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Perception and annoyance of low frequency noise versus infrasound in the context of wind turbine noise

Kristy L. Hansen - Flinders University, Sturt Rd., Bedford Park 5042, SA, Australia. kristy.hansen@flinders.edu.au

Bruce Walker - Channel Islands Acoustics, USA. noiseybw@aol.com

Branko Zajamsek - University of New South Wales, Sydney, 2052, NSW, Australia. branko.zajamsek@unsw.edu.au

Colin H. Hansen - University of Adelaide, North Tce., Adelaide, 5005, SA, Australia. colin.hansen@adelaide.edu.au

Summary

Limited subjective assessments of synthesized turbine infrasound and low frequency sound comprising frequencies 0.8 to 53 Hz suggest that near-threshold audible cues play a primary role in perception. Infrasound pulses recorded in field environments exhibit peak pressures on the order 0.1 to 0.2 Pa (74 – 80 dB peak SPL) at 400 meters, the approximate minimum setback allowed by any known noise guideline for wind farms. Review of recent field measurements taken at 1,100 meters from a small array of industrial turbines under very steady conditions show peak infrasound amplitudes of approximately 0.04 Pa (66 dB peak SPL) and evidence of blade-pass frequency periodic short bursts of tonal energy just above normal threshold in the frequency range 25 - 53 Hz. Syntheses of infrasound pulses accompanied by these tone bursts produce adverse subjective reaction with or without the infrasound pulses present and no reaction if the tone burst peak pressure is below threshold. The work described here tests the response of two test subjects to synthesized test signals of five-minutes duration. It is possible that longer term exposure could result in some test subjects becoming either more sensitized or acclimated to the noise, resulting in different responses to those described in this paper.

1 Introduction

The history of research into human response to low frequency noise and infrasound is long and rich as shown by Leventhall (2009). Nevertheless, the significance of wind farm infrasound is still the subject of considerable controversy. It is widely recognized that the infrasound levels at a typical residential distance from a wind farm do not exceed the audibility threshold for a person with normal hearing.

Early infrasound research regarding sonic booms by Niedzwiecki and Ribner (1978) concluded that increasing the proportion of infrasound in a noise spectrum has no significant influence on the subjective loudness. On the other hand, the results of a listening study carried out by Huang *et al*. (2008) indicated that for an equivalent A-weighted noise level, test samples containing more low frequency components were found to be more annoying. Furthermore, Waye and Ohrström (2002) conducted

listening tests using recorded noise from 5 wind farms, adjusted so they had the same values of L_{Aeq}. The outcome showed different ratings of annoyance for an equivalent A-weighted sound pressure level but with a different spectral content. In another research study, listening tests were conducted to assess the annoyance of low frequency wind turbine noise (Von Hunerbein *et al*., 2010). Their study used an idealized low-frequency wind turbine noise source containing broadband noise with a specific tone at a single frequency between 32 Hz and 400 Hz. It was concluded that low frequency tones with the same level above the masking noise level as high frequency tones, cause negligible increase in annoyance (Von Hunerbein *et al*., 2010). Therefore, it can be seen that there are conflicting views on the relationship between annoyance and low frequency noise and infrasound, which is the reason for undertaking the experimental work described in this paper.

Other studies have investigated the effect of amplitude modulation on the perceived annoyance. According to listening tests conducted by Lee *et al*. (2010), amplitude modulation of wind turbine noise significantly contributes to noise annoyance. An auditory experiment was also carried out by Yokoyama *et al*. (2013) using recordings of wind turbine noise, in order to examine the effect of amplitude modulation on fluctuation sensation. It was found that the perception of amplitude modulation only occurs at frequencies above 125 Hz (Yokoyama *et al*., 2013). However, the authors only considered amplitude modulation of the entire spectrum with different low-pass filters and did not investigate the effects of amplitude modulation of discrete frequencies, which could be more annoying. In fact, previous research in general has not considered the relationship between amplitude modulated low-frequency tonal noise and annoyance. Also, the effect of tonal infrasound components on the perception of amplitude modulation has not been investigated.

It has been hypothesized by Salt and Hullar (2010) and Kugler et al. (2014) that the ear can respond to much lower levels of infrasound than are required for audibility. The low levels trigger a response in the outer hair cells and thus cause a psychological response (Salt and Hullar, 2010). The possible effect of inner ear excitation on perceived annoyance has not been tested so far.

In multiple informal evaluations of infrasound alone conducted by Walker between 2012 and 2014, periodic signals with fundamental frequency 0.8 Hz and an upper harmonic frequency of 32 Hz or below were perceived by two out of approximately 25 persons who were presented with the signal in three different environments, if the peak pulse amplitude exceeded approximately 0.5 Pa. On the other hand, most evaluators were unaffected at peak pulse amplitudes of 1.5 Pa, the approximate linearity limit of the audio reproduction system.

The aim of this work is therefore to examine the effect of infrasound tonal components on perceived low frequency noise annoyance for short exposure durations. The investigated spectra are synthesized based on measured wind turbine noise, which consists of amplitude modulated tonal components. It is important to understand the effects of infrasound and low frequency noise, since the predicted future increase in wind turbine size will most likely give rise to an increase in noise levels in this frequency range (Møller & Pedersen, 2011).

2 Development of a synthesized signal

For the purpose of the listening tests, a synthesized signal was developed based on data measured outside a residence located 1.3 km from the Waterloo wind farm in South Australia. Details of the field measurements are outlined in Hansen *et al*. (2014). Indoor spectral results were considered; however it was observed that upper

harmonics were subject to room mode effects and hence the outdoor results were considered to be more representative of the actual wind turbine noise signal. A synthesized signal was used in place of the original signal to allow greater control over the adjustment of various signal attributes. In this way, various components of the signal could be isolated to gauge their relative importance in subjective reaction to the overall signal.

2.1 Characteristics of measured wind farm noise

Previous measurements carried out in the vicinity of the Shirley wind farm (Walker *et al*., 2012) have shown that wind farm noise is characterized by discrete peaks at the blade passage frequency (BPF) and harmonics that generally extend to approximately 8-10 Hz. These peaks are followed by broadband noise, often with "haystacks" of acoustic energy in the 20-60 Hz range as indicated in Figure 1. It was originally presumed that the haystacks were broadband noise resulting from blade interaction with incoming medium-scale turbulence. However, data collected in the vicinity of the Waterloo wind farm demonstrates that under conditions that allow very steady turbine operation, these "haystacks" resolve into a series of spectral lines with spacing equal to the BPF. In the case of the Waterloo data, there appear to be three such stacks, centered at approximately 28, 43 and 49 Hz as shown in Figure 2.

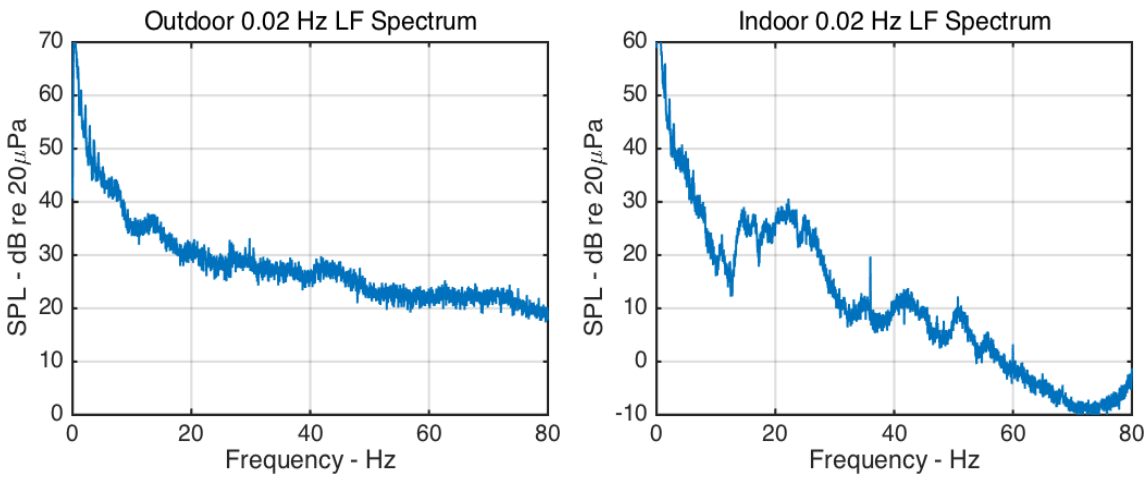

Figure 1 – Spectra measured in the vicinity of the Shirley wind farm 400 meters from nearest turbine. Resolution is 0.02 Hz.

By careful analysis of each spectral line and its neighbors, the mean BPF for this measurement was determined to be 0.8033 Hz. The spectra were re-plotted vs. BPF order in Figure 3a-c. It is seen in the expanded spectra that while the spectral peaks up to 16BPF and above 50BPF are closely centered on the actual harmonic number, most of the peaks between 28 BPF and 42 BPF are about 0.15 BPF lower in frequency and therefore BPF-spaced sidebands of some other process. The set of spectral peaks in Figure 3b also shows generally minor peaks that are not BPF harmonics but BPF-spaced sidebands. The presence of sidebands spaced at the BPF suggests that noise at the center frequencies is amplitude modulated at the BPF. Hence, the broadband nature of the low frequency "haystacks" measured near the Shirley wind farm is attributed to changes in the BPF with time caused by variations in the wind turbine operating speed.

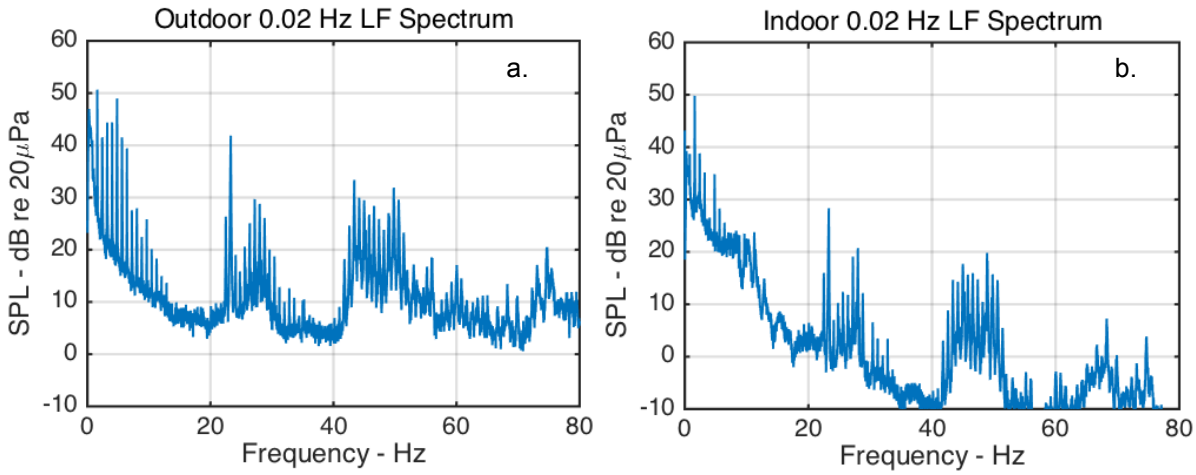

Figure 2 – Outdoor and indoor spectra measured at a residence located 1300 m from the nearest wind turbine. Resolution is 0.02 Hz.

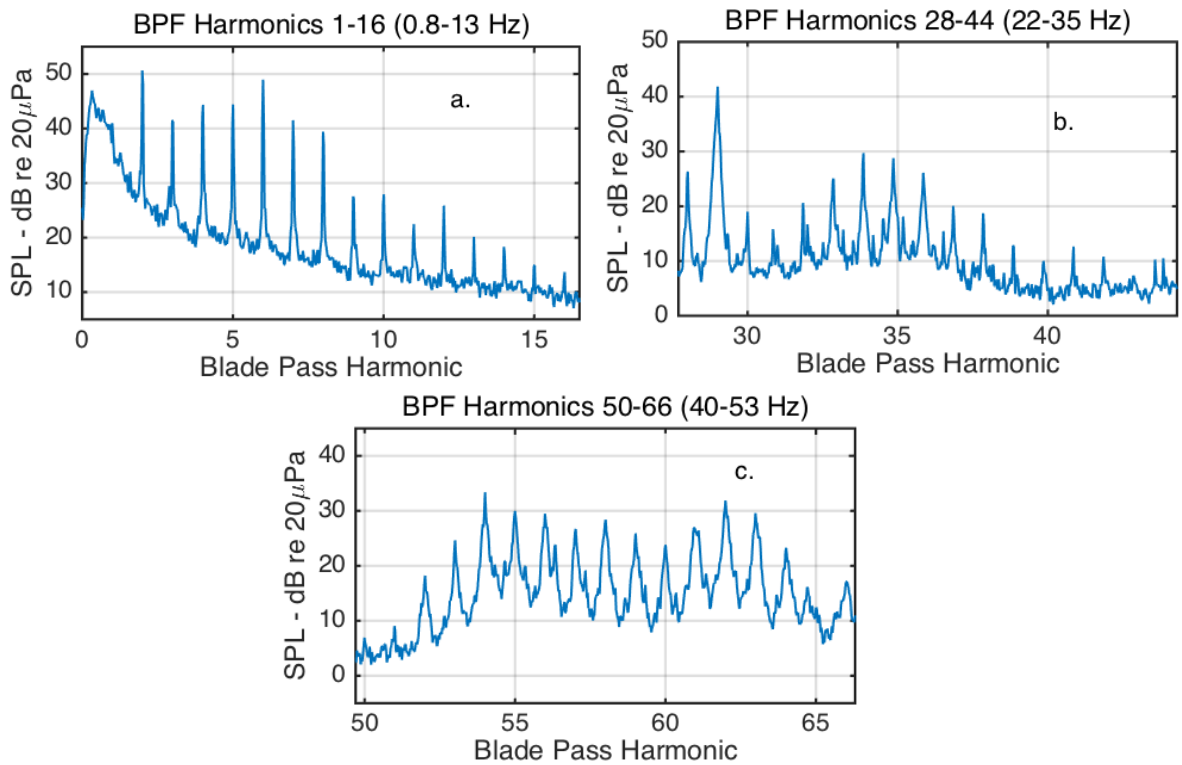

Figure 3 – Expanded BPF order spectra.

