APPLICATION OF PSYCHOACOUSTIC PHENOMENA AS A METHOD OF LOW FREQUENCY NOISE CONTROL FOR EVENTS

P Wheeler Hoare Lea & PhD Student, School of Engineering & Innovation, Open University
D Sharp School of Engineering and Innovation, Open University
S Taherzadeh School of Engineering and Innovation, Open University.

1 INTRODUCTION

Our existing research into low frequency noise from events, presented at previous IOA conferences, has outlined the increased presence of, and expectation of, low frequency music content at concerts and festivals. This predilection for low frequency content brings with it challenges in the form of noise management and control. The increased low frequency content in modern music is unlikely to change any time soon, and therefore methods of controlling and mitigating this low frequency should be a priority for events to avoid unwanted complaints and adverse effects for residents in the near vicinity.

This paper outlines the psychoacoustic phenomenon 'the missing fundamental' and explores its potential application in the world of live event sound as a method of low frequency noise control. Initial predictions and calculations to determine feasibility, in addition to onsite measurements to test the real-world application, are presented in detail.

2 INITIAL CONCEPT

Sounds with a sense of pitch are typically made up of multiple frequencies which are harmonically related. Of these frequencies it is predominantly the lowest frequency, the fundamental frequency, that determines the pitch of the sound; related to its importance in defining the periodicity of the waveform. However, there is a psychoacoustic phenomenon, known as the missing fundamental, whereby the fundamental frequency can be reduced, or even removed, and the perceived pitch of the sound remains the same.

When several harmonics of a certain stem frequency occur together, an additional lower pitched tone is often heard. This perceived tone or pitch is referred to as the missing fundamental phenomenon, because the perceived pitch of the sound matches the fundamental frequency of the harmonics, for which there is no actual source energy. The frequency component doesn't exist, but we can still perceive it.

3 PROPOSED APPLICATIONS

While the missing fundamental has been a known phenomenon since the mid-20th century[1], it is currently limited in its application to everyday use. In April 1997, a patent was filed for an algorithm[2] that synthesises the higher harmonics of a sound with limited low frequency to create the psychoacoustic feeling of the missing fundamental. The applications of this were primarily targeted at those working in small or home studios where the studio speakers lacked the capabilities to produce the required low frequencies that would be expected at the final listening location; for example, a small music studio producing a song which is likely to be performed at a festival. This application allowed the creator to perceive the finalised result, without the low frequency content being present.

Considering that the above-described application is used to invoke the perception of bass that is non-existent or boost the perception of already present bass without the requirement of any increase in low frequency energy, both could be said to have applications to outdoor events, or at least smaller events with limited low frequency production. But what if there was another application that could be used for noise management?

At events where there are already high levels of low frequency content, and a requirement to appropriately mitigate and control unnecessary levels of low frequency noise for those not attending the event, what if some application of the missing fundamental phenomenon could enable the maintained perception of the attendee while reducing the low frequency energy present for those offsite?

Not only would this be effective as a form of mitigation for temporary outdoor events, but it could also be applied to existing venues who wish to maintain their attendees' experience, while reducing their low frequency exposure. In terms of noise mitigation, it would be particularly beneficial as low frequency noise is often the element primarily responsible for complaints or poor relationships with neighbours.

4 PROOF OF CONCEPT CALCULATIONS

A series of initial proof of concept calculations has been carried out to determine the potential positive impacts that reductions to the fundamental frequency might have on overall music levels. The outcomes of the calculations provide an indication as to whether the approach of reducing the fundamental frequency is a viable method of low frequency noise control. To assess this, the A-weighted, C-weighted, and Z-weighted overall levels have been considered, in addition to the affected harmonics.

4.1 Creation of Spectra

Four assessment spectra were created and analysed, each with a specific purpose. Each of the four spectra consisted of 40 pure tones/harmonics which ranged from 50 Hz up to 2kHz in steps of 50 Hz (i.e. 50 Hz…100 Hz…150 Hz…200 Hz etc). This was deemed to be representative of the energy that would be likely to propagate to offsite receptors, while being simple enough to make the representation of the data and the calculations clear.

The first was a 'flat spectrum' representative of 'ideal' white noise with equal contributions from all frequencies. The second spectrum, 'LF Boost', was the same as the flat spectrum, however the bottom three components (50 Hz, 100 Hz, and 150 Hz) were all boosted by 6 dB.

The third and fourth spectra, 'Urban' and 'Pop', were determined from measured levels from music within the Urban and Pop genres. For each genre, the measurements were extrapolated from octave band measurements to create a spectrum containing 40 components at 50 Hz steps. It has been shown previously[3] that, of the four chosen spectra, the Urban spectrum has the highest C-weighted level and is therefore representative of the worst-case low frequency content. Pop music is the most common genre of music and is therefore representative of the most likely spectrum to occur at events.

