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Indoor Simulation of Wind Turbine Amplitude Modulated Noise

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Summary

Wind energy is the world's fastest-growing renewable energy source and, thus, the number of people exposed to wind farm noise pollution is increasing. Due to its broadband amplitude modulated characteristic, wind turbine noise (WTN) is more annoying than others common community/industrial sources. As higher frequencies are attenuated by air absorption and building transmission, the noise from modern large wind farms is mainly below 1000 and 500 Hz for outdoor and indoor conditions, respectively. Many WTN complains are for indoors and during night time when background levels are lower. As recently reported, indoor noise has the potential to cause sleeping disorders. Human annoyance response studies to amplitude modulated WTN have been mainly focused on the outdoor case were an abundance of measured data exits. This is not the case for indoor where it is much harder to gather data. Thus, there is a need to understand the transmission of WTN into dwellings and develop indoor annoyance metrics. In this work, the transmission of WTN into residential type structures is investigated. Using a wind turbine outdoors noise recording and structures with different properties/configuration, a series of computer simulations for indoor noise predictions were made. These indoor results were assessed using several metrics conventionally used for WTN, e.g. spectral content, modulation depth, and overall levels. In general, the indoor noise levels are higher and the average modulation depth is similar as compared to outdoors recording. In addition, there is a significant change in the spectral shape. These results could potentially explain WTN indoor annoyance.

1. Introduction

Power production by renewable wind energy has risen sharply in recent years. During the last 20 years, wind energy has developed very successfully all over the world. This energy source has the highest growth rate of all renewable sources at >20% increase of installations annually. Most of the onshore wind turbines are subjected to noise constraints and ever more stringent regulations. Additionally, wind turbines are continuously increasing in size to achieve higher outputs per unit for profitability and efficiency. Thus, these larger turbines are louder and potentially more annoying to the people living nearby.

The blade broadband aerodynamic noise is the dominant noise source in modern large wind turbines. Moreover, it is also responsible for the amplitude modulation (AM) observed in mainly large turbines, i.e. pulsating broadband sound (Stigwood et al. 2013). This AM, commonly referred as "swishing", "whooshing" or "pulsating noise", is currently considered as the main cause of annoyance for residents nearby wind farms (Van den Berg, 2005; Bolin et al., 2011). Recently, infrasound from wind turbines has also received significant attention (Leventhall

2006; Bolin et al. 2011). However, the generation of this noise component is not well understood and very limited number of conclusive measurements is available.

Turbines aren't typically as loud as other sources of industrial or transportation noise at a similar distance. The AM quality is what makes wind turbine noise (WTN) more annoying than other types at the same sound level. Very quiet rural communities without the masking of nighttime traffic noise are particularly affected. Amplitude modulated (AM) noise is perceived as more annoying than a constant amplitude sound containing the same spectrum and average noise level (Fastl and Zwiker, 2007; Lee et al., 2011). Thus, WTN is commonly more aggravating than other industrial and community noise source (Lee et al., 2011; Janssen et al., 2009; Pedersen et al., 2009). For example, it was found that 10-20% of residents are annoyed outdoors (6% very annoyed) by AM WTN at A-weighing equivalent immission levels between 35 and 40 dB_A (Bolin et al. 2011). This is about twice the annoyance rate for industrial noise at the same levels (Janssen et al., 2009).

Broadband AM noise is typically defined by the modulation depth (ΔL), difference between the peak and trough sound pressure levels (SPL), and the modulation frequency (f_{mod}). For WTN, modulation depths of up to 10 dB have been observed and the modulation frequency is in the 0.5 to 1.5 Hz range, e.g. turbine blade passing frequency. The swishing AM sound of wind turbines is stronger in the mid-frequency range (400 to 1000 Hz) and in the downwind directions (Di Napoli, 2011; Bowdler and Leventhall, 2011). Though the SPLs decrease with distance, the modulation depth doesn't until background noise levels began to reach the WTN levels. This effect has been demonstrated in several noise measurement studies (Di Napoli, 2011; Bowdler and Leventhall, 2011; Van den Berg, 2006). When AM is present at lower frequencies (20-300 Hz), it is often described as a thumping noise.

In psychoacoustics, sounds with modulation frequencies below 20 Hz provoke hearing sensation of fluctuating sound strength. Moreover, modulation frequency of about 4 Hz matches the normal speaking rate of 4 syllables/second (Fastl and Zwiker, 2007). The perception of amplitude modulated sound can be quantified using the fluctuation strength metric, developed to measure the human perception of amplitude modulation in sounds (Fastl and Zwiker, 2007).

Several metrics has been suggested for assessing WTN annoyance (Bowdler and Leventhall, 2011). In one of the first reported studies, indoors annoyance from low frequency (< 300 Hz) WTN was determined using 6 weighted overall noise levels, including the conventional A-weighting (Kelley, 1987). In this study, it was confirmed that people indeed perceive and are annoyed by low frequency WTN. Based on the results, it was suggested to use LSL or C-weighting and to stablish a 67 and 76 dB_C level criteria for the perception and annoyance thresholds, respectively. It was also concluded that A-weighting is not an adequate indicator of annoyance. There is an international standard that defines limits for infrasound and low frequency levels (ISO 7196, 1995). It stablishes that G-weighted sound pressure levels below 90 dB_G won't be normally significant for human perception or disturbance. Being stricter the Danish guidelines stablish a limit of 85 dB_G using this metric (Jakobsen, 2001). Though fluctuation strength was originally develop to quantify perception, it has recently been investigated for outdoors WTN annoyance in several studies (Di Napoli, 2011; Bowdler and Leventhall, 2011; Van den Berg, 2006; Lenchine, 2009; Legarth, 2007). They found good correlation between fluctuation strength and annoyance. However, these studies cannot be applied for indoor WTN since the contextual and attitudinal aspects are completely different (Hünerbein et al., 2013).

A few European countries such as the Netherlands and Denmark have regulations for WTN. Danish regulation for WTN stablishes an outdoors noise limit of 44 dBA at a wind speed of 8m/s no more than 15 meters from dwellings (Jakobsen and Mogensen, 2013). However, a Swedish and Dutch study found that about 20% of people were very annoyed at WTN levels of

40-45 dBA (Pedersen et al., 2009). This again confirms the inadequacy of the A-weighting for WTN.

Many WTN complains are for indoors and during night time when background levels are lower (Van den Berg, 2006). As recently reported, indoor noise has the potential to cause sleeping disorders (Bolin et al., 2011; Kantarelis and Walker, 1988; Fastl and Zwiker, 2007; Pedersen et al., 2009; Di Napoli, 2011; Bowdler and Leventhall, 2011; Van den Berg, 2006). The problem of WTN indoors is more complicated due to the effect of the structural and room dynamics, particularly at low frequencies where resonant modal response dominates. Typically, the structure provides significant transmission loss at the mid and high frequencies. At lower frequencies (< 400 Hz), however, the system resonances can result in actual increase in indoors noise levels as compared outdoors (Bolin et al., 2011). Though some recent studies have shown that indoors levels from wind farms comply with guidelines, it was concluded there could be low frequency WTN problem in some cases (Bolin et al., 2011). Some people prefer to sleep with the windows open or slightly open, and is recommended by the World Health Organization (WHO) that noise regulations should permit for this condition (Moller and Pedersen, 2011; World Health Organization, 2009). Denmark takes this into account, and stablished for the low-frequency noise regulation that measurements should be made with open windows but only if the complainant asks for it (Moller and Pedersen, 2011).