2.2 Waveform analysis

The test data from which the spectrum of Figure 2 was computed is 10 minutes in length, comprising just over 160 rotor revolutions. Ensemble average waveforms were computed in two ways. First, the data were divided into blocks of data of length 38,242 samples. This is the number of samples for one rotor revolution based on the mean blade passage period of 0.8033 Hz and data sampling rate of 10,240 Hz. The resulting blocks of data were averaged to preserve periodic components and suppress spurious noise and atmospheric pressure fluctuations. The result of the ensemble averaging for outdoor test channel 1 and its shaft-order spectrum are shown in Figure 4. This approach matched the infrasound portion of the measured spectrum within about 1 dB but falls significantly short in the upper frequencies, as minor fluctuations in rotor

speed and quantization error in the selection of block length affect the higher harmonics disproportionately. The complexity of the mean wave-shape indicates contributions from two or three turbines, which is consistent with the 7-turbine array that forms a row located 1370-3150 meters south of the measurement location.

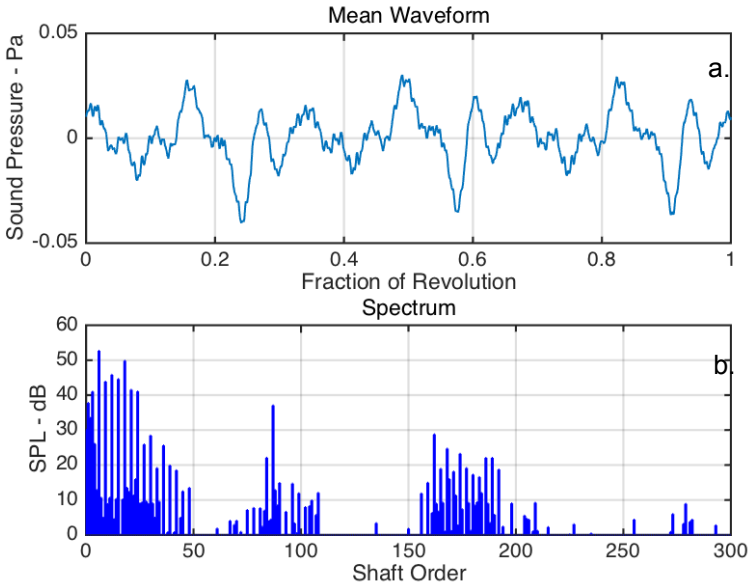

Figure 4 - Mean Outdoor Waveform Computed from Data Blocks of Length = Sample Rate divided by Mean BPF (0.80331 Hz).

The second approach assumes the strong peak near 23.3 Hz is a mechanical tone at the 87th shaft order, and uses that as a tachometer to track the relative rotor position and resample the data at a constant 40,000 samples per revolution. The ensemble average and its shaft-order spectrum from this approach are shown in Figure 5. This recovers the level of the 87th shaft order but appears to reduce the level of many of the other measured peaks, suggesting that the 23.3 Hz tone may be a mechanical tone from one of the less dominant turbines in the row.

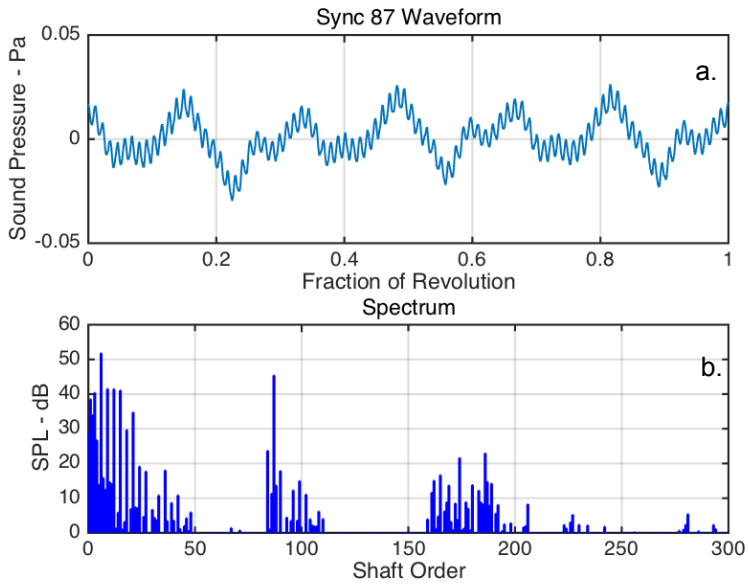

Figure 5 - Mean Outdoor Waveform from 23 Hz synchronization.

2.3 Modulation analysis

Review of the spectra indicates the possibility of amplitude modulation which results in BPF-spaced sidebands on either side of dominant tones. Two different characters of modulation are indicated. First, at approximately 23.3 Hz, (blade-order 29, shaft-order 87), the indication is of a single tone flanked by relatively weak (-15 and -20 dB) side bands. A modelled example of this is shown in Figure 6. A possible source for this modulated tone could be quasi-sinusoidal gearbox stresses resulting from rotor torque fluctuations in atmospheric wind shear conditions.

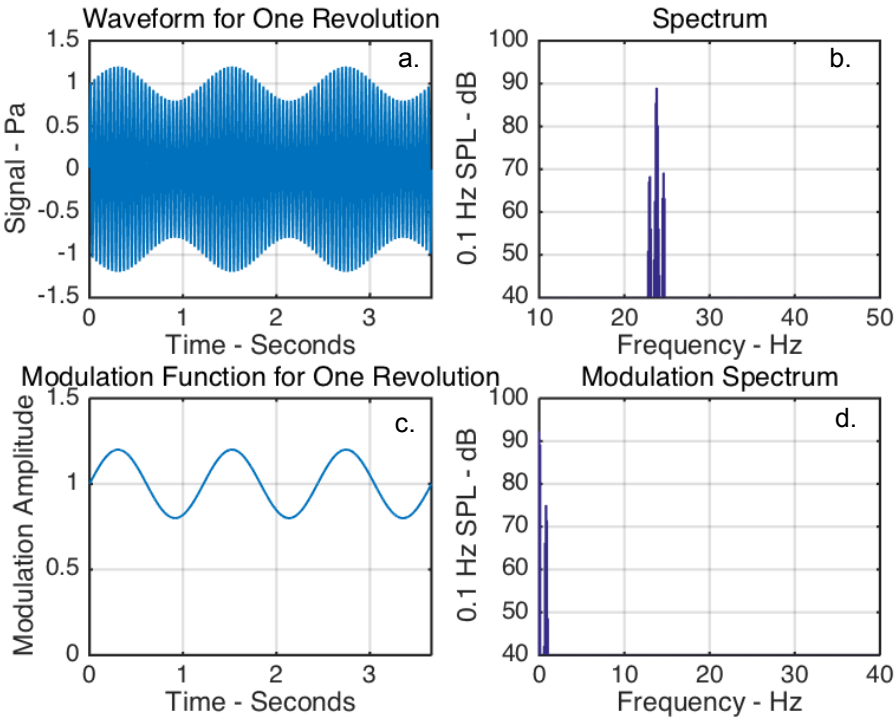

Figure 6 - Wave and spectrum of 23 Hz tone amplitude modulated by 0.8 Hz.

The second type of modulation spectrum consists of a “mound” of spectral lines, of which three appear to be present in the data. One possible explanation for the generation of these “mounds” is short duration gating (with a modulating function to modify the amplitude of each sample) of a tone, or BPF harmonic (as in the case of the “mound” between 25 and 34 Hz), not directly related to the BPF. Gating implies that the tone is sampled for a number of short durations during a revolution of the turbine. In practice, this means that the tone only exists for these short durations and during each gating period, the tone has a loudness that gradually increases and then decreases. For a 3-bladed turbine, the number of time periods for which the tone exists is three per revolution (as shown in Figure 7a) and each would correspond to the blade passing the tower. This mechanism can be simulated by sampling a continuous tone using the modulating function illustrated in Figure 7c. The results so obtained are shown in Figure 7, indicating that such modulation does produce a “mound” of spectral lines.

For comparison with the measurement data, Figure 8 shows the modulation spectrum of Channel 1 for a frequency band limited to 40-53 Hz. Although not identical to the modulating spectrum in Figure 7d, the similarity is remarkably clear considering the potential contamination by multiple turbines and propagation distance of over 1 km. For interest, modulation spectrograms were computed for several 1/3-octave

bands, with examples in the frequency range of interest shown in Figure 9. Figure 10 illustrates the effect of gating three tones simultaneously.

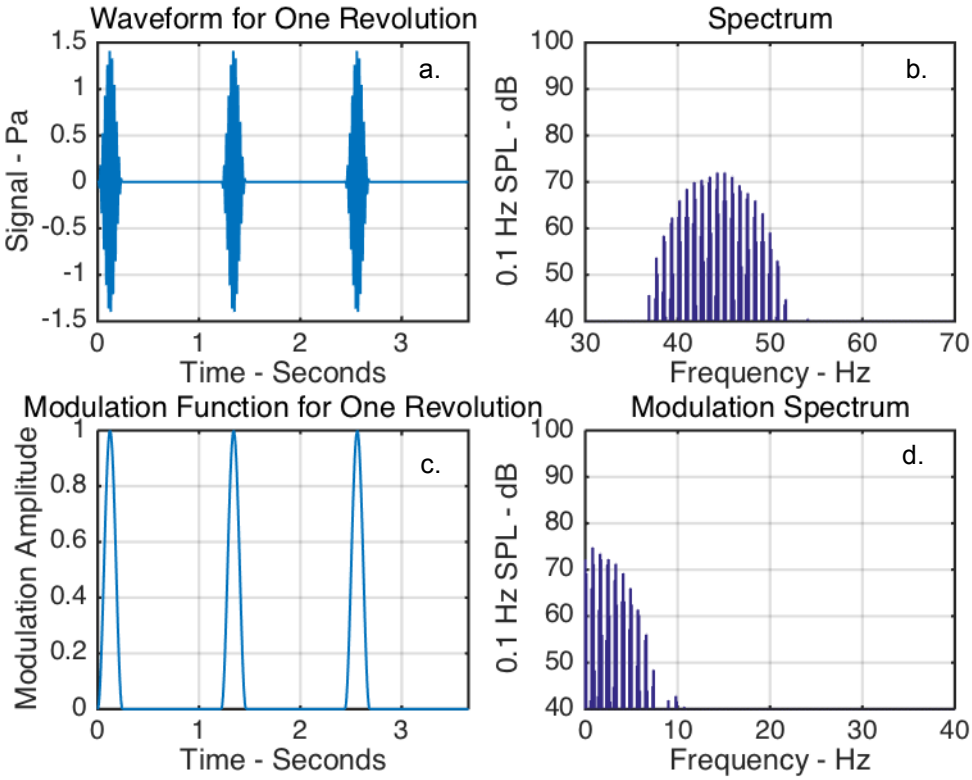

Figure 7 - Wave and spectrum of 45 Hz tone gated by 0.2 second Hanning windows at 0.8 Hz.

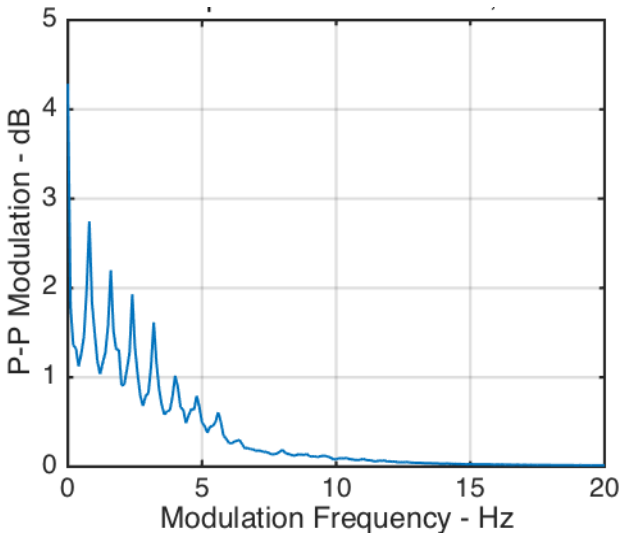

Figure 8 - Modulation spectrum of 40 - 53 Hz frequency band from Channel 1.

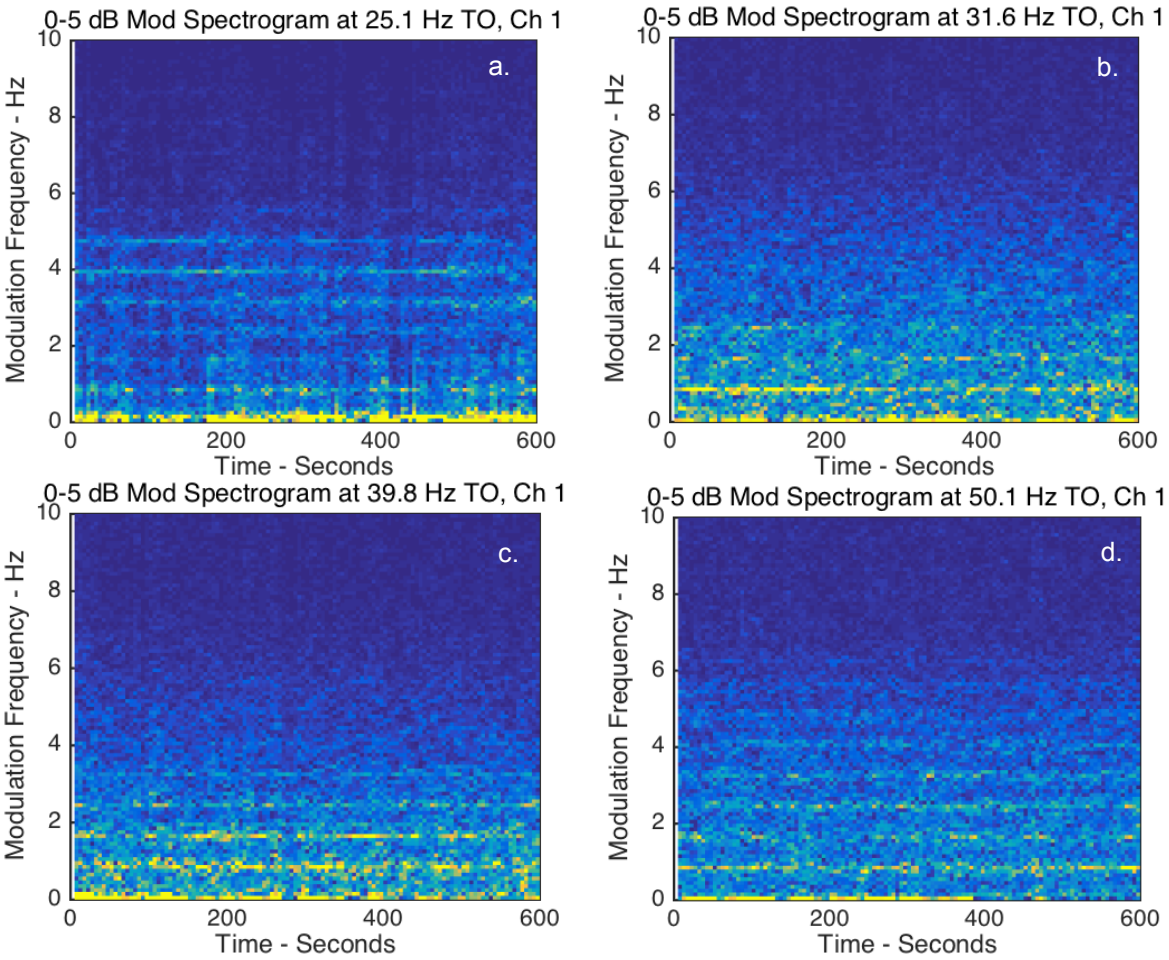

Figure 9 - Modulation spectrograms for 25 Hz to 50 Hz 1/3-octaves from Channel 1.