A summary of the four chosen assessment spectra is presented below in Figure 1.

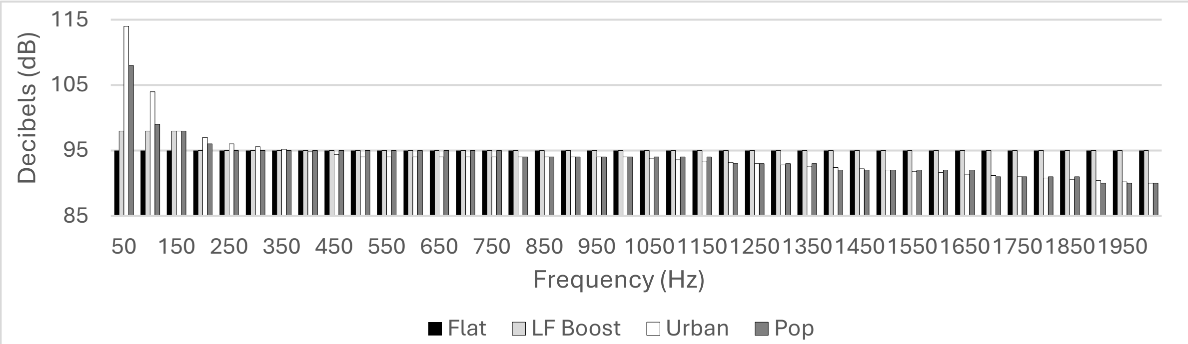

Figure 1 - Summary of the Assessment Spectra 50 Hz to 2 kHz.

To produce the 'missing fundamental' spectra, each of the four assessment spectra were recreated with varying reductions to the fundamental frequency (50 Hz). The reduction sizes were -6 dB, -10 dB and complete removal. This resulted in a total of 16 spectra with 4 for each assessment spectrum: an original spectrum, a spectrum with -6 dB from the fundamental, a spectrum with -10 dB from the fundamental and a spectrum with no fundamental.

4.2 Calculation Method

To determine the level after propagating over a set distance, the spectra were run through a calculation that follows the general principles outlined in the International Standard ISO 9613-2.

4.3 Distance Predictions

To explore the differences between the original spectra and the amended spectra, the overall spectral levels were calculated before propagation and after propagation. The overall Z-weighted, A-weighted and C-weighted levels of the spectra after propagation were taken away from the corresponding levels before propagation to determine the weighted level differences. This process was undertaken for all spectra and all fundamental frequency reductions. Results for propagation distances of 1 km and 2 km are detailed in Table 1 and Table 2 below.

Where the level difference (between source and receiver) of the amended spectrum is greater than that of the original spectrum, the cells have been highlighted. For an improvement over the original spectrum of between 0.1 dB and 3 dB the cell has been highlighted grey.

F0 reduction	Weighting	Calculated Level Difference Between Source and 1km (dB)							
		Flat		LF Boost		Urban		Pop	
		Original	-F0	Original	-F0	Original	-F0	Original	-F0
No F0	Z	79.9	80.0	78.8	79.2	76.3	78.2	77.3	78.9
	A	81.6	81.6	81.5	81.5	80.9	80.9	80.9	80.9
	C	79.9	80.0	78.9	79.2	76.4	78.2	77.6	78.9
F0 – 10 dB	Z	79.9	80.0	78.8	79.2	76.3	77.6	77.3	78.6
	A	81.6	81.6	81.5	81.5	80.9	80.9	80.9	80.9
	C	79.9	80.0	78.9	79.2	76.4	77.7	77.6	78.7
F0 – 6 dB	Z	79.9	80.0	78.8	79.1	76.3	77.1	77.3	78.3
	A	81.6	81.6	81.5	81.5	80.9	80.9	80.9	80.9
	C	79.9	80.0	78.9	79.1	76.4	77.3	77.6	78.4

Table 1 - Summary of the calculated level difference (between source and receiver) for each original spectrum and fundamental reduction at 1km from the source.

F0 reduction	Weighting	Calculated Level Difference Between Source and 2km (dB)							
		Flat		LF Boost		Urban		Pop	
		Original	-F0	Original	-F0	Original	-F0	Original	-F0
No F0	Z	88.5	88.9	86.4	87.2	82.6	85.4	84.1	86.7
	A	92.3	92.3	92.2	92.2	90.0	90.0	90.1	90.1
	C	88.6	88.9	86.6	87.3	82.8	85.5	84.4	86.7
F0 –10 dB	Z	88.5	88.9	86.4	87.1	82.6	84.5	84.1	86.2
	A	92.3	92.3	92.2	92.2	90.0	90.0	90.1	90.1
	C	88.6	88.9	86.6	87.2	82.8	84.7	84.4	86.3
F0 –6 dB	Z	88.5	88.8	86.4	87.0	82.6	83.7	84.1	85.6
	A	92.3	92.3	92.2	92.2	90.0	90.0	90.1	90.1
	C	88.6	88.8	86.6	87.1	82.8	84.0	84.4	85.8

Table 2 - Summary of the calculated level difference (between source and receiver) for each original spectrum and fundamental reduction at 2km from the source.