With the increasing use of wind turbines around the world, the number of people exposed to WTN is also rapidly increasing. The use of a metric that takes AM into account for assessing the potential of community annoyance from WTN is needed and overdue, and each year becomes more urgent to define proper guidelines and standards. As stated in the New South Wales Wind Farm Guidelines (2011), suitable models must be developed to predict the 'worst-case' scenario at all relevant receivers, both outdoors and indoors. These tools are of critical importance for manufactures, regulators, and operators to predict and avoid the detrimental effect of WTN. Human annoyance response studies to amplitude modulated WTN have been mainly focused on the outdoor case were an abundance of measured data exits. This is not the case for indoor situations where it is much harder to gather data. Thus, there is a need to accurate predict and understand the transmission of AM WTN into dwellings and develop indoor annoyance metrics.

In this work, a fluid-structural computational model to predict the indoor acoustic response due to AM WTN is presented. This numerical model was developed to investigate transmission and assess the indoor annoyance of sonic booms from future commercial supersonic aircrafts into typical residential structures (Burdisso, 2013). It is proposed to use this code for the study of indoor annoyance from AM noise from wind turbines and farms. The accuracy of this code for this AM WTN application is presented here. Using a wind turbine outdoor AM noise recording and a realistic structure, a series of computer simulations for indoor noise predictions were made. Since WTN amplitude modulated noise is mainly below 1000 Hz, the simulations were performed for the 0-1000 Hz range. The indoor predictions were then processed to compute various metrics conventionally used for WTN, e.g. spectral content, modulation depth, etc. These predicted metrics were compared to the measured results to assess the accuracy and validity of the computer model.

2. Vibro-acoustic Prediction Model

The simulation tool used for this research was developed for the vibro-acoustic response of structures subjected to aircraft generated sonic booms. The code is referred as **V**ibro-**A**coustic **R**esponse of buildings to **S**onic booms or **VARS** (Burdisso and Corcoran, 2013). The computer program has the capability to solve the exterior-to-interior transmission of sound through three-dimensional, thin-walled, elastic structures over 0 to 6000 Hz frequency range. The model has three main modules. The first module computes the pressure loading on the structure from the incident wave generated by a source using an image source method with edge diffraction

developed by Peter Svensson (Svensson et al., 1999; Svensson and Calamia, 2006). There are several orders of diffraction depending on the number of edges a ray encounters when propagating from the source to the receiver. The linear structural and interior acoustic responses over the full frequency range are computed using two modelling methods for low and high frequencies, respectively. These predictions are then mixed together using digital filters.

For low frequencies, the fully coupled vibro-acoustic response of the interior fluid-structure system is computed in the time domain using a truncated modal-displacement expansion approach. The coupled dynamic equations of the problem include an equation for the whole structural motion with source terms corresponding to the interior and exterior pressures and wave equations (one equation per room) with source terms corresponding to the structural motion. The structural displacement is decomposed onto the in vacuo normal modes of the structure and the pressures inside the rooms are decomposed onto the normal acoustic modes of the cavities with perfectly reflecting surfaces (acoustically rigid boundaries). The structural modes are computed with the finite-element (FE) method using thin-shell theory where the shell elements are derived from the degenerated solid approach. A four node quadrilateral shell element was specifically derived to model the structural components of typical residential buildings, e.g. plaster-wood walls, windows, and doors. Acoustic modes are computed analytically assuming rectangular geometries of the rooms. Using the structural and acoustic modes, the modal vibro-acoustic responses are solved by numerical integration and then transformed to the physical domain (Burdisso, 2013).

At high frequencies, the vibro-acoustic responses are solved in successive steps. Each loaded exterior surface of the structure is taken in isolation from the other surfaces and assumed to be infinite in dimension. These assumptions are typically valid at high frequency because wavelengths of the incident acoustic waves are short in comparison to the dimensions of the structure and the structure will not exhibit individual low global modal behavior due to the high-modal density. In other words, the responses of individual modes of vibration are not seen due to the significant modal overlap. Analytical expressions are used to predict the interior velocity response of various types of partitions due to incident plane waves. To this end, the exterior pressure loading on a partition can be decomposed into a number of incident plane waves at high frequency. Each of these plane waves can then be transmitted through the partitions using the analytical expressions implemented. The structurally transmitted sound is modelled as a distribution of equivalent monopole sources. To accomplish this, the exterior loaded surfaces transmitting sound into the interior rooms of interest is divided into a number of elements. Then, the volume velocity response for each incident wave over each element is computed. Adding the effect for each incident wave, total volume velocities are computed. Monopole sources inside the room are then defined to have the same volume velocities. The commercial pyramid tracing software package, ***Ramsete***, is used to predict the interior acoustic response (Farina, 1995).

For validation purposes, the code predictions were compared to real measurements for four test structures subjected to simulated and actual booms (Burdisso, 2013). The accuracy of the predictions is shown here from results obtained in the NASA Interior Effect Room (IER) shown in (Klos, 2012). This structure is an indoor listening environment to enable systematic study of parameters that affect psychoacoustic response to sonic booms. The single-room facility, built using typical residential construction methods and materials, is surrounded on adjacent sides by two arrays of loudspeakers in close proximity to the exterior walls. The arrays, containing 52 subwoofers and 52 mid‐range speakers, have a usable bandwidth of 3 Hz to 5 kHz and sufficient output to allow study of sonic boom noise. The vibration of the building components also induces non-linear vibro-acoustic responses due to rattle (intermittent loss of contact between two structural components), friction (relative motion of two components with rough

surfaces), and so forth. Unique to the IER facility is the capability to isolate the linear vibro-acoustic responses.

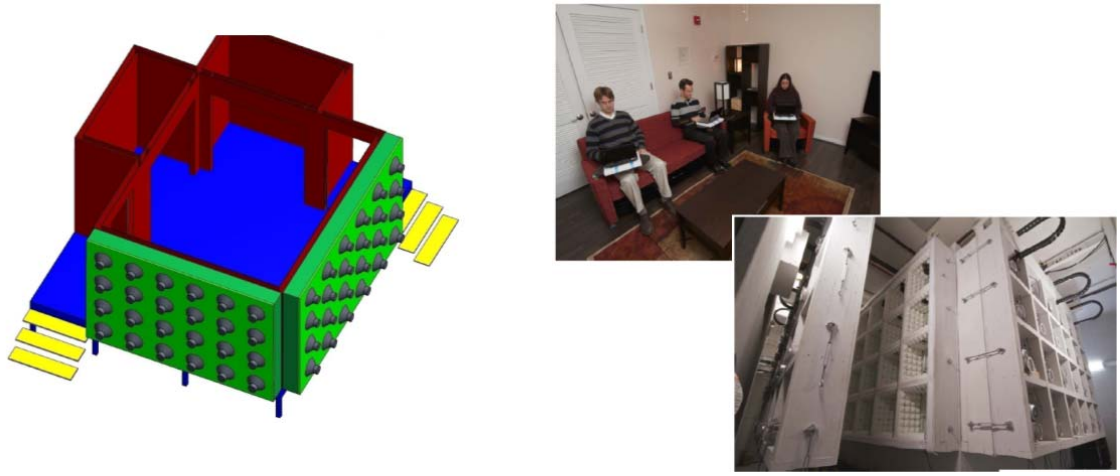

Figure 1: Schematic of NASA Interior Effect Room IER and pictures of facility.