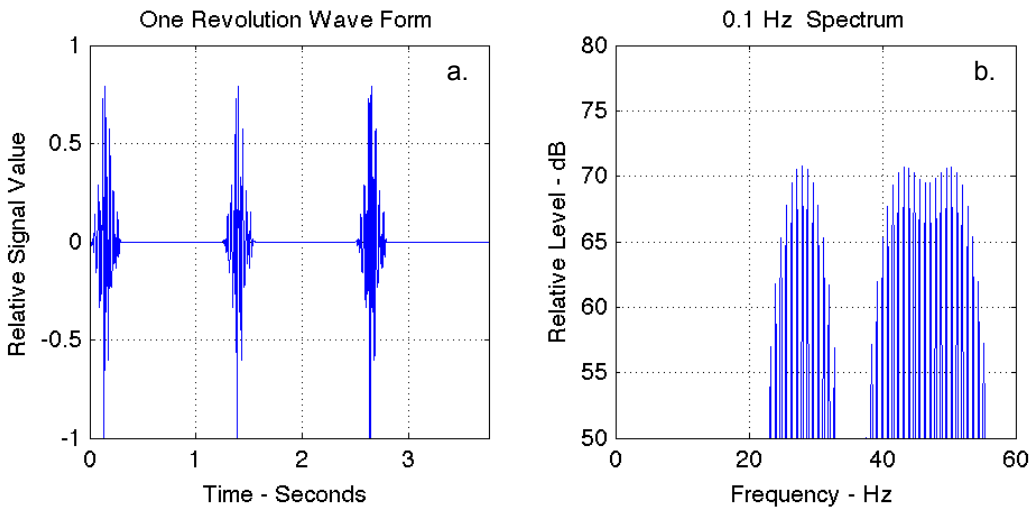

Figure 10 - Waveform and spectrum for 28, 43 and 50 Hz tones gated simultaneously.

2.4 Signal synthesis

Fourier synthesis can be used to combine the turbine-related elements for subjective evaluation if it is assumed that the signal is periodic at a reasonable repetition period and if the relative phases of all the harmonics are known. Strictly speaking, the frequency shift, away from the exact harmonic frequencies, of spectral peaks in the

25-34 Hz range would make Fourier synthesis difficult, and for purposes of this work, the spectral peaks were forced to the nearest integer BPF harmonic.

To obtain a “best estimate” of phase relationships, measurement signals were filtered in frequency bands encompassing the major “haystack” ranges and then plotted in 100 ms L_{eq} and L_{max} blocks as shown in Figure 11. Periodic peaks with spacing of approximately 1.25 seconds can be seen in Figure 11a and b, and the difference between L_{max} and L_{eq} of the filtered signals is seen to be 10 dB or more. Based on these observations and the results of numerous time-domain analyses of turbine infrasound measurements, synthesized harmonics were taken as sine waves, all with zero phase at time zero, although this phasing does not maximize the signal crest factor (that would require all cosine waves or sine waves with phase 90 degrees at time zero).

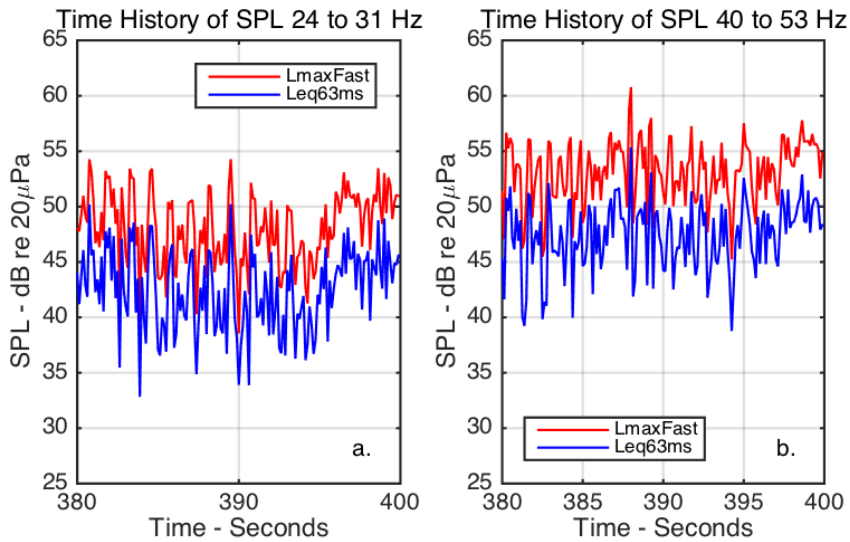

Figure 11 - Portion of time history of filtered signal from outdoor measurement

A comparison between harmonic sine waves with zero phase at time zero and sine waves with random phases is shown in Figure 12. It was suspected, and has subsequently been confirmed, that at sound pressure levels near threshold, the peaks in the phase-aligned signal (Figure 12a and b) would give the subjective impression of a sequence of “thumps” while the un-aligned signal (Figure 12c and d) would be inaudible.

In a paper by Palmer (2014), evidence was presented that persons affected by turbine “infrasound” reported that room position had an important effect on severity. At true infrasonic frequencies, the sound pressure is nearly uniform in an enclosed space. This further suggests that exposure to near-threshold periodic bursts of low frequency sound, rather than deeply subliminal levels of infrasound, could be the true perception or annoyance triggers.

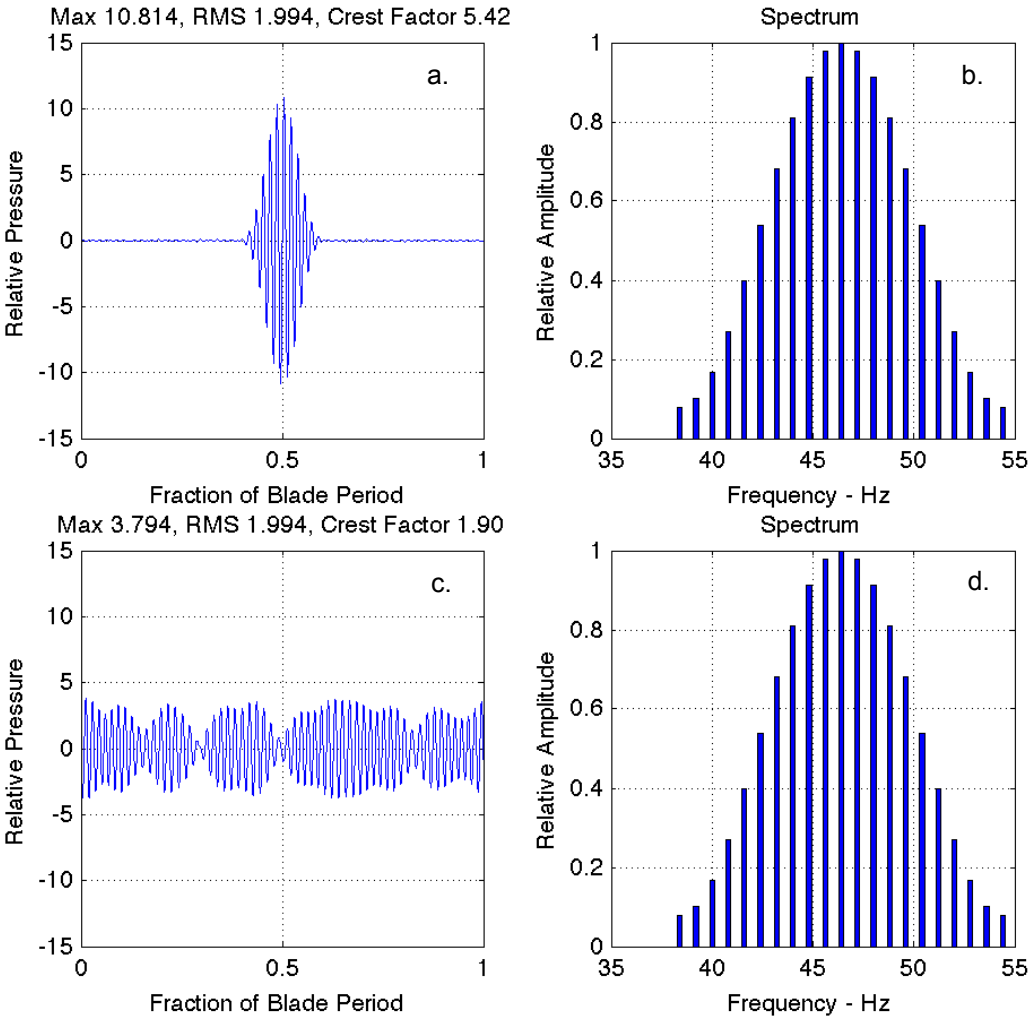

Figure 12 - Effect of phase alignment on signals with equal spectra and SPL.

2.5 Synthesized Signal Testing

In an approximately 4.4 × 3.8 × 2.7 m residential room, a loudspeaker capable of producing 75 dB or greater sound pressure level from 0.8 to 60 Hz was set in one corner and a sofa-bed was set along an adjacent wall as shown in the schematic plan of Figure 13. The evaluator's head position was just over 2.5 meters from the center of the loudspeaker, 1.2 meters above the floor. For evaluation relative to the Waterloo data, the full spectrum from 0.8 to 53 Hz (66 harmonics) was synthesized and monitored with a low frequency microphone immediately above the evaluator's head. System response was equalized so that room effects and loudspeaker response were neutralized as described in Walker and Celano (2015).

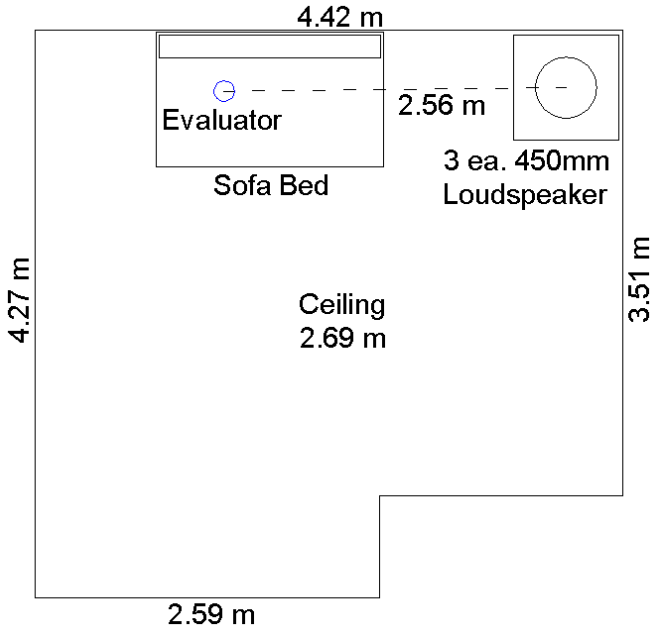

Figure 13 – Schematic of test room showing source and evaluator positions.

The synthesis system is equipped with a 5 dB per step attenuator to allow "bracketing" of hearing or other sensitivity thresholds. The test spectrum, as shown in Figure 14a, is equivalent to that shown in Figure 2a, with the exception that upper harmonics are stabilized so that all energy is exactly at the harmonic frequency instead of spreading with slight variations in turbine speed, and the lowest BPF harmonics are adjusted upward by approximately 5 dB to allow for possible multi-turbine interference effects. These effects could, at times of particular synchronicity of the turbines, increase low frequency levels above those captured in the measurements. The pulse waveform associated with the spectrum is shown in Figure 14b. The isolated spectrum line at 23 Hz shows as a quasi-steady oscillation and the "haystack" spectra appear as a burst of 40-50 Hz energy aligned with the pulse produced by the summation of the lowest harmonics (below 20 Hz).

