminate, the tonal noise. No off-the-shelf solutions for this type of masking system existed, hence NDY was approached to design, prototype and implement software that would eventually become the *NDY Tonality Masking System*.

3.1 Tonality Masking Methodology

There were several challenging aspects to providing a masking system for this application, due to the way in which the industrial plant equipment operated:

- The noise was considered to be intermittent during plant operation and could be off for long periods (hours or days).
- The troublesome tones produced by the equipment were below 250Hz and varied in pitch during the processing cycle and depending on which product was being produced.
- The overall A-weighted noise level at the boundary was marginally compliant (if the tonal penalty was ignored), therefore the masking system had to remove the tonal penalty whilst not raising the overall level by more than 1dB.

The masking system needed to be subtle in its operation, reacting and adapting to the equipment noise output in real time.

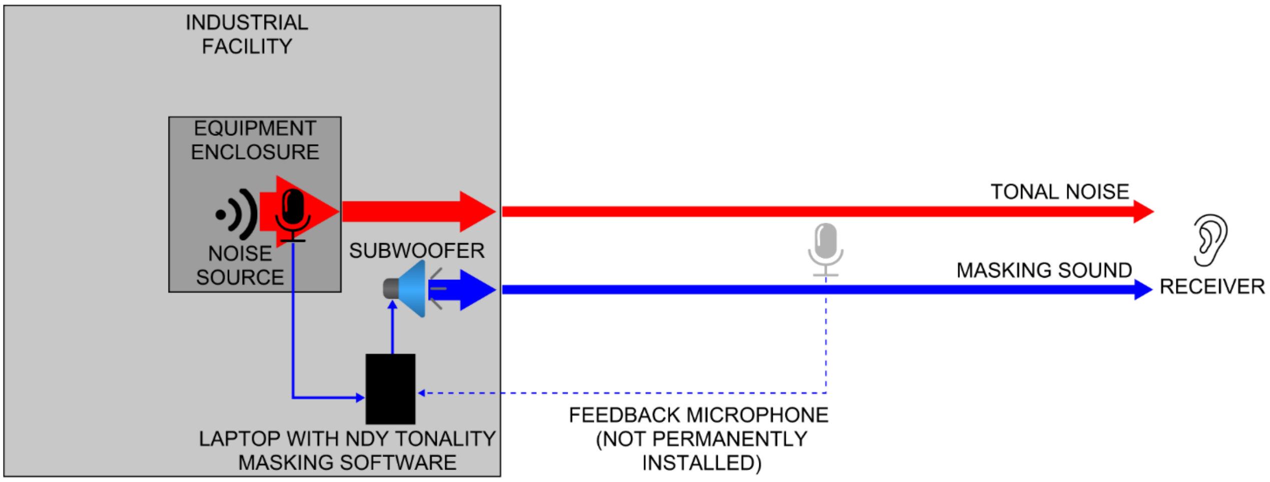

Figure 2 – Diagram of the key NDY Tonality Sound Masking System elements.

On the basis of the digital signal processing technology developed by NDY for the *AiHear®* auralisation software, a feed-forward system was developed which could detect when the equipment was in operation and detect tones generated by the equipment via microphones located within the equipment enclosure, as illustrated in Figure 2. The system would calculate the optimum masking signal in a custom-made *Unity* software application and play the signal through a subwoofer located within the industrial facility, with the intention that the combined noise levels (equipment noise + masking) received at the residential properties would no longer be classified as tonal.

3.2 System Setup

The *NDY Tonality Sound Masking System* was installed on a laptop computer which connected to several devices that captured the noise levels, processed data and output the masking signal via a subwoofer. The equipment and devices used are listed below:

- Computer – This provided the processing power required for the *NDY Tonality Masking Software* to autonomously calculate and adjust the required masking signal in real-time.
- Internet modem – Enabled remote access, control and adjustment of the *NDY Tonality Masking Software*.
- Analogue-to-digital and digital-to-analogue converter (ADC/DAC) unit – Digitised the analogue microphone inputs and also converted the digital masking signal audio outputs into an analogue signal for the subwoofer.
- Subwoofer – This acted as the sound source that reproduced the masking signal, which, when combined with the noise produced by the industrial equipment, masked the tonal components at the residential receiving locations.
- Detection microphones – Two G.R.A.S. Type 40PH-10 microphones placed inside the equipment enclosure were used to provide feed-forward information to the *NDY Tonality Masking Software* about the state of the equipment (on/off) and the tones it was producing. One further temporary microphone (B&K 2250 logger) was placed outside near the receiving residential boundary for commissioning of the system.

Refer to Figure 3 for an image of the equipment setup at the facility.