Illustrative time domain and 1/3rd octave band spectrum validation results are shown in Figure 2 for an accelerometer mounted on the window and a microphone near the room centre, respectively. The time domain predictions, which are dominated by the low frequency components, show very good agreement. The 1/3rd octave band spectra show good accuracy in the predictions, in particular at low frequency (< 500 Hz). At higher frequencies (> 500 Hz), the errors are more important, in general increasing with frequency. Note that at higher frequencies, the excitation boom didn't have significant content potentially contributing to the poorer agreement (Burdisso, 2013). For these tests, the loudness level for five microphones using the measured and predicted data was determined. The agreement for this metric is very good with an average absolute and maximum error of 0.7 and 1.4 dB, respectively.

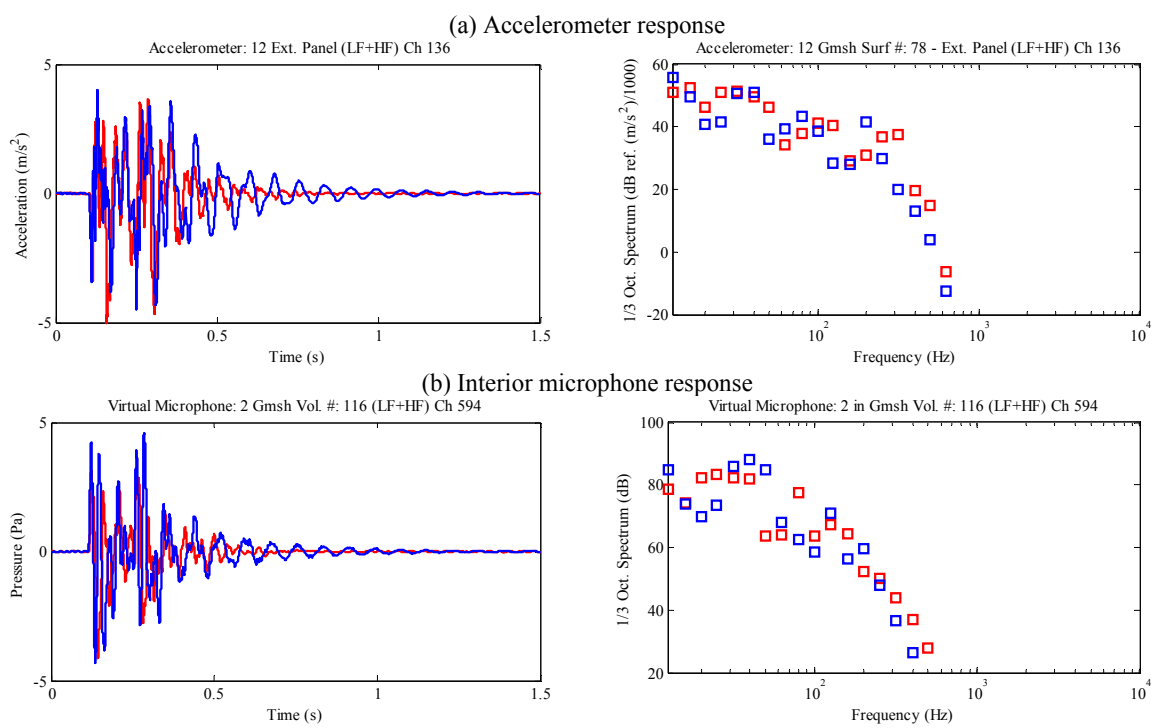

Figure 2: Illustrative comparison of predicted and measured vibro-acoustic responses for a sonic boom excitation: Acceleration of widow and (b) Interior pressure near centre of room (—— measured and —— predicted).

The results here show that the vibro-acoustic model **VARS** is a reasonable accurate tool to predict indoor noise due to sonic booms. However, this type of impulsive loading is significantly different than the broadband amplitude modulated characteristic of WTN. Thus, the accuracy of this tool for AM WTN must still be determined and it will be discussed in the next section.

3.0 Simulation and Validation

In this section, the VARS code is used to simulate indoor responses to AM WTN in a realistic structure. The simulations are validated using experimentally measured impulse response functions that are in turn used to predict the interior responses due to the AM WTN. The AM WTN input signal, the test structure, and the result of the validation are described next.

3.1 Input Signal The AM WTN signal used in the simulations is the data collected by Bowdler (www.dickbowdler.co.uk) at about 50 meters downwind from a modern turbine. The noise signal contains clear AM thumping noise on the second half of the recording. The duration of this signal in the simulations was 10 seconds, corresponding to this second half of the original recording. For the sake of consistency, the AM WTN input signal was adjusted to have an equivalent A-weigthed SPL of 45 dB_A. This level was selected since it has the highest proportion of annoyance as shown in the Swedish and Dutch study (Pedersen et al., 2009). Since the structural analysis is linear, any gain applied to the input signal applies equally to the interior acoustic responses. Since the AM is most dominant at low frequencies and the structure provides significant transmission loss at higher frequencies, the simulations were limited to the low frequencies, e.g. below 1k Hz.

Since modulation frequency and depth have been used to describe AM WTN (Bowdler and Leventhall, 2011), they are computed here for both the input and indoor responses. The modulation frequency and depth were calculated using the approaches described by Lundmark (2011) and Cooper and Evans (2013). The overall A-weigthed and C-weigthed sound pressure levels, L_{Aeq} and L_{Ceq}, were obtained for 125 ms time windows, selected so as to be comparable to the integration time of the human ear. To compute the equivalent levels, a Hanning filter was applied to the 125 ms time windows, the narrowband spectrum computed using Fast Fourier Transform (FFT) with no overlap applied, and the spectral energy added. The magnitude of spectrum of $L_{Aeq}(t)$ and $L_{Ceq}(t)$ is then obtained taking a single FFT of the entire signal. This spectrum is referred as the amplitude modulation spectrum (AMS). From this spectrum, the frequency of the dominant peak indicate the modulation frequency, f_{mod}, and the peak level is the modulation depth, ΔL , average over the whole signal duration. This approach works well when there is a single dominant peak in the spectrum of $L_{Aeq}(t)$. Another approach to find the modulation depth was determined by identifying the local maximums and minimums in $L_{Aeq}(t)$ or $L_{Ceq}(t)$ and computing the difference between the mean maximum and minimum levels (Cooper and Evans, 2013). Both approaches to compute modulation depth yielded very similar results for the outdoor input signal. To gain insight into the frequencies showing amplitude modulation, the average narrowband and 1/3rd octave band spectrums corresponding to the maximum and minimum were also computed.

The signal processing described was applied to the input signal and results are shown in Figure 3. The input time signal is shown in Figure 3a where the amplitude modulation is obvious. The A-weigthed equivalent 125 ms time signal, $L_{Aeq}(t)$, is plotted in Figure 3b with local maximums (red) and minimums (green) indicated with symbols. The figure shows an average and maximum modulation depth of 9.1 and 12.5 dB, respectively. The modulation frequency was estimated to be ~0.8 Hz. Figure 3c shows C-weighted average 1/3rd octave band spectra for the maximums, minimums, and all 125ms time windows. These results provide a clear insight into the frequency components contributing to the AM. For the WTN input, strong AM are observed in the range of 63 to 500 Hz 1/3rd octave band with a maximum modulation depth of 14.3 dB in the 160 Hz band.