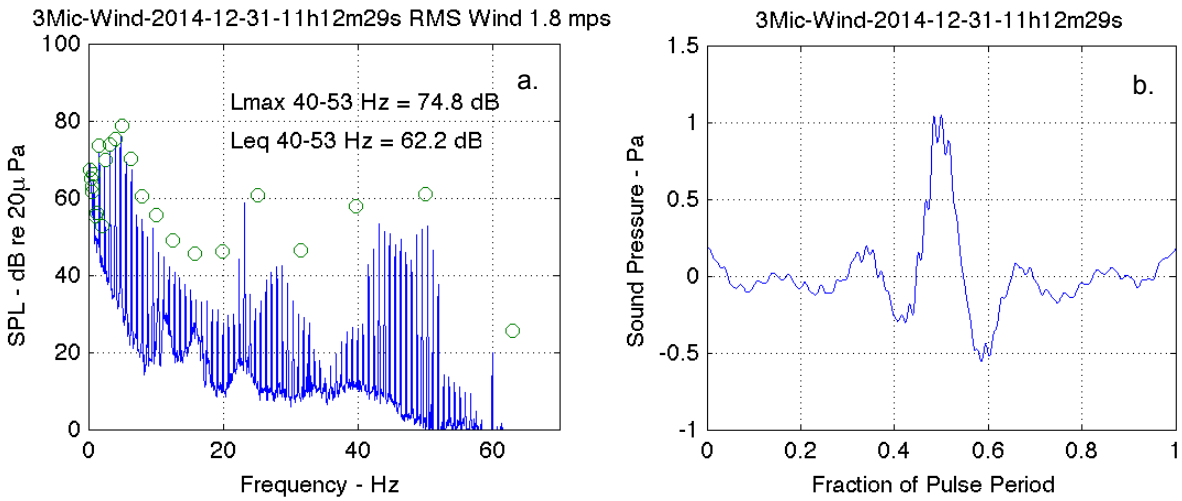

Figure 14 – a. Synthesized and monitored Waterloo-based all-pass spectrum and b. Pulse waveform from Waterloo all-pass spectrum.

The evaluators consisted of test person (D) who has normal hearing and an extreme propensity to sea-sickness and test person (J) who has very acute hearing,

particularly at low frequencies. In early tests at high amplitude (1.5 Pa peak) with strong harmonics up to 32 Hz, he was made ill and took a while to recover. However, in a subsequent test (months later), synthesized blade “whoosh” with no infrasound started making him queasy. The two evaluators participated as a matter of availability and interest in the overall synthesis project. Their low frequency hearing and sea-sickness propensities were incidental but judged to be relevant to their evaluations.

Evaluators were presented with the all-pass spectrum (containing energy from 0.8 Hz to 60 Hz) for periods of 5 minutes at each incremental amplitude and they were required to determine which two settings of the 5 dB attenuator bracketed their sensation threshold. The procedure was repeated with three modifications to the spectrum as shown in Figure 15:

- H: 20 Hz high-pass
- K: 30 Hz high-pass
- L: 20 Hz low-pass

All tests were blind in that the evaluators were not aware of which spectrum they were being presented with and the signals were selected randomly.

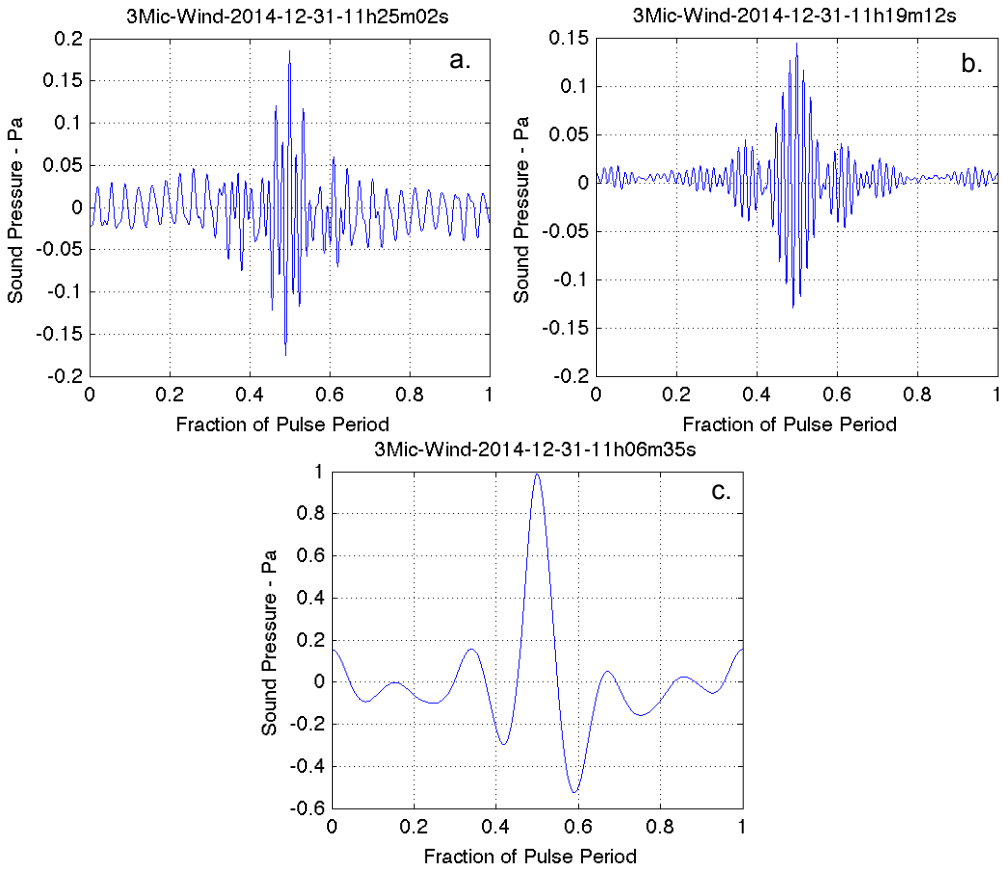

Figure 15 - Pulse wave forms of filtered signals, a-c: high pass at 20 Hz, high pass at 30 Hz and low-pass at 20 Hz.

3 Results

Results are presented in Table 1 which indicate the opinions of two test subjects on the various noises to which they were subjected. The subjects were asked whether the noise was annoying, and if so, how annoying. They were also asked to comment on the character (rough, smooth, raspy) of the noise and whether it would cause them

difficulty in going to sleep. The level of the noise that was presented to the evaluators has been expressed relative to the measured outdoor level in Table 1.

The following analysis discusses the various signal characteristics that resulted in the evaluators reporting “no sensation”, “slight audibility”, “audibility”, “annoyance” and “high annoyance.” In some cases, comments from the two evaluators were expressed differently but appeared to reflect the same perception and therefore some interpretation has been necessary. One of the evaluators provided some insight into the character of the noise and this will also be discussed. Table 1 provides a summary of the evaluators’ comments which are presented in their original format.

The perception of “no sensation” was expressed when the all-pass filter (0.8 Hz – 53 Hz harmonics summed) was used and the signal amplitude was 5 dB lower than the measured outdoor signal at a residence 1.3 km from the Waterloo wind farm. Not surprisingly, applying a 30 Hz low-pass filter to this signal produced the same result of “no sensation”.

Increasing the signal amplitude to the range encompassing the outdoor measurements resulted in the all-pass signal having “slight audibility” for evaluator “J”, known to have acute hearing, and apparently “no sensation” for evaluator “D”. Applying the 20 Hz and 30 Hz high-pass filters to the signal produced a similar result. It should be noted that the crest factor and L_{Aeq} (low-pass at 100 Hz) of the signal were lower than the measured value outdoors.

The all-pass signal had “slight audibility” for evaluator “D” when the amplitude was increased by 5dB relative to the measured outdoor signal. At this level, evaluator “J” expressed a similar opinion, although differences in wording make comparison difficult. It is also worth noting that evaluator “D” commented that she would be able to sleep if the signal were at this level. At this level, the L_{Aeq} (low-pass at 100 Hz) was in the same range and the crest factor was lower than the measured value. Evaluator “D” found no difference in the signal audibility when the 30 Hz all-pass filter was applied.

A further increase in the signal amplitude by 9 dB relative to the outdoor measured level resulted in “audibility” of the all-pass signal for evaluator “D” and “annoyance” for evaluator “J.” The crest factor was in the same range as the measured signal outdoors for one of the tests and was about half this value for the other but since the latter signal was louder, it was found to be more intrusive to evaluator “D.” This evaluator observed that she couldn’t sleep in the presence of such a noise. With the 30 Hz high-pass filter, this signal was perceived as “slightly softer” but the evaluator commented that she would still not be able to sleep. Despite this assertion, evaluator “D” actually fell asleep when a 20 Hz high-pass filter was applied to the signal, which was in apparent contradiction with her previous comments.

Table 1 – Signal characteristics of test spectra as well as evaluator comments

Date	Time	dB relative to measured	Spectrum	Peak Ens Avg Wave SP	L1 40-53 Hz	Leq 40-53 Hz	40-53 Hz Crest Factor	Judgement J	Judgement D	0.3 HP	LGeq	LC100eq	LA100eq	0.3-100 Hz Leq	0.3-100 Hz L1	0.3-100 Hz L0.1	Overall Crest Factor
27/01/15	18:02	-5	All Pass	0.028	52.9	39.8	4.5	No Sensation	N/A	58.3	44.9	40.4	11.4	58.3	66.9	70.5	1.7
31/12/14	10:59	-5	30 Hz HP	0.010	53.4	41.8	3.8	No Sensation	No Sensation	71.9	54.0	43.5	13.6	71.9	83.0	87.9	0.1
27/01/15	13:17	0	All Pass	0.044	58.0	45.6	4.1	N/A	Just Below Audible	63.0	51.4	45.9	17.7	63.0	72.3	75.6	1.6
31/12/14	10:38	0	All Pass	0.184	60.1	47.6	4.2	Just Barely Audible	No Sensation	75.3	60.2	49.8	18.8	75.3	84.9	88.4	1.6
27/01/15	17:57	0	All Pass	0.056	58.3	45.7	4.3	Pulses Just Audible	N/A	60.0	49.2	46.2	18.5	60.0	69.1	71.4	2.8
31/12/14	10:44	0	20 Hz HP	0.042	60.1	48.1	4.0	Just Barely Audible	No Sensation	78.5	62.5	51.3	20.7	78.5	88.1	92.2	0.2
31/12/14	10:52	0	30 Hz HP	0.025	60.1	47.5	4.3	Just Faintly Audible	No Sensation	70.6	52.3	46.8	16.9	70.6	81.0	83.3	0.4
27/01/15	18:06	0	30 Hz HP	0.018	58.0	45.5	4.2	Pulses Audible Same as All Pass	N/A	58.7	41.3	44.4	14.6	58.7	67.0	69.6	1.1
27/01/15	13:21	5	All Pass	0.086	63.4	50.8	4.3	N/A	Just Audible	63.0	54.1	50.6	20.8	63.0	72.5	74.8	3.0
31/12/14	10:31	5	All Pass	0.330	65.1	52.4	4.3	Slightly Audible	Just Audible	77.5	62.4	53.5	21.5	77.5	87.8	91.4	2.2
27/01/15	13:26	5	30 Hz HP	0.033	63.4	51.1	4.2	N/A	Just Audible, No Difference	62.4	53.9	50.3	21.6	62.3	70.8	73.9	1.2
29/12/14	11:12	9	All Pass	0.487	68.5	55.8	4.3	Equally Annoying	Audible	75.8	64.1	56.7	25.0	75.8	87.4	88.2	4.0
12/11/14	15:02	9	All Pass	0.512	69.9	57.2	4.3	N/A	Louder, More Freq., Couldn't Sleep	81.3	66.0	58.1	28.1	81.3	88.1	101.1	2.2
29/12/14	11:06	9	30 Hz HP	0.062	68.6	55.9	4.3	Annoying	Audible	62.8	52.0	54.8	25.2	62.8	72.8	76.6	2.3
12/11/14	16:05	9	30 Hz HP	0.074	69.9	57.2	4.3	N/A	Slightly Softer, Prob. Couldn't Sleep	80.1	61.3	56.6	27.4	80.1	79.1	100.6	0.4
12/11/14	16:35	9	20 Hz HP	0.087	69.8	57.0	4.4	N/A	Fell Asleep	79.2	61.7	57.0	28.6	79.1	77.1	100.0	0.5
29/12/14	11:20	9	20 Hz LP	0.466	43.4	35.1	2.6	No Sensation	No Sensation	75.9	62.5	50.0	17.1	75.9	87.2	88.0	3.7
31/12/14	10:04	10	All Pass	0.600	70.1	57.3	4.4	Clearly Audible	Audible	78.3	65.5	58.1	27.8	78.3	89.2	90.9	3.6
31/12/14	10:17	10	30 Hz HP	0.083	70.1	57.3	4.4	Less Raspy than 20 Hz HP, Less Smooth than A.P.	Audible	69.5	51.1	56.0	26.2	69.5	79.9	82.6	1.4
31/12/14	10:11	10	20 Hz HP	0.107	70.0	57.3	4.3	More Raspy than A.P.	Audible	69.9	60.9	57.1	26.7	69.9	81.0	85.6	1.7
31/12/14	10:24	10	20 Hz LP	0.564	40.9	31.9	2.8	No Sensation	No Sensation	79.0	64.2	51.3	12.2	79.0	89.3	91.7	3.2
31/12/14	11:12	15	All Pass	1.045	74.8	62.2	4.3	Obnoxious	Very Audible	82.4	70.1	62.8	31.1	82.4	93.9	94.9	4.0
31/12/14	11:19	15	30 Hz HP	0.145	75.1	62.3	4.4	Obnoxious	Very Audible	71.9	54.1	60.9	31.1	71.9	82.2	84.2	1.8
31/12/14	11:25	15	20 Hz HP	0.186	75.1	62.4	4.3	Obnoxious	Very Audible	73.7	65.7	62.1	31.3	73.7	84.8	88.7	1.9
31/12/14	11:06	15	20 Hz LP	0.990	44.3	34.7	3.0	No Sensation	No Sensation	82.4	68.4	55.7	11.3	82.4	93.8	94.7	3.8
27/01/15	13:12	20	All Pass	0.479	78.2	65.5	4.3	N/A	Very Audible Thump	75.6	68.3	65.1	34.2	75.6	86.2	88.0	4.0
				0.022	55.9	47.8	2.5		Waterloo Channel 1	60.0	52.7	48.8	20.7	59.9	68.6	73.6	4.8
				0.023	57.8	49.7	2.6		Waterloo Channel 2	61.1	48.6	49.6	22.2	61.0	69.5	72.2	3.6
				0.021	56.1	47.8	2.6		Waterloo Channel 3	59.9	50.4	48.4	20.5	59.9	69.1	73.2	4.6
				0.016	42.4	34.3	2.5		Waterloo Channel 4 (indoor)	56.1	45.5	36.6	7.0	56.1	64.4	66.8	3.4

There was little variation in the results when the amplitude of the signal was increased by 10 dB relative to the outdoor measured level. On the other hand, evaluator “J” commented on some aspects of the noise character which varied depending on the filter type applied to the signal. When a 30 Hz high-pass filter was applied, the signal became more “raspy” or less “smooth.” The signal was even more “raspy” with a 20 Hz high-pass filter.