The A-weighted level across all four assessment spectra (flat, LF boost, urban, pop), and across both attenuation distances shows no overall level difference between the original spectra and their amended missing fundamental counterparts. This was expected with the mid frequencies having the largest contributions to the weighting.

For the Z-weighted spectra, at 1 km there is an increase in level difference compared with the original spectra of between 0.1 dB and 1.9 dB dependent on F0 reduction; and at 2 km the increase in the level difference compared with the original spectra sits between 0.3 dB and 2.8 dB, dependent on F0 reduction.

This effect is also seen for the C-weighted spectra where there is an increase in level difference compared with the original spectra of between 0.1 dB and 1.8 dB at 1 km dependent on F0 reduction; and at 2 km the increase in the level difference compared with the original spectra sits between 0.3 dB and 2.7 dB. As can be anticipated, the greater the F0 reduction, the greater the increase in level difference in dB(C) and dB(Z).

The calculations indicate that a reduction of the fundamental frequency can limit the low frequency content of the sound, as well as producing an overall Z-weighted and C-weighted level that is lower than for the original spectrum at a range of distances. The effect is particularly apparent for spectra which contain large amounts of low frequency energy (e.g. the Urban spectrum).

It should also be noted that while the assessment focusses on the effect of the reductions on the overall weighted level of the spectra, in every instance where a reduction has been made to the fundamental frequency, this reduction is maintained over distance, meaning any reduction of that frequency component at source creates the same reduction at any set distance. With low frequencies propagating further and being more problematic in terms of complaints from nearby residents, this reduction in a single octave band could spell the difference between a significant adverse effect (with associated complaints) and no adverse effect (and no complaints).

4.1.4 Façade Predictions

To further test the concept, calculations have been undertaken to outline the potential effect of a façade on the predicted levels. To determine the effect of the façade on the sound levels, the sound reduction index of a window, was applied to each of the four original assessment spectra and each of their F0 reductions.

Each of the spectra were normalised to an external level of 75 dB(A), which is the most common offsite noise limit for outdoor events. Using an extrapolated sound reduction index for a standard double-glazed window (buildup of 6 mm /12 mm /6mm) of dB Rw 30[4] each of the normalised spectra were then reduced at each frequency band according to the corresponding sound reduction to produce an indicative internal level. While the internal noise level of a room is dependent on reverberation time, size, and other façade elements of the room, this method of assessment provides a simple and indicative representation of the likely effect of the façade.

As per the previous level difference calculations, a table detailing the level difference has been produced for each spectrum, and for each F0 reduction. This is presented in Table 3 below.

Where the level difference of the amended spectrum is greater than that of the original spectrum, the cells have been highlighted. For an improvement over the original spectrum of between 0.1 dB and 3 dB the cell has been highlighted light grey. For an improvement of between 3.1 dB and 5 dB the cells are highlighted mid grey and an improvement over the original spectrum of greater than 5 dB the cells have been highlighted in dark grey.

Spectrum	F0 Reduction	Calculated level difference Between Outside and Inside (dB)		
		A-weighted	Z-weighted	C-weighted
Flat	Original	28.9	25.5	25.7
	Original - F0	28.9	26.4	26.4
	Original - 10 dB	28.9	26.3	26.4
	Original - 6 dB	28.9	26.1	26.2
LF Boost	Original	28.8	23.2	23.6
	Original - F0	28.8	25.2	25.2
	Original - 10 dB	28.8	24.6	24.7
	Original - 6 dB	28.8	24.9	25.0
Urban	Original	28.0	17.3	17.6
	Original - F0	28.2	23.9	23.9
	Original - 10 dB	28.2	21.0	21.5
	Original - 6 dB	28.1	19.3	19.9
Pop	Original	28.3	19.3	19.9
	Original - F0	28.3	24.9	25.0
	Original - 10 dB	28.3	23.4	23.8
	Original - 6 dB	28.3	22.0	22.6

Table 3 - Summary of the calculated Outside vs Inside level difference

It is evident that for all four assessment spectra (flat, LF boost, urban, pop), reducing or removing the fundamental leads to a significant increase in the reduction provided by the façade when assessed in dB(Z) (between 0.6 dB and 6.6 dB) and dB(C) (between 0.5 dB and 6.3 dB). This is particularly prevalent for pop music and urban music where the removal of the F0 provides an average dB(Z) improvement of 6.0 dB and an average dB(C) improvement of 5.7 dB over the original spectra.