3.3 Development and Commissioning

The *NDY Tonality Masking System* was developed and trialled remotely in Auckland over several months in the leadup to the system's deployment. Audio recordings of the industrial equipment, played through a loudspeaker, were used as the noise source during these trials. A meeting room inside the NDY office served to approximate the equipment enclosure in which the loudspeaker and detection microphones were placed. Much of this trial work was completed out of hours to avoid annoyance to other office occupants.

Deployment of the tonality masking system was carried out in phases with three calibration sessions in total. The calibration sessions were conducted on-site between 10pm and 4am, when the background noise at the residential receivers was at its lowest. The site had many significant extraneous environmental noise sources which could affect the outdoor noise measurements, and for this reason it was decided early in the development of the *NDY Tonality Masking System* that using a permanently fixed outdoor microphone for feedback into the system would be too unreliable.

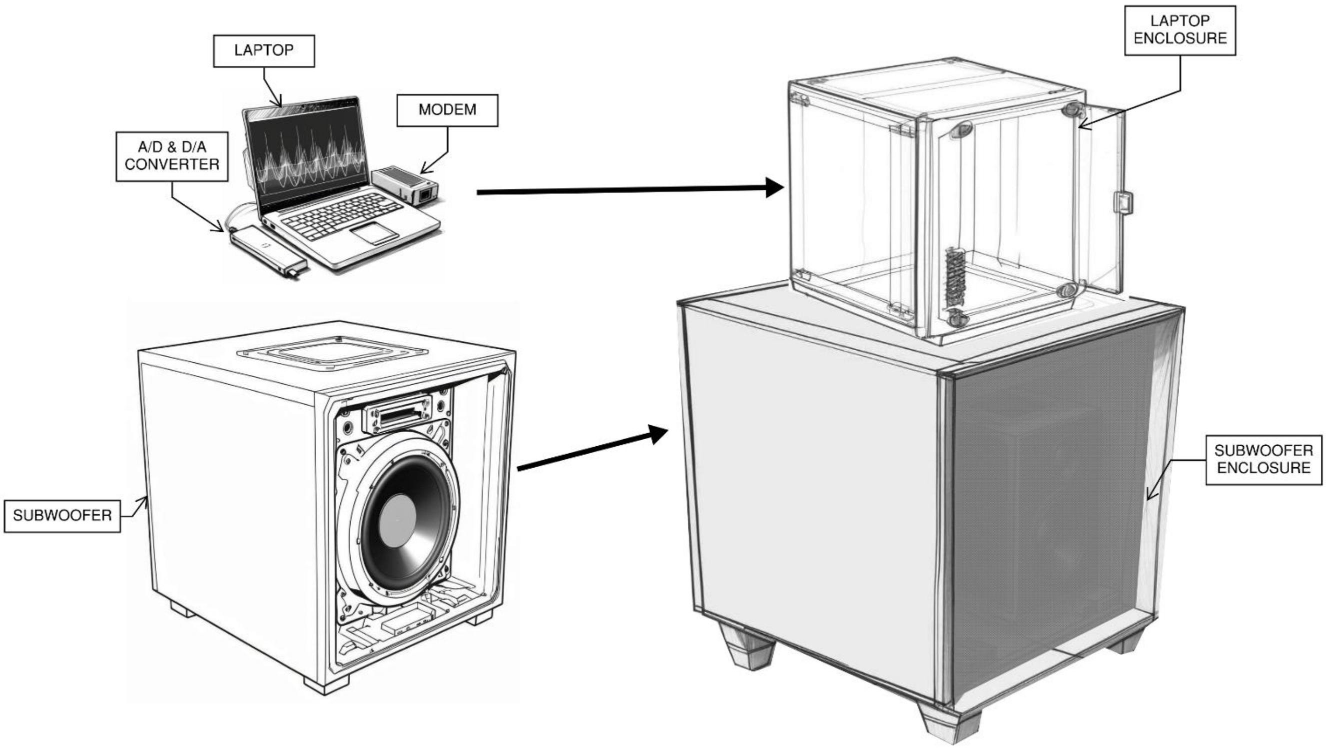

Figure 3 – Equipment and enclosure setup.

The main task during the calibration sessions was to determine two key insertion losses, namely:

- The difference between the 1/3 octave microphone levels measured inside the equipment enclosure and the sound pressure levels occurring simultaneously at the residential locations (as measured by the temporary feedback microphone).

- The difference between the subwoofer output located inside the facility and the sound pressure levels occurring simultaneously at the residential locations (as measured by the temporary feedback microphone).

Once these insertion losses were established and input into the *NDY Tonality Masking System*, the calibration was complete on the basis that nothing in the industrial facility's sound insulation performance significantly changed (e.g., rollers doors remained shut, noise barriers remained in place, etc.). A sample image of the system's user interface is shown Figure 4.