Both evaluators reported that they experienced “no sensation” when they were presented with signals that had been low-pass filtered at 20 Hz at an amplitude of 9 dB above the measured outdoor level. This result did not change as the amplitude was increased by 10 dB and 15 dB. The low frequency content of the corresponding three cases was higher than the measured outdoor signal as shown by the higher relative values of L_{Geq} and L_{Ceq}. On the other hand, the overall crest factor of the signal was slightly lower for these cases.

For a signal amplitude corresponding to 15 dB above the measured outdoor noise level, evaluator “J” expressed “high annoyance,” referring to the signal as “obnoxious.” Evaluator “D” found the signal “very audible.” The same judgements were passed when the signal was high-pass filtered at both 20 Hz and 30 Hz. It is interesting to note that the L_{Aeq} (low-pass at 100 Hz) was only slightly greater than 30 dB(A). According to the World Health Organisation night time guidelines (WHO, 2009), there should be no effects on sleep at levels of 30 dB(A) and below, which would not be expected for a “very audible” or “obnoxious” signal. This indicates that in the presence of very low background noise, the loudness of a signal with strong low-frequency components is not well-described by an A-weighted value.

A very audible “thump” was produced according to evaluator “D” when the amplitude of the signal was increased to 20 dB above the outdoor measured level and the all-pass filter was applied. For this test, the L_{Geq} was equal to 68.3 dB(G), which is well below the commonly stated threshold limit of 85 dB(G). This G-weighted threshold was calculated based on unweighted hearing thresholds published by Watanabe and Møller (1990). In considering the 95th percentile of people, two standard deviations should be subtracted from the mean of the original published data, giving approximately 85 dB(G). Nonetheless, it is important to note that the published hearing thresholds (Watanabe & Møller, 1990) were established based on listening tests with pure tones. Therefore the overall G-weighted threshold of audibility could be much lower for complex tones, modulated signals and signals with high crest factors. This is corroborated by the results of this study.

Another point of interest is that despite having an extreme propensity to sea sickness, evaluator “D” did not comment that she felt sick during any of the tests. On the other hand, residents living in the vicinity of wind farms have reported symptoms such as dizziness and nausea and this has been attributed to the cyclic pressure variation caused by wind farm infrasound by Dooley (2013). A possible reason for this discrepancy is that symptoms of dizziness and nausea only occur for longer-term exposures. This is consistent with the phenomena of sea sickness which can take longer than the test period of 5 minutes to manifest in nausea. Thus long-term exposure could result in different perceptions to those reported here. Nonetheless informal tests, not reported in here, indicated that running the full spectrum for periods of up to a couple of hours incidental to sleep did not result in nausea for evaluator “D.”

4 Conclusions

At noise levels in the range of those measured outdoors in the vicinity of a wind farm, an evaluator with acute hearing found the noise “slightly audible” whereas another

evaluator reported “no sensation” when exposed to 5-minute recordings in a listening test environment. As the signal amplitude was increased, the noise became progressively more audible, eventually reaching the point where it became annoying. At this point the overall A-weighted level (low-pass filtered at 100 Hz) and the G-weighted level were within ranges that are normally considered acceptable.

Applying a high-pass filter to the signal did not affect the audibility, regardless of whether the lower limit of the filter was 20 Hz or 30 Hz. This result was consistent for all signal amplitudes that were presented to the evaluators. The implication of this finding is that the low frequency part of the spectrum between 30 Hz and 53 Hz governed the response of the evaluators. This was further confirmed by the observation that applying a 20 Hz low-pass filter resulted in “no sensation,” even at high signal amplitudes.

There was even some indication at high levels (clearly audible pulses, 0.5 to 1.5 Pa peak SPL if infrasound present), that including the infrasound made the total sound less intrusive. There are a few conjectures about why this might be. One is that the movement of the loudspeaker diaphragms required to generate the infrasound affects the radiation of the audible components. Another is that the infrasound is modulating the evaluator’s hearing sensitivity to periodically reduce sensitivity to some part of the audible signal. This is a corollary to an idea posited by Swinbanks (2012). A further possibility is that this was a coincidence. At all levels, the infrasound presented alone produced “no sensation."

Our sleep subject fell asleep while an audible example (20 Hz high-pass) was being presented. However, she claimed that at this level, the full spectrum and 30 Hz high-pass would prevent sleep. She claimed that the full spectrum 5 dB lower would allow sleep. At this level, the infrasound peak pressure was just under 0.3 Pa (84 dB), which is in the higher range of levels seen in the field. It is possible that this evaluator was more tired at some times than others and she may also have become acclimated to the noise which would lead to a difference between her estimate of its affect on sleep and its actual effect. In a subsequent test, both all-pass and 30 Hz high pass sounds were initially judged as potentially sleep-interfering but in practice, the evaluator fell asleep within minutes of other sounds being removed while the synthesized turbine sound and/or sound plus infrasound continued.

Hence, for evaluation times of 5 minutes, it has been shown that for the persons tested, the presence of infrasound at realistic levels does not influence audibility, annoyance or ability to fall asleep.

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Appendices

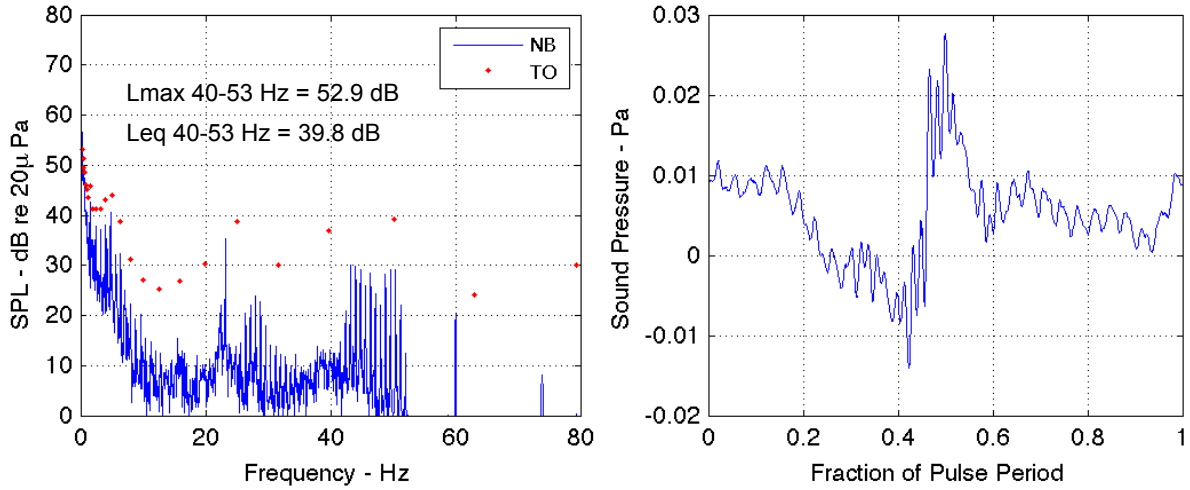

Figure 16 – All-pass, 5 dB below measured outdoor level, (a) spectrum, where NB = narrowband, TO = third-octave, (b) pressure signal over pulse period.

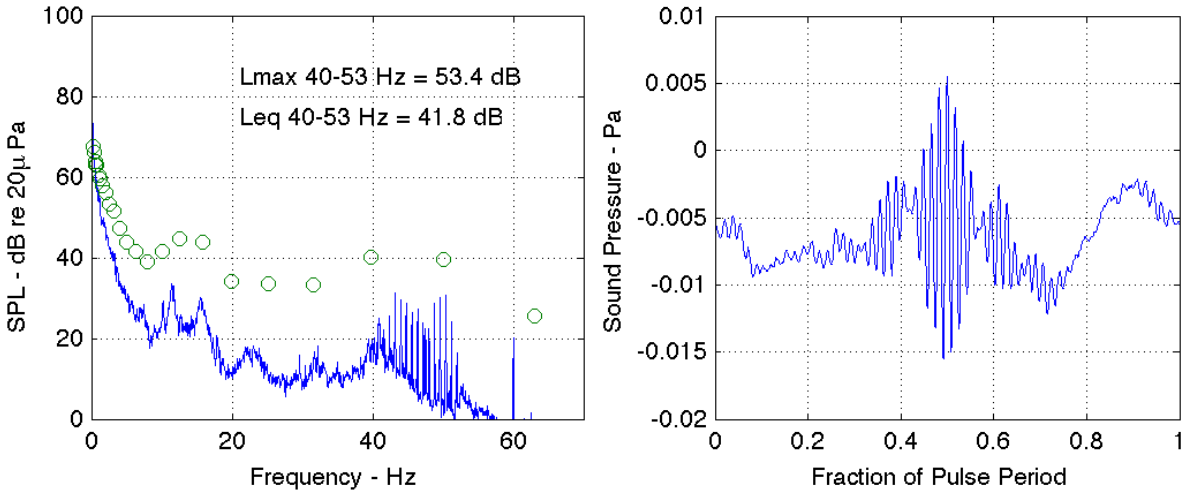

Figure 17 – 30 Hz HP, 5 dB below measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

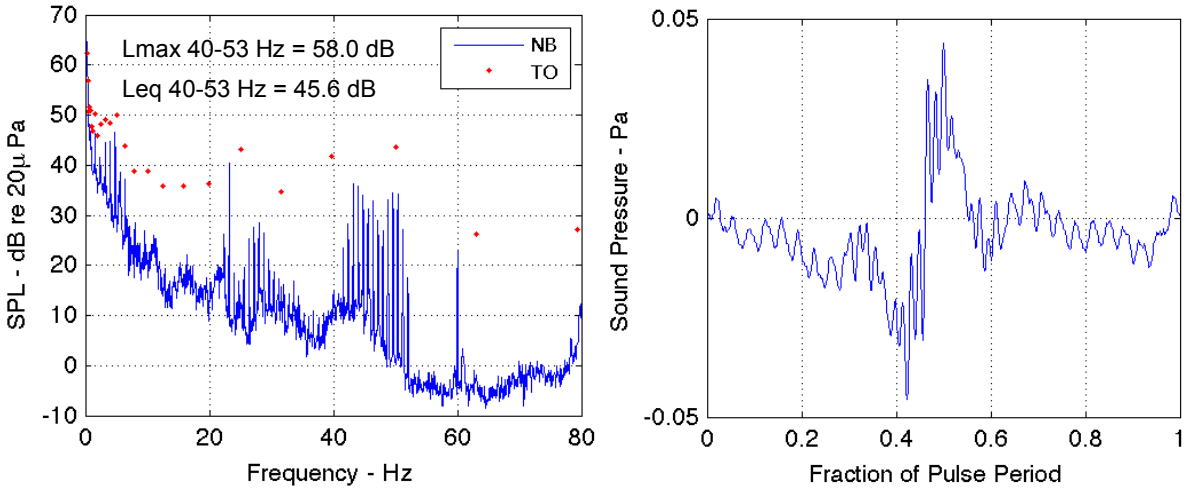

Figure 18 – All-pass, approximately the same as measured outdoor level, (a) spectrum, where NB = narrowband, TO = third-octave, (b) pressure signal over pulse period.

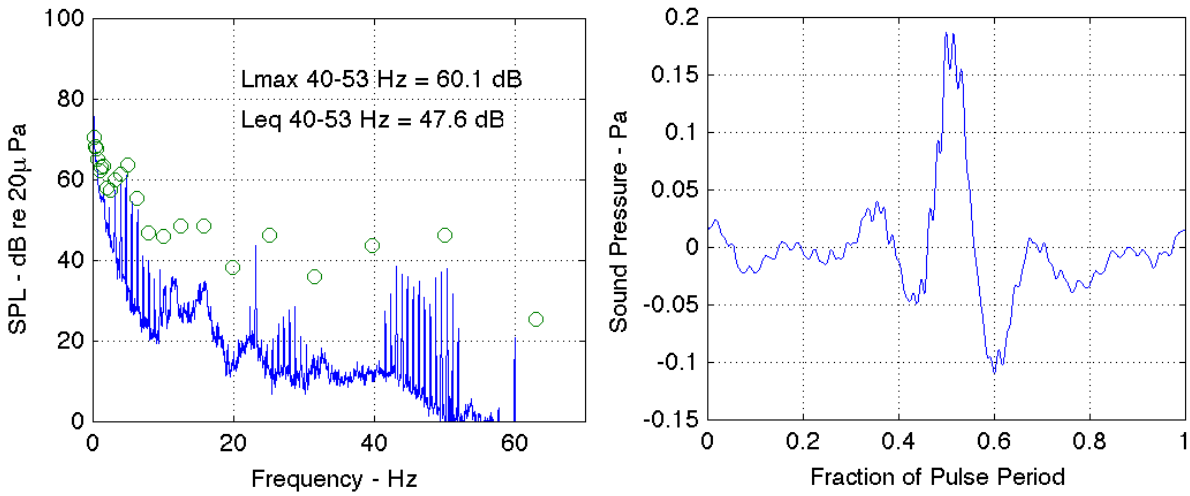

Figure 19 – All pass, approximately the same as measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

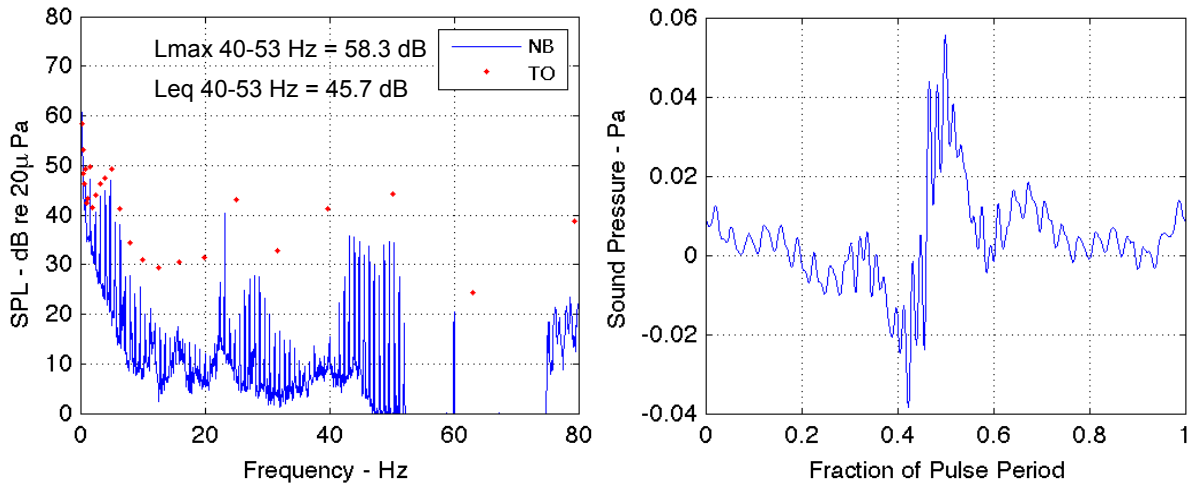

Figure 20 – All-pass, approximately the same as measured outdoor level, (a) spectrum, where NB = narrowband, TO = third-octave, (b) pressure signal over pulse period.