An important consideration in the estimation of the modulation depth in Figure 3b is that the signals were A-weighted significantly reducing the impact of the low frequencies. However, in WTN the majority of the modulated sound occurs at low frequencies as shown in Figure 3c. This fact in conjunction with the unsuitability of the A-weighting to assess annoyance (Kelley, 1987) potentially indicates that modulation depth as computed is not an appropriate metric, in particular for indoor responses where mid and high frequencies are significantly reduced. Here, the modulation depth is also computed by applying the C-weighting. The C-weighted 125 ms equivalent time signal, $L_{Ceq}(t)$ is plotted in Figure 3d. The average and maximum modulation depth using C-weigthed levels is 7.5 and 14.1 dB, respectively. The average noise level is 61.6 dB_C.

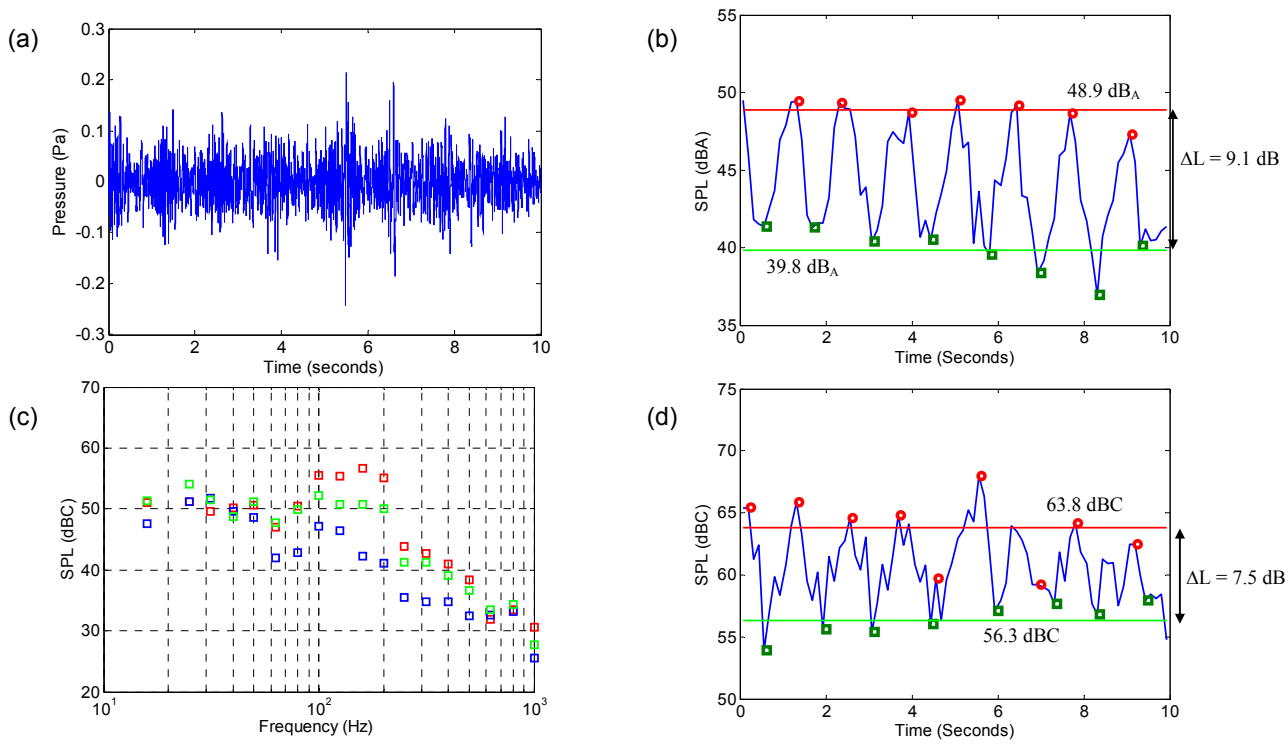

Figure 3: Amplitude modulated WTN input signal used in simulations (Bowdler, www.dickbowdler.co.uk). *(a) Time history, (b) A-weighted equivalent 125 ms time signal, (c) C-weighted 1/3rd octave band spectra for WTN signal of maximums, minimums, and all 125 ms windows and (c) C-weighted equivalent 125 ms time signal* $L_{Ceq}(t)$.

3.2 Structure The structure used for the simulations was a wood frame construction typically used in dwellings in the United States (Burdisso, 2013). The structure consists of a single room made of plaster-wood wall with two double-pane windows and a door. This room was constructed, instrumented and tested at Virginia Tech. The room dimensions are 2.7 x 4.8 x 2.7 [m]. This structure is shown in Figure 4a and it is referred as the VT single room structure. Figure 5a shows the finite element mesh of the structure used for the calculation of the modal properties. The structure was discretized into 3048 quad shell elements with 3024 nodes. The relative rotation between partitions was relaxed by reducing the bending stiffness of the edge quad elements. For the low frequency predictions, 1300 structural modes were computed, which covers a frequency range of 0 to 738 Hz. The fundamental frequency of the structure is 12.3 Hz. The modal damping ratios are assumed the same for all modes at 5%. The sound field in the room and window cavities is modeled with 1686 and 20 modes, respectively. The acoustic modal damping ratios are set to 0.4 and 0.1% for the room and window cavities, respectively. Thus, a total of 3006 coupled modal differential equations were numerically integrated. For the high frequency predictions, the mesh used to define the number and location of the virtual monopole sources used to model the transmission of the exterior pressure into the volume is shown in Figure 5b. A total of 594 monopoles were used to model

the interior sound field. The high and low frequency predictions were combined using high-pass and low-pass filters with cut-off frequency at 500 Hz.

As shown in Figure 4b, the structure was experimentally excited by a simulated sonic boom generated at 91 m from the structure using explosives. The sound wave arrived nearly normal to the front wall of the structure. In an effort to fully understand the vibro-acoustic characteristics of the structure, the interior and exterior of the structures were extensively instrumented with 102 microphones and 127 accelerometers. In addition, the excitation's propagation path was instrumented with 20 high quality B&K microphones (Haac et al., 2009). The signals from all sensors were recorded simultaneously with a sampling frequency of 50 kHz.