3.4 Technical Challenges

Several technical challenges were encountered during the development of the *NDY Tonality Masking System*, however, the primary challenge was overcoming how to accurately measure the equipment noise emitted to the boundary based on relatively near-field measurements inside the equipment enclosure.

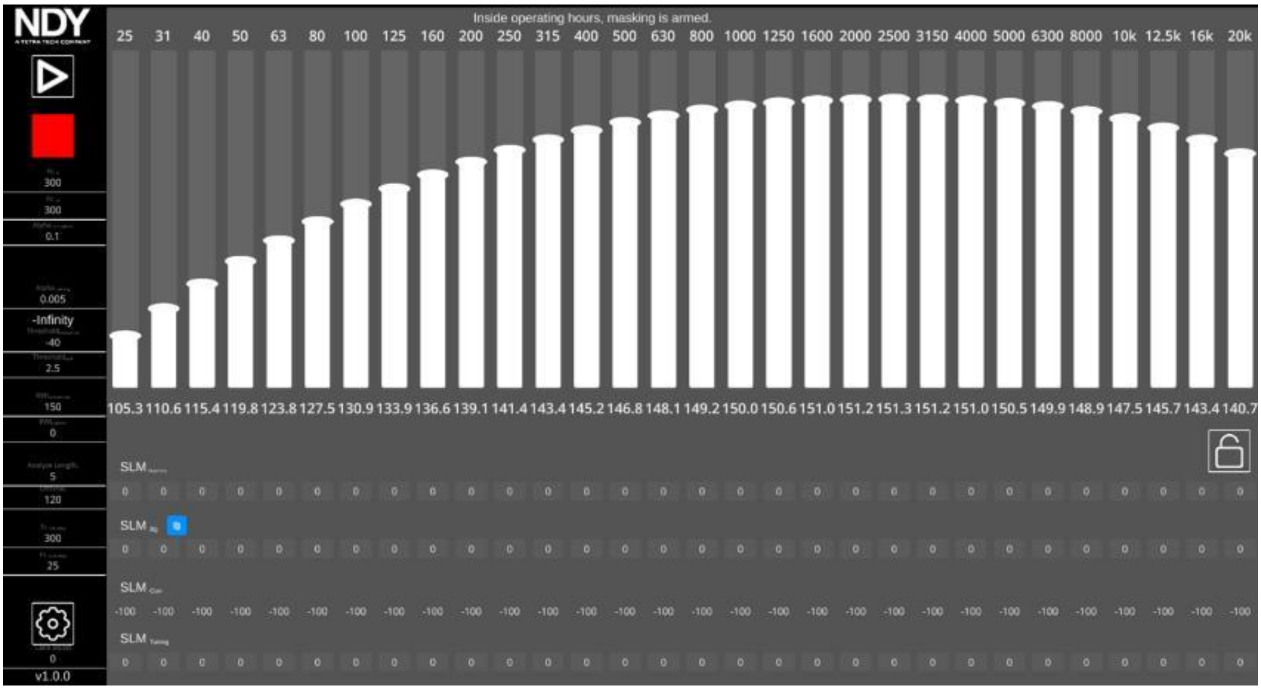

Figure 4 – NDY Tonality Masking System (sample window)

It is common practice and convenient in acoustic engineering to assume that inside an enclosure there is a diffuse sound field (due to high modal density), where the sound pressure level is constant or easily predicted throughout the space. This makes estimating the acoustic insertion loss of the enclosure a relatively simple task, by utilising a single measurement location inside and outside the enclosure.

However, because the tones of interest generated by the industrial equipment were of low frequency (20-250Hz), their wavelengths were relatively long in comparison to the size of the equipment enclosure, and the modal density inside the enclosure at these frequencies was low. This meant that the sound pressure of a low frequency tone varied significantly throughout the enclosure, depending on where the measurement microphone was located. Different tones would exhibit different peaks and troughs in sound pressure level around the enclosure, making a single fixed microphone position an unreliable setup.

This issue was identified during the initial development trials, where a single input microphone had initially been used. It was found that by adding a second microphone inside the enclosure and averaging the two measured levels, an acceptable degree of accuracy could be obtained (approximately ±0.3dB). More microphones would have led to even greater accuracy, however, due to budgetary and other practical constraints, a two-microphone system was adopted.

4 RESULTS AND CONCLUSIONS

For the case study detailed in this paper, the *NDY Tonality Masking System* was developed and installed in an industrial facility that was producing tonal noise impacting on nearby residential receivers. It was observed that when the industrial equipment was operating, low-frequency tonal noise was produced and the overall A-weighted sound pressure level measured at the receiver location that was just under the WA EPNR noise limit (excluding the tonality penalty) for night-time period (being the most stringent time period). The frequency spectrum for this unmasked equipment noise can be seen in Figure 5 (red graphed line). For each scenario (e.g. ambient/machine operating/tonal masking system on), at least 15 measurements (minimum 30 seconds each) were obtained in order to have enough data points for a consistent picture in terms of the frequency spectrum levels.