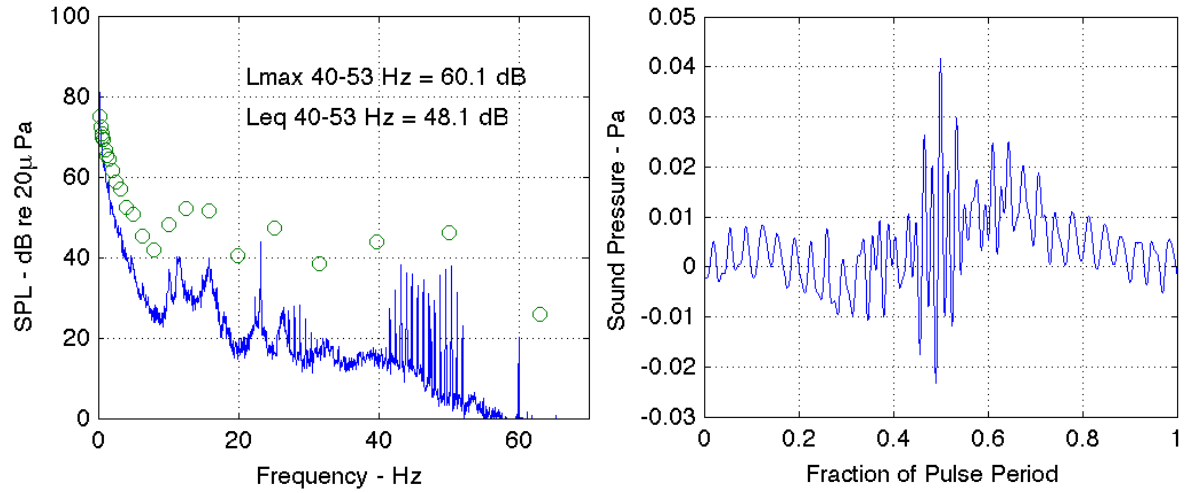

Figure 21 – 20 Hz HP, approximately the same as measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

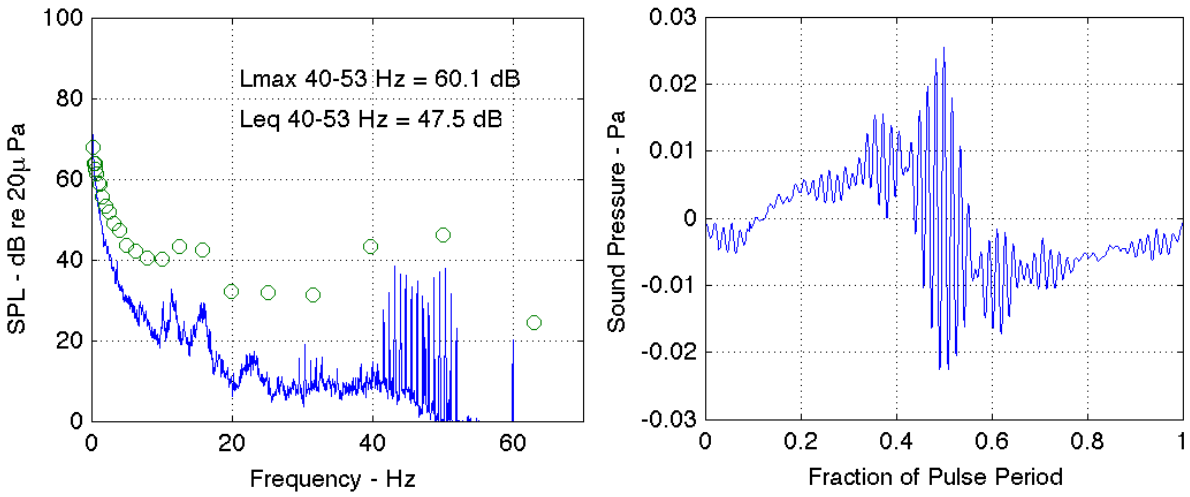

Figure 22 – 30 Hz HP, approximately the same as measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

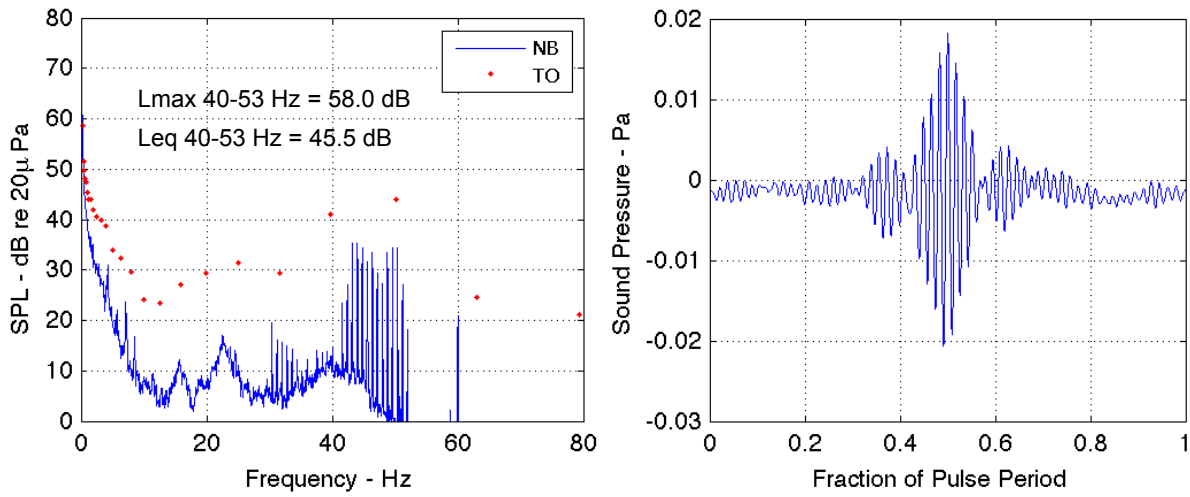

Figure 23 – 30 Hz HP, approximately the same as measured outdoor level, (a) spectrum, where NB = narrowband, TO = third-octave, (b) pressure signal over pulse period.

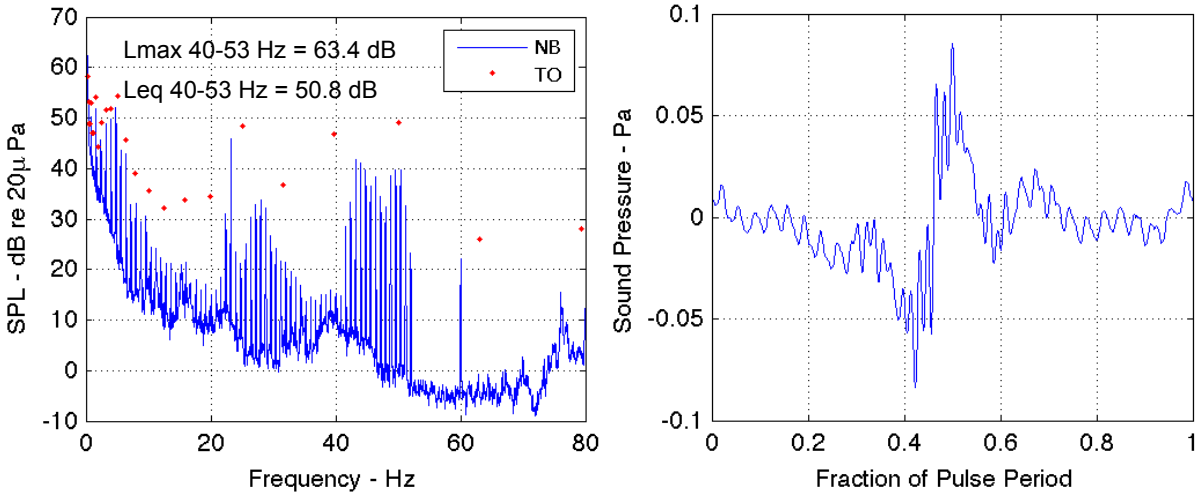

Figure 24 – All-pass, 5 dB above measured outdoor level, (a) spectrum, where NB = narrowband, TO = third-octave, (b) pressure signal over pulse period.

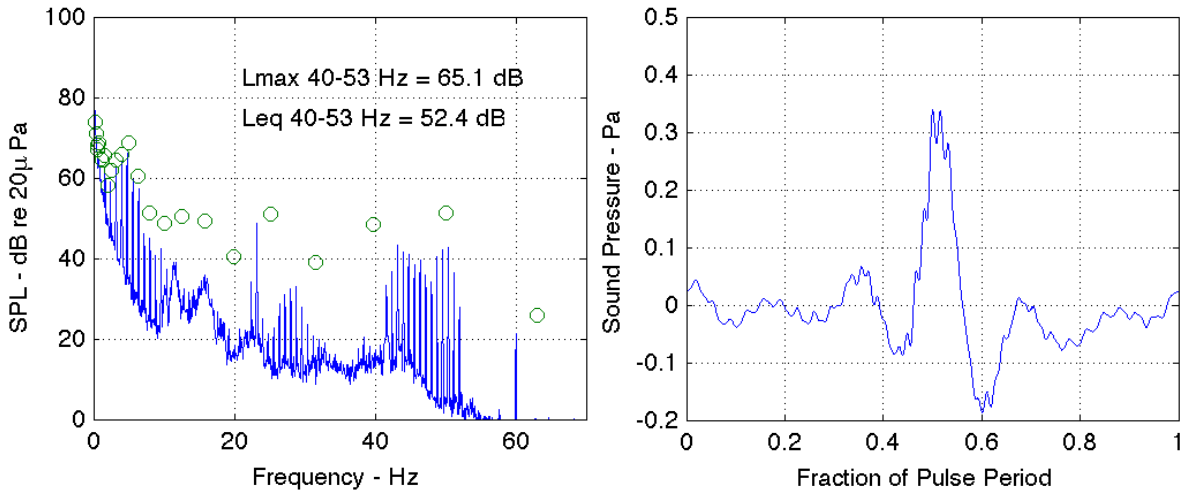

Figure 25 – All pass, 5 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

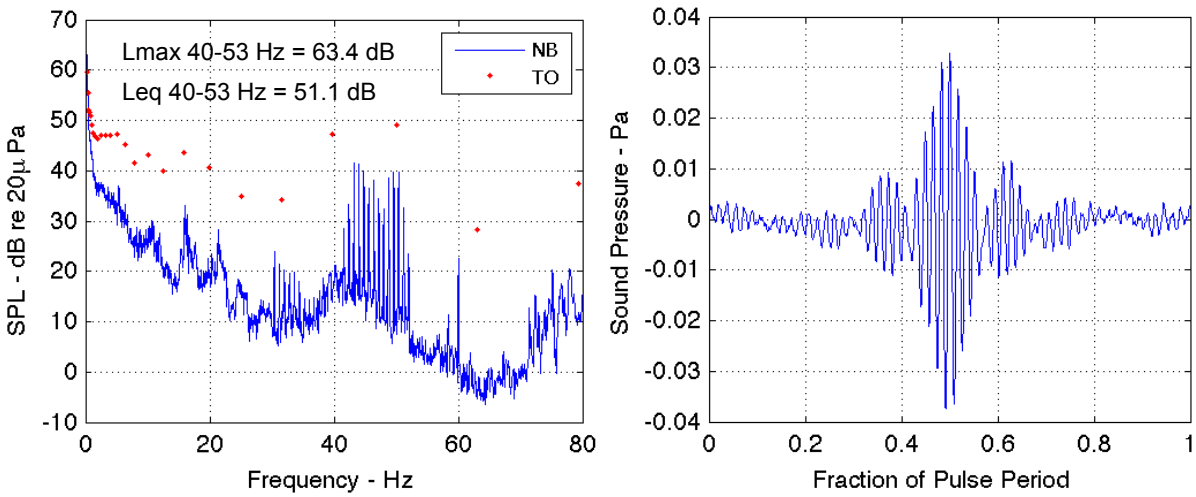

Figure 26 – 30 Hz HP, 5 dB above measured outdoor level, (a) spectrum, where NB = narrowband, TO = third-octave, (b) pressure signal over pulse period.