This would indicate that applying the missing fundamental phenomenon has the potential to significantly reduce the internal noise level from events experienced by residents nearby, as well as the level outside their properties.

5 OUTDOOR PROPAGATION MEASUREMENTS

To confirm that the calculations and predictions reported above have standing in a real-world scenario, outdoor propagation measurement tests have also been undertaken. The tests employed two 1-minute audio files, both consisting of the same 60 seconds of the same music track. One remained unedited, while the other was processed to apply a simplified version of the missing fundamental phenomenon, using a highpass filter.

The average fundamental frequency of the 1-minute piece of music was calculated, and then for ease of assessment, the associated octave band was noted. The fundamental frequency for the 1-minute section fell within the 63 Hz octave band. For the measurement tests, the 63 Hz octave band was treated as the fundamental, with the subsequent octave bands being treated as harmonics. It is understood this is not how this would be applied in a practical setting, however, it provides a simplistic representation of the proof of concept using octave band data. A filter was applied to the amended track to reduce the 63 Hz octave band by 6 dB.

A small outdoor event in Oxford was used for the propagation measurements, due to access to a remote and quiet monitoring position, and an appropriately sized audio system. Both tracks were calibrated to a front of house level of 89 dB(A), and were played one after the other, with a 10 second gap between. Measurements were undertaken offsite, at an approximate distance of 140 m off axis from the stage, with the overall A-weighted, C-weighted, and octave band data being recorded.

Location	Audio	Measured level (dB)		
		A-weighted	C-weighted	63 Hz Octave
Front of House	Original Audio	89	98	95
	Amended Audio	89	94	89
	Difference	0	-4	-6
Monitoring Locations	Original Audio	57	73	71
	Amended Audio	57	68	65
	Difference	0	-5	-6

Table 4 - Onsite Testing Summary

The 6 dB reduction applied at 63 Hz to the audio track is observed in the measurements at front of house; the original audio has a measured level of 95 dB for the 63 Hz octave band, while the amended audio has a measured level of 89 dB. As expected, this 6 dB reduction is maintained with propagation to the offsite monitoring location; here the original audio has a measured level of 71 dB for the 63 Hz octave band, while the amended audio has a measured level of 65 dB.

Examination of the measured A-weighted levels reveals no differences between the original and amended track, either onsite or offsite. However, the measured C-weighted levels do show differences. At front of house, a 4 dB reduction in measured C-weighted level is observed for the amended audio in comparison with the original track. Meanwhile, at the offsite monitoring location, a 5 dB reduction in measured C-weighted level is observed. The additional 1 dB reduction at the offsite location is consistent with the anticipated greater C-weighted level drop off for sounds where the fundamental has been reduced, predicted in the proof-of-concept calculations reported earlier. However, the propagation distance for the outdoor measurements was only 140 m, so the effect is likely to be much less than was predicted for the 1km and 2km distances used in the calculations. It is also acknowledged that the 1 dB difference could also be explained by fluctuations in background noise level at the monitoring location. Nonetheless, the outdoor propagation measurement tests support the concept of applying the missing fundamental phenomenon as a method of low frequency noise control at outdoor events.

6 FURTHER DEVELOPMENT AND DISCUSSION

One of the largest discussion points around this topic is the potential impact that the reduction (or complete removal) of the fundamental may have on the perception of the event attendees. Where possible any adjustment to the audio onsite should result in as small a change as possible to the event attendee’s perception of the music.

While the concept of applying the missing fundamental phenomenon is based around the premise of maintaining the pitch perception, by adjusting the harmonics of the sound there are other elements of the sound, such as timbre, which may be impacted. To determine to what extent the application of the missing fundamental changes the perception of timbre, and whether any perceived changes can be mitigated with auditory adjustments, a series of psychoacoustic tests are currently being carried out. Once these tests have been completed, the results will be analysed, and the findings presented in due course.

REFERENCES

1. Licklider, J.C.R. (1951). A Duplex Theory of Pitch Perception. The Journal of the Acoustical Society of America, 23(1), pp.147–147. doi:https://doi.org/10.1121/1.1917296.
2. K S Waves Ltd (2020). Smart Speakers, Communication Devices and IoT | Maxx by Waves. [online] Maxx by Waves. Available at: https://maxx.com/experience/home/ [Accessed 8 May 2020].
3. Wheeler, P.J., Taherzadeh, S. and Sharp, D. (2020). The Pop Code: Is It Fit for Purpose? Acoustics Bulletin, 46(3), pp.50–54.
4. Saint-Gobain Glass. (2014). Acoustic Calculator. [online] Available at: https://www.saint-gobain-glass.co.uk/tools/acoustic-calculator/ [Accessed 10 Sep. 2024].