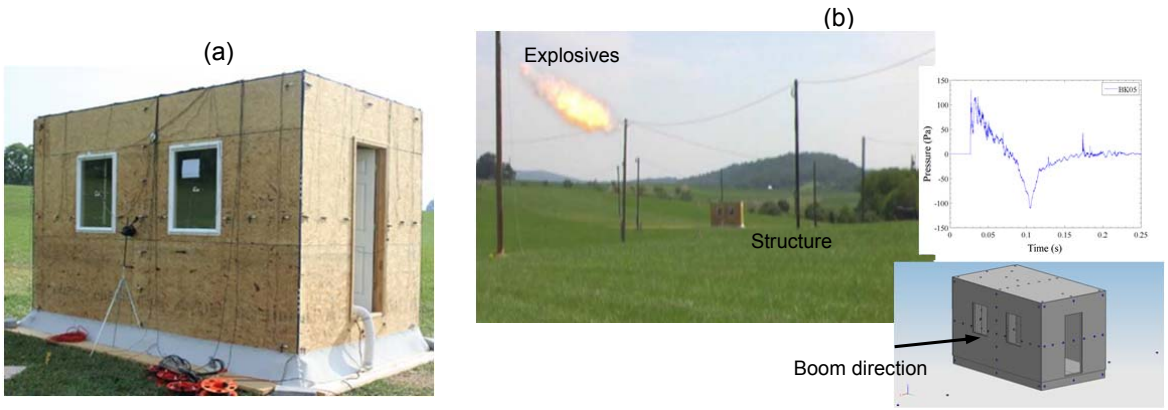

Figure 4: *(a) Structure used for interior acoustic response to the AM WTN signals and (b) the explosive technique used to simulate the sonic boom input.*

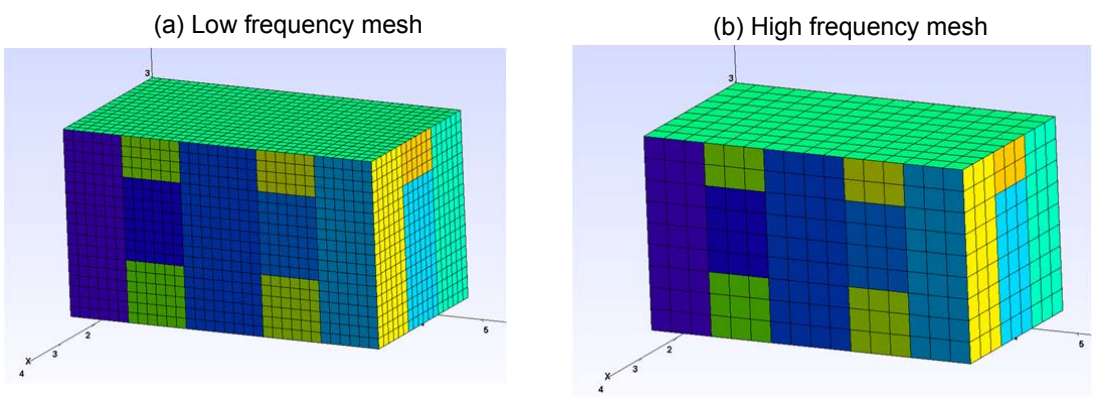

Figure 5: (a) Finite element mesh for the low frequency predictions and (b) mesh to define monopole sources for interior noise predictions at high frequency.

Both structural and interior pressure monaural and binaural time responses were obtained as outputs. For this work, only the monaural responses were used for analysis. The binaural responses can be used in the future for human response studies. The indoor acoustic response and the outdoor recording were analyzed for the metrics and methods typically used for amplitude modulated WTN.

2.3 Model Validation As mentioned before, the VARS simulation code was validated using sonic boom inputs. To assess the accuracy of the code for AM WTN, experimentally measured indoor response of the structure is needed but unfortunately it doesn't exist. To obtain "experimental" data for the AM thumping noise input, experimentally determined impulse response functions between an outdoor microphone and the interior microphones were used.

Briefly, in these transfer functions the outdoor signal is assumed to be the pressure produced by the WTN in the absence of the structure (but accounting for ground reflection) at the sensor located where the structure is. Thus, the exterior microphone used to compute the transfer functions was located on the ground at a distance of 30 meters from the structure so reflection effects from it are not significant. The response where the structure was located (but ignoring its effect) was estimated by correcting the microphone signal for ground reflection and spherical spreading. Then, the measured exterior (corrected) and interior microphone signals due to the simulated sonic booms were Fourier Transformed and the transfer functions computed (interior/exterior FFTs). Taking the inverse Fourier Transform of the transfer functions rendered the experimentally determined impulse response functions which were then convolved with the AM thumping noise input signal described in section 2.1. These signals are referred in the rest of the manuscript as measured responses and considered the experimental data used to validate the **VARS** predictions for the same AM WTN input.

The validation results are presented in detail in Figures 6 through 10. Figure 6 shows the time history of the interior microphone pressure over a second duration to easily compare the measured and predicted responses. From simply visual inspection, it is clear that the two signals are very similar. To gain more insight, the predicted and measured average narrowband spectrums are compared in Figures 7a and b. In these plots, the spectrum for the exterior microphone is also shown as reference. It is clear that the interior response is dominated by a number of structural and acoustic cavity resonances. To illustrate this fact, an experimental modal testing revealed that the resonance at 22.3 Hz is associated to the first mode of the wall with windows. The resonance at 37.6 Hz corresponds to the first acoustic cavity mode (Figure 7b). It is observed that the interior noise levels are higher than the exterior noise at these system resonances, in particular below 300 Hz. In general, the predictions follow the same trends as the measured data. However, the responses at the resonances are not perfectly matched most likely due to wrong damping values in the model.

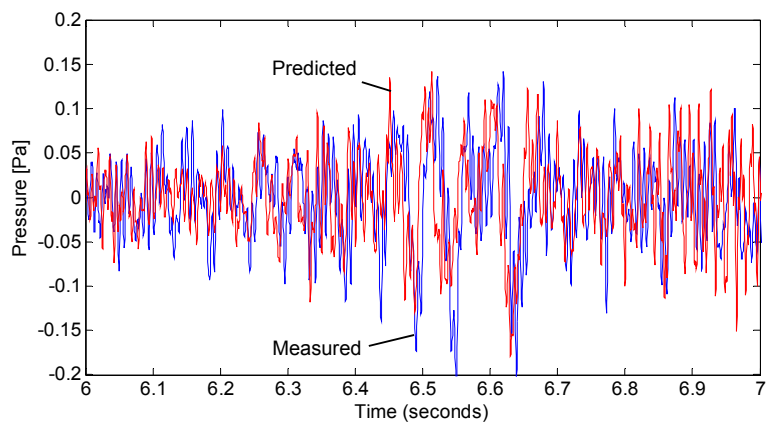

Figure 6: Predicted and measured interior acoustic response for microphone near room center.

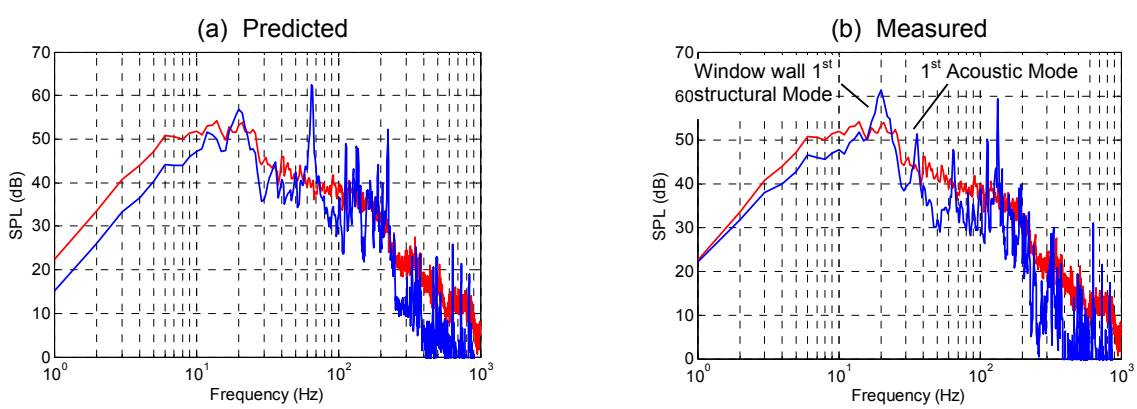

Figure 7: (a) Predicted and (b) measured average narrowband un-weighted spectrum of exterior and interior (near center of room) microphones.