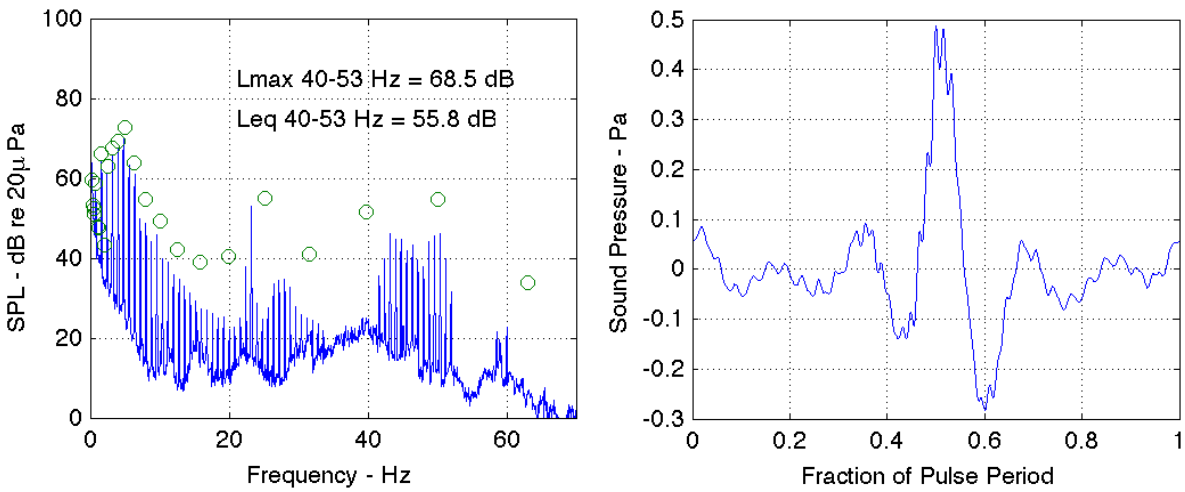

Figure 27 – All pass, 9 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

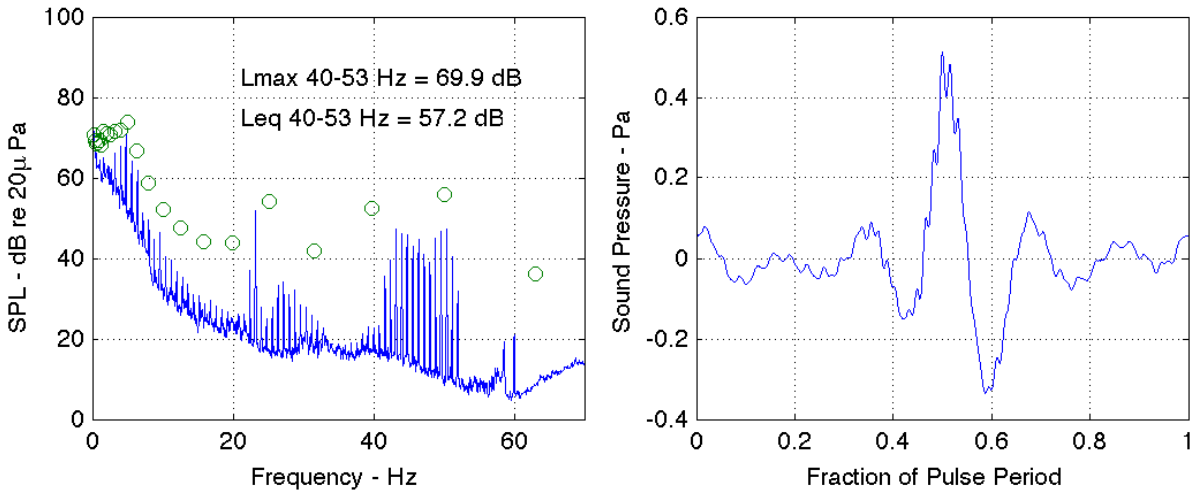

Figure 28. All pass, 9 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

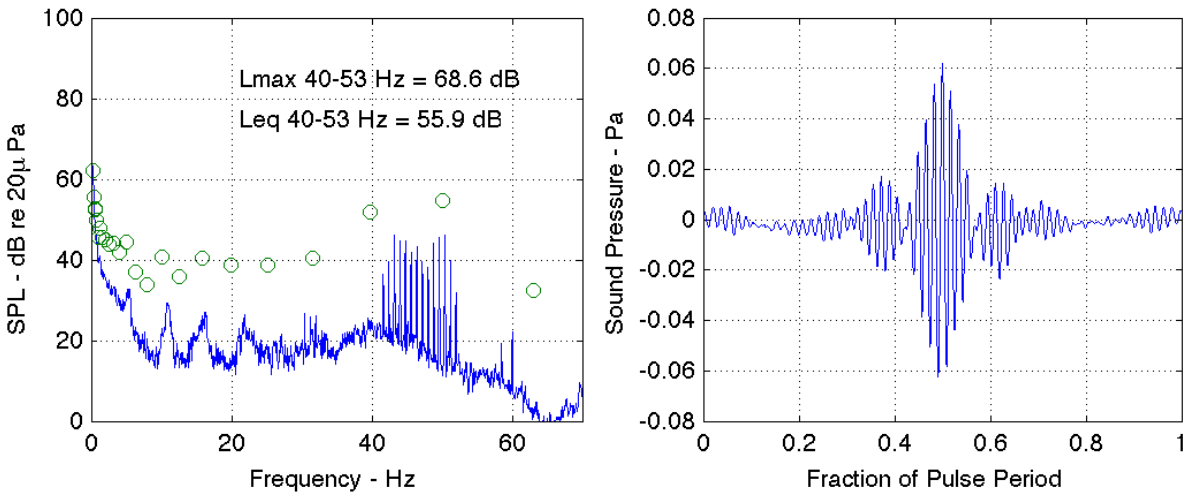

Figure 29 – 30 Hz HP, 9 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

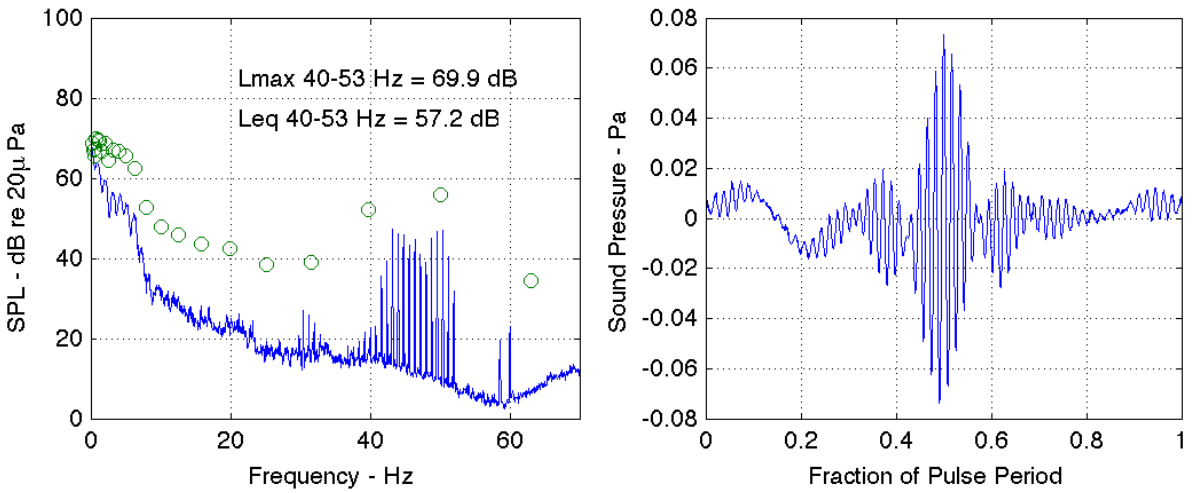

Figure 30. 30 Hz HP, 9 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

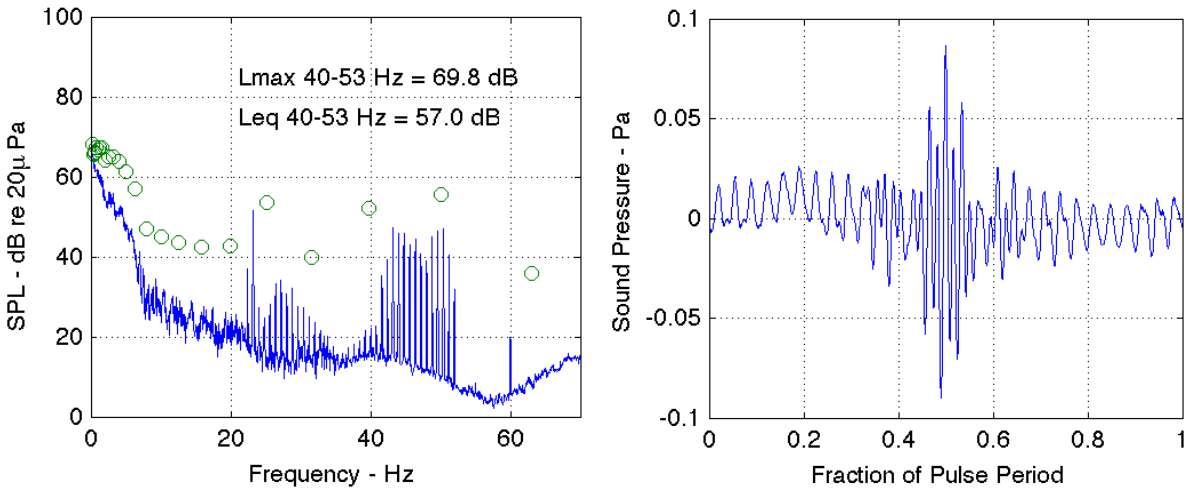

Figure 31 – 20 Hz HP, 9 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

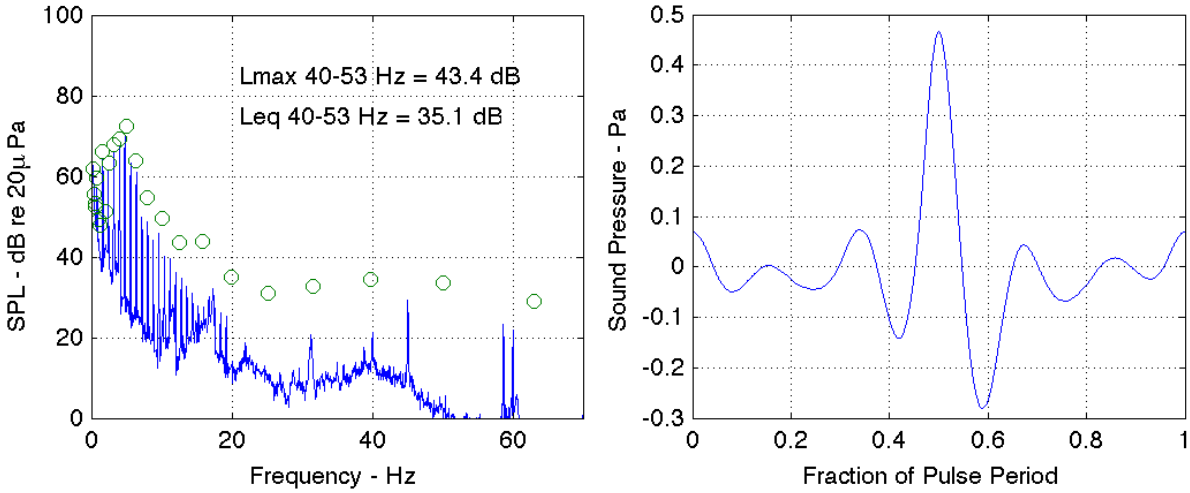

Figure 32 – 20 Hz LP, 9 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

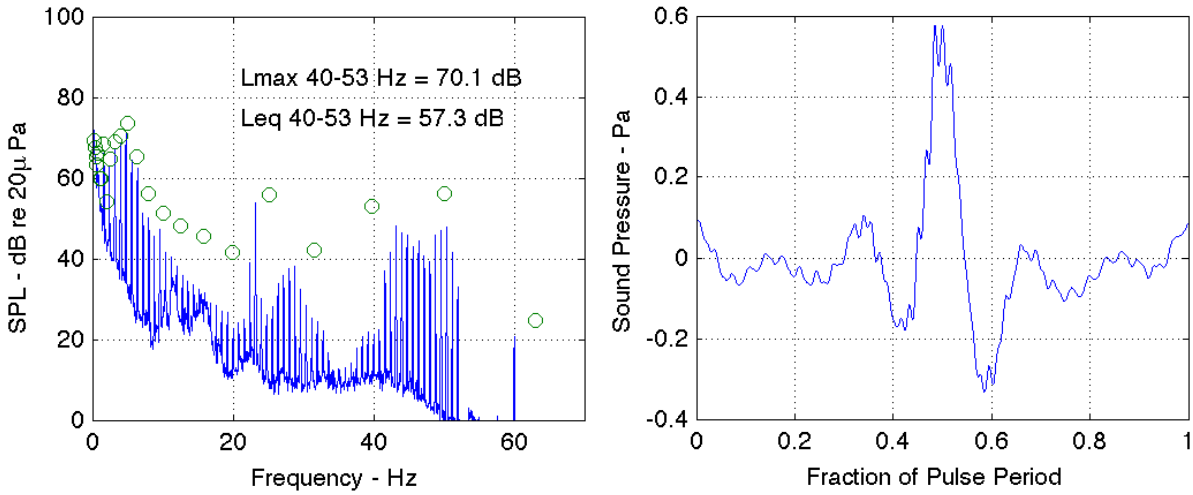

Figure 33 – All pass, 10 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

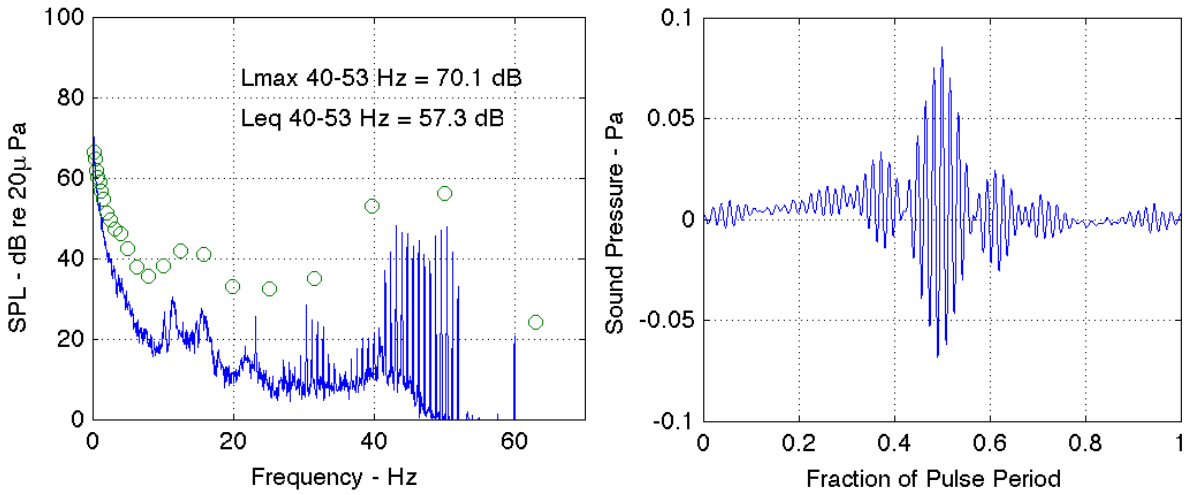

Figure 34 – 30 Hz HP, 10 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