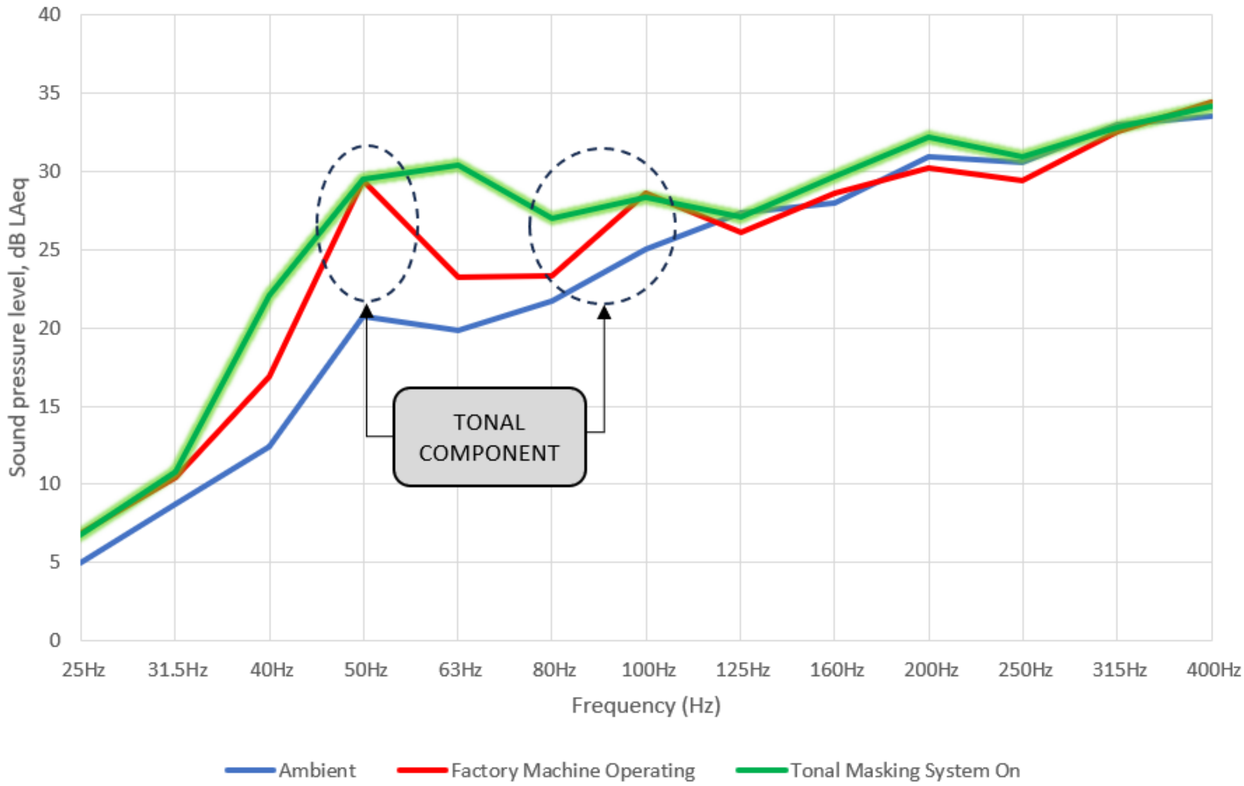

Figure 5 – Example of measured 1/3 octave noise levels at nearest residential receiver location.

When considering the ambient noise spectrum (blue graphed line), this did not exhibit any tonality, and hence did not contribute to the tonal behaviour of noise at the residential receivers' locations when the industrial equipment was not operational.

In the scenario with the *NDY Tonality Masking System* turned on, the smoothing effect around the tonal frequency bands was evident whereby the sound pressure level for the neighbouring 1/3 octave bands increased in relation to the tonal bands (e.g. 50Hz and 100Hz) to effectively mask the tonality of the equipment (green graphed line). Subjectively, the tonal noise from the facility was slightly less prominent when the masking was applied, and the masking itself did not exhibit any particularly identifiable characteristics when in operation.

Although the neighbouring 1/3 octave band levels were increased to allow for the smoothing effect, this only resulted in an overall increase in the A-weighted level of 0.8dB, allowing the final noise levels received at the residential location to be compliant with the WA EPNR noise criteria during the night-time periods. Since the system performed the adjustments autonomously in real-time, the noise levels could be kept below the relevant noise criteria throughout the night-time period.

The *NDY Tonality Masking System* was successful in achieving the goal of removing the tonality penalty from the noise while achieving the overall noise limits applicable to the site. Given the similar definition of tonality in many environmental regulations, the *NDY Tonality Masking System* could find application in any number of future projects.

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