The measured and predicted interior responses were also analyzed in the same manner as the input signal to uncover the amplitude modulation characteristics of the interior response. Figures 8a and b show the predicted and measured C-weigthed equivalent 125ms time history, $L_{Ceq}(t)$. Again as reference, the exterior microphone time C-weigthed equivalent 125ms time history is shown in the same figures. As expected, the interior response also shows the AM characteristics of the exterior response. Since the input modulation frequency (0.8 Hz) is much lower than the fundamental frequency of the structure (12.5 Hz), the same modulation frequency is found in the interior response. The predictions capture very well the higher interior levels over the full 10 seconds.

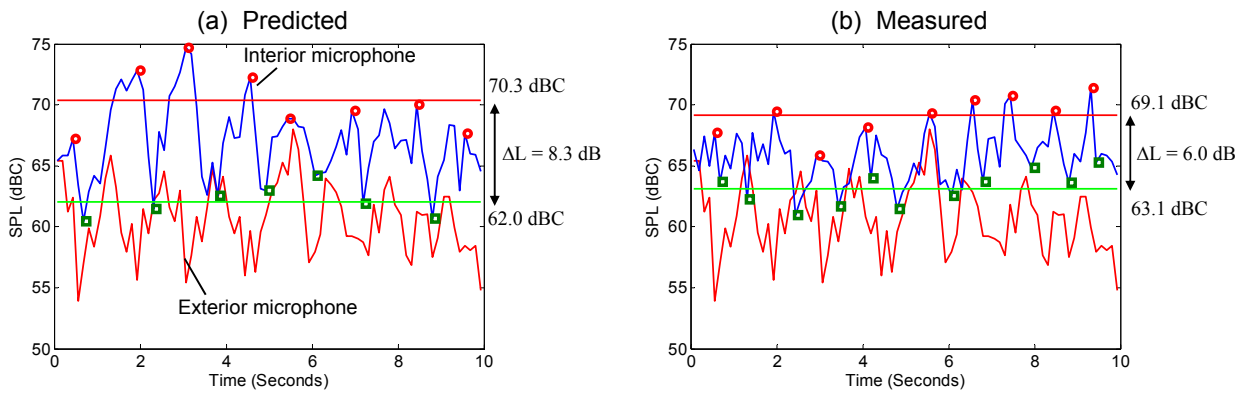

Figure 8: *Predicted and measured $L_{Ceq}(t)$ time history for interior microphone 4 and exterior microphone. Average amplitude modulation: Predicted = 8.3 dB and Measured = 6.0 dB. Maximum amplitude modulation: Predicted = 14.2 dB and Measured = 10.5 dB.*

To better quantify the accuracy of the predictions in terms of noise metrics used for WTN annoyance studies, the average noise level and modulation depth (ΔL) were computed for 4 microphones inside the room. The average of these valued was also computer. The results are tabulated in Table 1. The predicted overall SPL and modulation depth are slightly higher that the measured results. It is interesting to note that the noise levels inside the room (67.3 and 64.5 dB_C predicted and measured) are higher than the overall level of 61.6 dB_C outside.

Table 1: *Predicted and measured C-weighted average SPL and modulation depth for 4 indoor microphones.*

	Predicted		Measured	
Mic.	Average SPL dB_C	Mod. Depth, ΔL [dB]	Average SPL dB_C	Mod. Depth, ΔL [dB]
1	66.6	6.1	63.9	9.0
2	66.7	10.7	64.5	5.9
3	67.7	8.8	65.3	4.7
4	68.1	8.3	66.3	6.0
Mean	67.3	8.8	64.5	6.7

NOTE: Outside microphone overall C-weighted SPL is 61.6 dB_C.

Since indoor WTN is mainly a low frequency noise problem, specific noise metrics were suggested to quantify annoyance. A 1/3rd octave bands criterion curve was suggested for low frequency noise indoor annoyance assessment (Moorhouse et al., 2005). This criterion basically compares the average indoor spectrum taken during a period when the noise is present to this curve. This criterion is recommended as guidance to determine if there is LFN that might be expected to cause disturbance. Thus, the predicted and measured average 1/3rd octave band spectrum were computed and compared to this criterion as shown in Figures 9a

and b. Once again the outdoor 1/3rd octave band average spectrum is also shown in the figure. The results show a reasonable good agreement between the predicted and measured results.

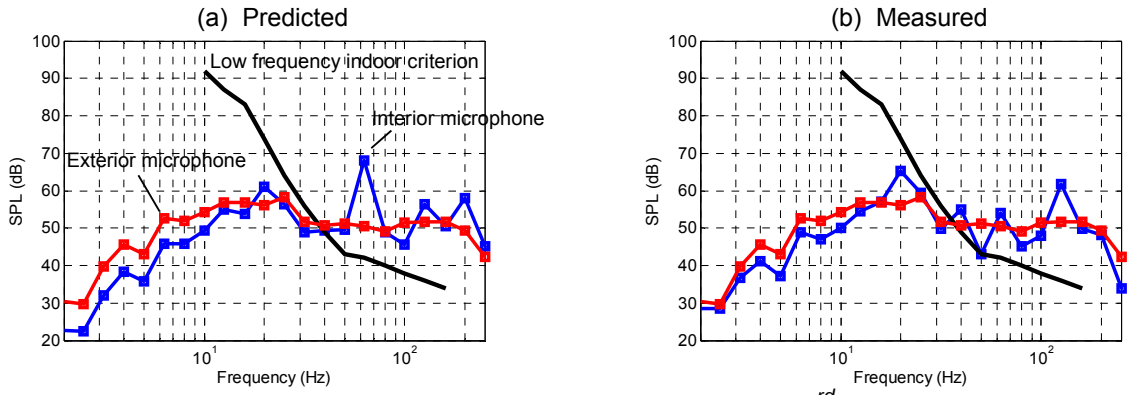

Figure 9: *Predicted and measured Z-weighted indoor average 1/3rd octave band spectrum and comparison to the reference curve for low frequency noise indoor annoyance (Moorhouse et al., 2005). Z-weighted outdoor average 1/3rd octave band spectrum also shown.*

It is important to note that there is no evidence that the infrasound in the input signal (if any) used here is from the wind turbine measured. Though the indoor infrasound is not the primary goal in this work, it was decided to compare the predicted and measured indoor G-weighted spectrum commonly used to assess low frequency noise problems. Figures 10a and b show the average G-weighted spectrum for the indoor and outdoor responses. The overall G-weighted results for 4 indoor microphones (and the average for the room) are shown in Table 2. Again the predicted results agree well with the measured data. In general, the predicted overall G-weighted levels are lower than the measured ones.