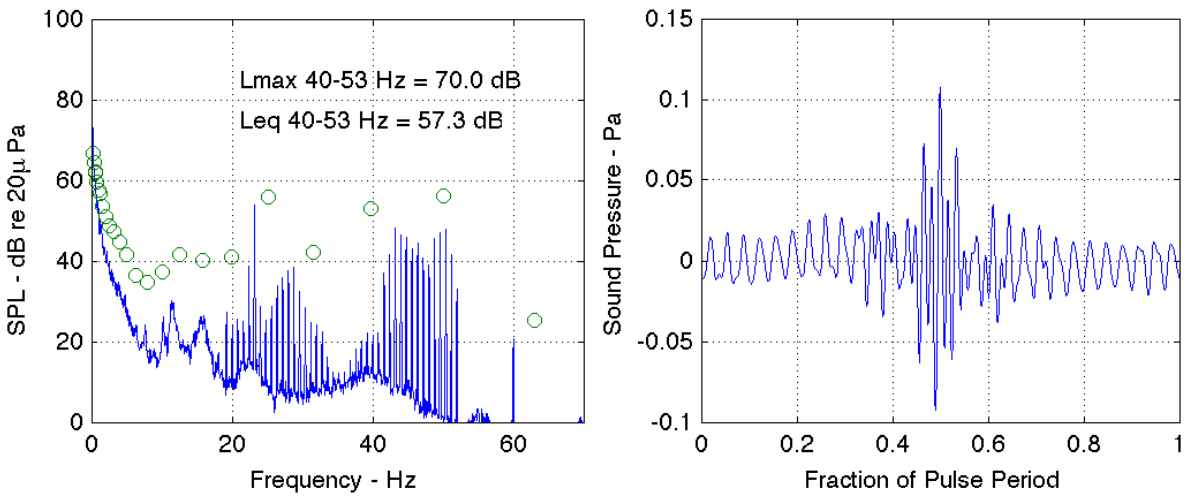

Figure 35 – 20 Hz HP, 10 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

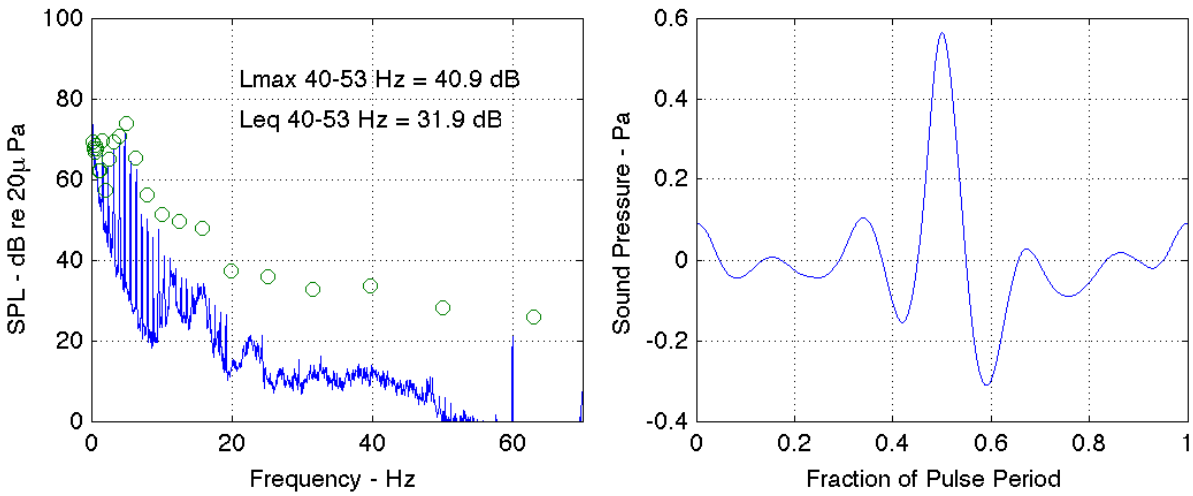

Figure 36 – 20 Hz LP, 10 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

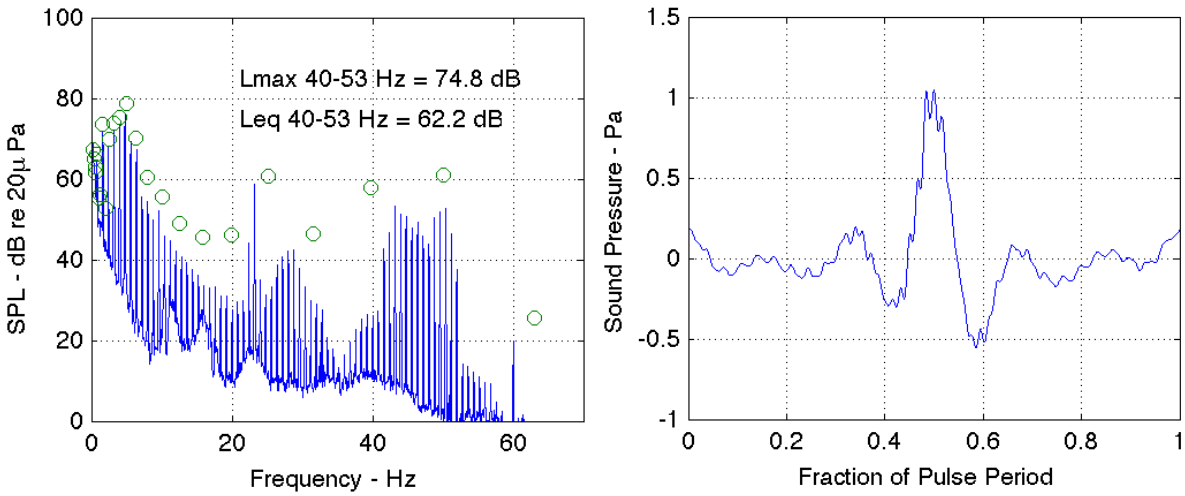

Figure 37 – All pass, 15 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

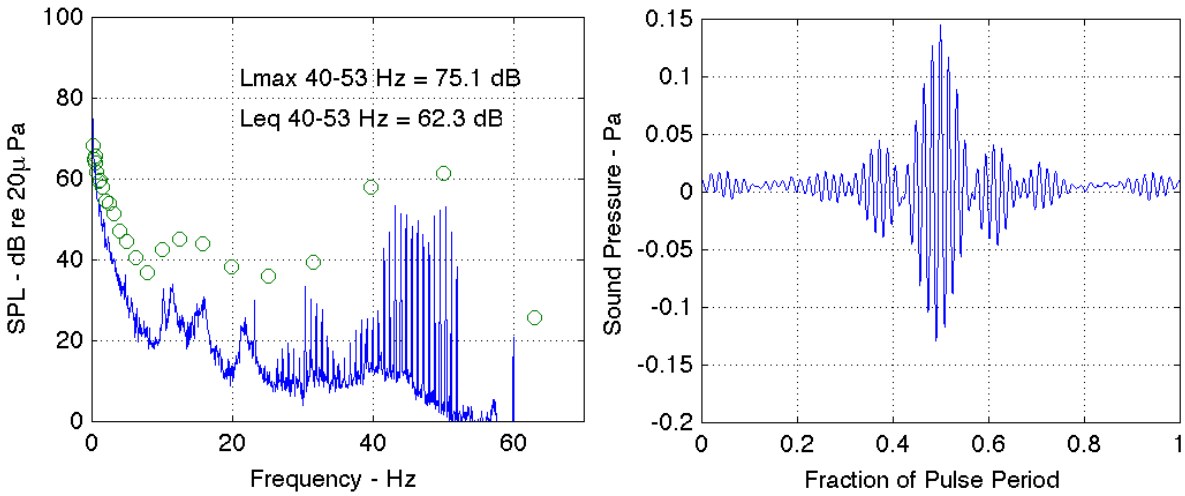

Figure 38 – 30 Hz HP, 15 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

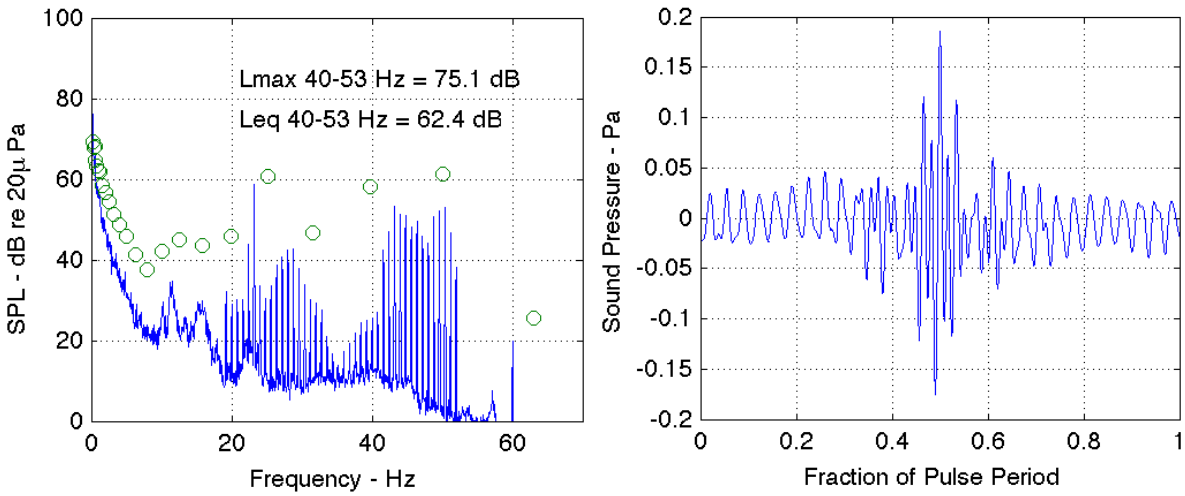

Figure 39 – 20 Hz HP, 15 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

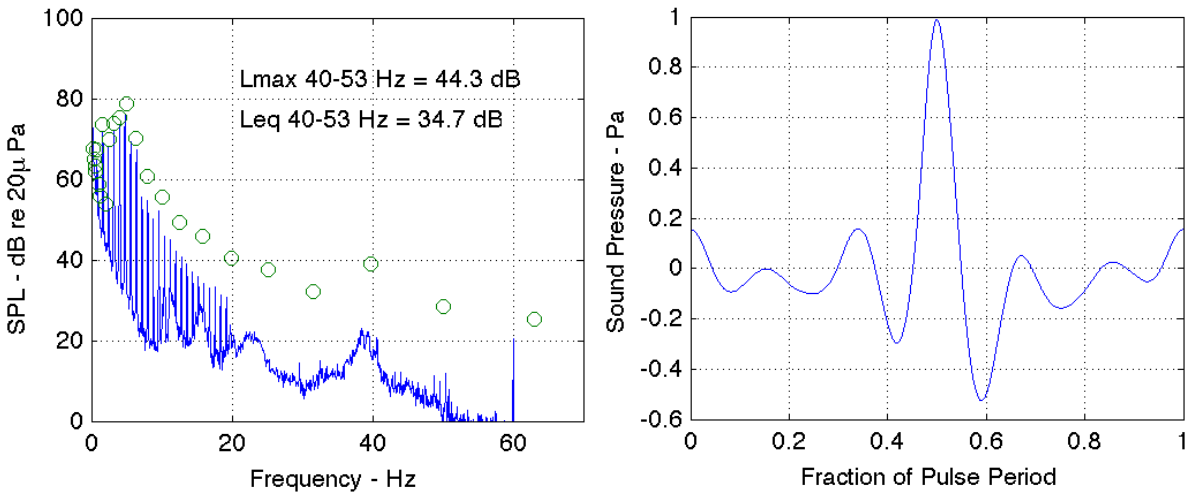

Figure 40 – 20 Hz LP, 15 dB above measured outdoor level, (a) spectrum, (b) pressure signal over pulse period.

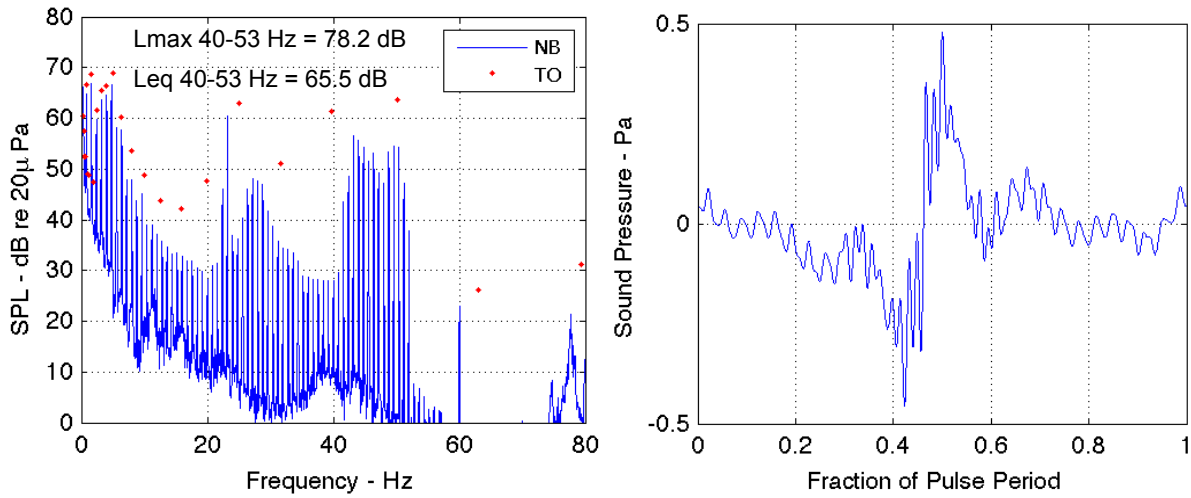

Figure 41 – All-pass, 20 dB above measured outdoor level, (a) spectrum, where NB = narrowband, TO = third-octave, (b) pressure signal over pulse period.