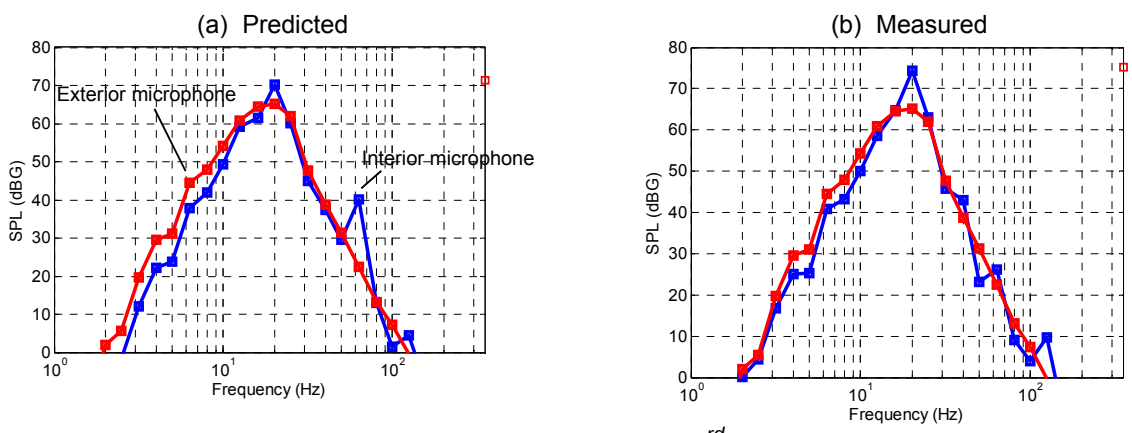

Figure 10: *(a) Predicted and (b) measured average 1/3rd octave band G-weighted spectra (typically used for infrasound studies).*
G-weighted outdoor average 1/3rd octave band spectrum also shown.

Table 2: *Predicted and measured overall G-weighted SPL for 4 indoor microphones.*

Mic.	Predicted dB_G	Measured dB_G
1	76.3	78.5
2	72.3	75.7
3	71.3	75.2
4	73.2	78.4
Mean	73.7	77.2

NOTE: Outside microphone overall G-weighted SPL is 69.7 dB_G.

2.4 Predictions for Open Window Case As mentioned in the introduction, the regulation in Denmark considers the case of open windows in assessment of wind turbine noise impact. Thus, to illustrate the capabilities of the numerical tool, a simulation was carried for the case where one of the windows is open. Figure 11 shows the results for this case. The average narrowband spectrum in Figure 11a reveals a very strong resonance at ~ 7 Hz where the levels indoors are 25 dB louder than outdoors. This peak is due to the Helmholtz resonator formed by the bulk compressibility of the air in the room (spring) and the fluid at the window (mass), for wavelength larger than window dimension. Thus, the open window not only doesn't provide meaningful transmission loss but it also creates a new detrimental dynamics (resonance) in the infrasound frequencies. These results demonstrate the significant role played by the structural dynamics at low frequencies. Figure 11b shows the predicted C-weigthed equivalent 125ms time history, LCeq(t). Again as reference, the exterior microphone time C-weigthed equivalent 125ms time history is shown in the same figure. The maximum modulation amplitude is for this case 12.6 dB (69.2 – 56.6 dB_C). Finally, Figures 11c and d present the 1/3rd octave band spectrum vs the low frequency noise indoor annoyance criterion (Moorhouse et al., 2005) and the average G-weighted spectrum for the indoor and outdoor responses, respectively. The indoor G-weighted level is 74.9 dB_G or 5.2 dB louder than outdoors.

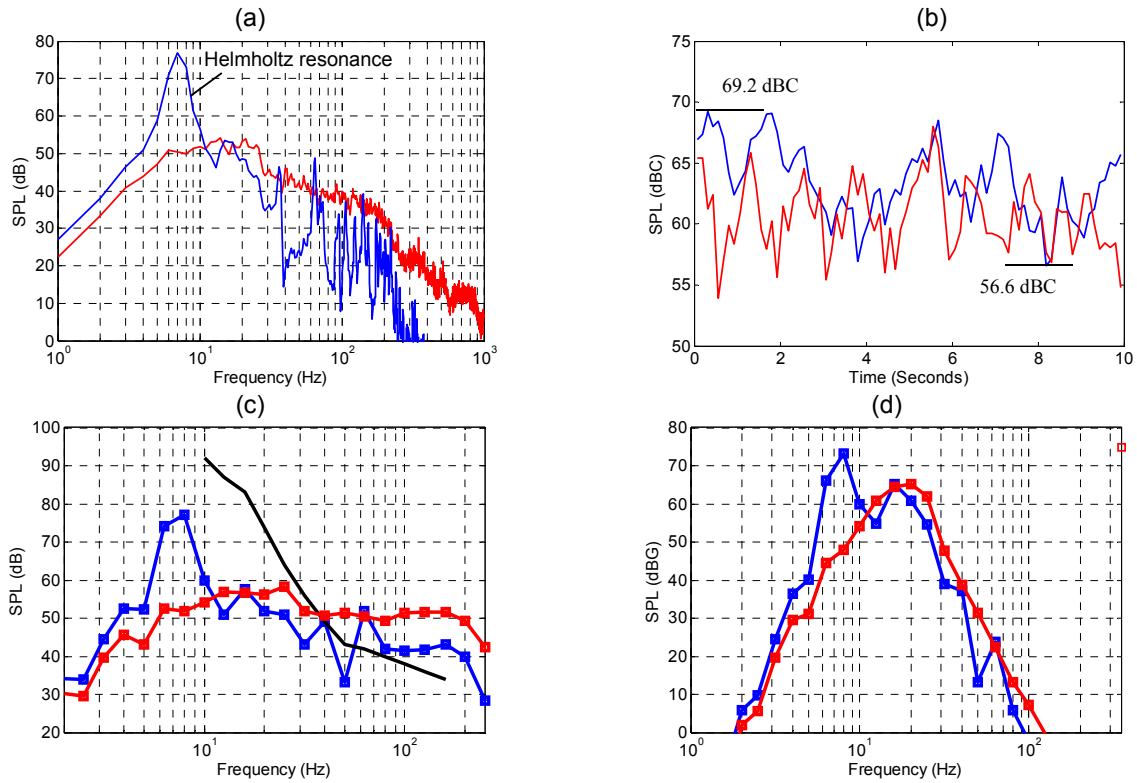

Figure 11: I*ndoor and outdoor responses: (a) Average narrowband Z-weighted spectrum, (b) L_{Ceq}(t) time history, (c) Z-weighted indoor average 1/3rd octave band spectrum and comparison to the reference curve for low frequency noise indoor annoyance (Moorhouse et al., 2005), and (d) average 1/3rd octave band G-weighted spectra (typically used for infrasound studies) for the case of the structure with one window open.*

4.0 Conclusions

A numerical tool for the prediction of indoor AM WTN was presented. This numerical model was originally developed to investigate the transmission and to assess the indoor annoyance due to the impulsive sonic booms from future commercial supersonic aircrafts into typical residential structures. It is proposed to use this code for the study of indoor annoyance from AM noise from wind turbines and farms. Thus, the work here presents the validation of the numerical tool for a "thumping" AM WTN exciting a realistic single room structure. Comparisons between predictions and measurements are carried out in terms of time history, spectrum, and

typical noise metrics using to assess annoyance such as modulation depth, overall C- and G-weighted levels, and so forth. The results shows that the code captures the interior response reasonable well both in terms of the spectral content and overall noise levels. The accuracy of the predictions depends strongly on the capability of the model to properly capture the dynamics of the structure (resonances and damping properties).

In addition to the validation, the results presented here shows that the interior noise levels are higher than outdoors even though the structure tested offers significant transmission loss (doors and windows are closed). The increase in indoors levels is primarily at the fluid-structure resonance frequencies below ~ 400 Hz. It was also found that in the case of having an open window, the structure behaves as a large Helmholtz resonator with a natural frequency in infrasound region. The increase in levels at this Helmholtz resonance is very significant (~25 dB) relative to the outside. Typically, this situation is ignored and not considered in environmental assessment indoors. These results could potentially explain the reported higher annoyance for indoor AM WTN.

The future application of this tool is twofold. Firstly, for predicting stimuli WTN indoors under different structural conditions for studies of human response. These studies can serve to develop metrics and criteria for WTN indoor annoyance specifically targeted for the indoor problem. Second, use the tool to evaluate the environmental impact of future wind farm projects predicting potential "worst case scenarios".

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References

Bolin K., Bluhm G., Eriksson G. Nilsson M. E. *Infrasound and low frequency noise from wind turbines: exposure and health effects*. Environmental Research Letters, IOP Publishing, 22 September (2011). http://iopscience.iop.org/1748-9326/6/3/035103/

Bowdler, D., Leventhall, G. Wind Turbine Noise. 1st edition, Multi-Science Publishing. UK. (2011).

Burdisso R. A. *Auralization of Transient Interior Response of Structures Subjected to Sonic Booms*: Final Report. Sponsor: NASA Langley Research Center, Virginia Polytechnic Institute and State University, Blacksburg, USA, 21 October (2013).

Burdisso R. A., Corcoran J. M. *Auralization of Transient Interior Response of Structures Subjected to Sonic Booms*: *VARS* USER MANUAL. Sponsor: NASA Langley Research Center, Virginia Polytechnic Institute and State University, Blacksburg, USA, 21 October (2013).

Cooper J., Evans T. *Automated detection and analysis of amplitude modulation at a residence and wind turbine*. Proceedings of Acoustics, Victor Harbor, Australia, 17-20 November (2013).

Danish Wind Energy Association. Statistics. (2013). Retrieved from: http://www.windpower.org/en/knowledge/statistics.html

Department of Planning and Infrastructure. New South Wales Planning Guidelines: Wind Farms. December (2011).

Di Napoli, C. *Long Distance Amplitude Modulation of Wind Turbine Noise*. Fourth International Meeting on Wind Turbine Noise, Rome, Italy. 12-14 April (2011).

Farina, A. Ramsete – *A new pyramid tracer for medium and large scale acoustic problems*. Proceedings of Euro-Noise 95, Lyon, France, 21-23 March (1995).

Fastl H., Zwiker E. *Psycho-Acoustics: facts and models*. 3rd edition, Springer, NY (2007).

Haac, T.R., Corcoran, J.M., Remillieux, M.C., Burdisso, R.A. and G. Reichard., “Development of a model for predicting the transmission of sonic booms into buildings,” Part II: experimental

characterization of the vibro-acoustic response of simple structures to simulated sonic booms, November 2009.

Hünerbein, S., King, A., Piper, B., Cand, M. *Wind Turbine Amplitude Modulation: Research to improve understanding as to its cause and effect*, Work Package B(2): Development of an AM Dose-Response Relationship. RenewableUK, 16 December (2013).

ISO 7196. *Acoustics – Frequency-weighting characteristic for infrasound measurements*. (1995).

Jakobsen, J. *Danish guidelines on environmental low frequency noise, infrasound and vibration*. J. Low Frequency Noise, Vib., Act. Control 20(3), 141–148 (2001).

Janssen, S., Eisses, A., Pedersen, E. *Exposure-response relationships for annoyance by wind turbine noise: a comparison with other stationary sources*. EURONOISE 2009, Edinburgh, Scotland, October 26-28 (2009).

Jakobsen, J., Mogensen, J. *Danish regulation of low frequency noise from wind turbines*. 5th International Conference on Wind Turbine Noise, Denver, Colorado, USA, 28-30 August (2013).

Kantarelis C., Walker, J. G. *The identification and subjective effect of amplitude modulation in diesel engine exhaust noise*. J. Sound Vibr., 120(2), 297-302 (1988).

Kelley, N. D. *A proposed metric for assessing the potential of community annoyance from wind turbine low-frequency noise emissions*. Windpower '87 Conference and Exposition, San Francisco, California, October 5-8 (1987).

Klos, J. *Overview of an indoor sonic boom simulator at NASA Langley Research Center*. INTER-NOISE 2012 Conference, New York City, USA, August 19-22 (2012).

Lee S., Kim K., Choi W., Lee S. *Annoyance caused by amplitude modulation of wind turbine noise*. Noise Control Eng. 59 (1), Jan-Feb (2011).

Legarth, S. V. *Auralization and Assessments of Annoyance from Wind Turbines*. Second International Meeting on Wind Turbine Noise, Lyon, France, 20-21 September (2007).

Lenchine, V. V. *Amplitude modulation in wind turbine noise*. Proceedings of ACOUSTICS 2009, Adelaide, Australia, 23-25 November (2009).

Leventhall, G. *Infrasound from Wind Turbines – Fact, Fiction or Deception*. Canadian Acoustics, vol. 34 No.2, p.34 (2006).

Lundmark, G. *Measurement of Swish Noise. A new method*. 4th International Meeting on Wind Turbine Noise. Rome, Italy. 12-14, April (2011).

Moller, H., Pedersen, C. *Low-frequency noise from large wind turbines*. J. Acoust. Soc. Am., Vol. 129, No. 6, June (2011).

Moorhouse, A., Waddington D., Adams M. *Procedure for the assessment of low frequency noise complaints*. DEFRA report contract no NANR45, Acoustics Research Centre, Salford University, February (2005).

Pedersen, E., van den Berg, F., Bakker, R., Bouma, J. *Response to noise from modern wind farms in The Netherlands*. The Journal of the Acoustical Society of America, 126(2), 634-643, August (2009).

Stigwood M., Large S., Stigwood D. *Audible amplitude modulation – results of field measurements and investigations compared to psychoacustical assessment and theoretical research*. 5th International Conference on Wind Turbine Noise, Denver, Colorado, USA, 28-30 August (2013).

Van den Berg, G. *The Beat is Getting Stronger: The Effect of Atmospheric Stability on Low Frequency Modulated Sound of Wind Turbines*. Journal of Low Frequency Noise, Vibration and Active Control. Vol 24, No. 1, pp. 1−24 (2005).

Van den Berg, G. *The sounds of high winds: the effect of atmospheric stability on wind turbine sound and microphone noise*. Thesis presented for the PhD in Mathematics and Natural Sciences, University of Groningen, May 12 (2006).

Svensson U.P., Fred, R.I., Vanderkooy, J. *An analytic secondary source model of edge diffraction impulse responses*. Journal of the Acoustical Society of America, 106, pp. 2331−2344 (1999).

Svensson U.P., Calamia, P.T. *Edge-diffraction impulse responses near specular-zone and shadow-zone boundaries*. Acta Acustica United with Acustica, 92, pp. 501–512, (2006).

U.S. Department of Energy. History of Wind Energy. (2014, February 10). Retrieved from: http://energy.gov/eere/history-wind-energy

World Health Organization. Night Noise Guidelines for Europe. Copenhagen, Denmark (2009).