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RESEARCH ARTICLE

Indoor simulation of amplitude modulated wind turbine noise

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ABSTRACT

Wind energy is the world's fastest-growing renewable energy source; as a result, the number of people exposed to wind farm noise is increasing. Because of its broadband amplitude-modulated characteristic, wind turbine noise (WTN) is more annoying than noise produced by other 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 complaints relate to indoor, nighttime conditions when background noise levels are lower. As recently reported, indoor noise has the potential to cause sleeping disorders. Studies on human response to amplitude modulated WTN have been mainly focused on the outdoors, where a large amount of measured data exists. This is not the case for indoors, where it is much harder to gather data. Hence, there is a need to understand the transmission of WTN into dwellings and to develop indoor annoyance metrics. In this article, we investigate the transmission of WTN into residential-type structures. Using an outdoor WTN recording and structures with different properties/configurations, we made a series of computer simulations for indoor noise predictions and assessed the results employing several widely used metrics for WTN, for example, spectral content, modulation depth and overall levels. In general, the indoor noise levels are higher, and the average modulation depth is similar to those of outdoor recordings. In addition, there is a significant change in the spectral shape. These results could potentially explain indoor WTN annoyance. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS
wind turbine; indoor simulation; modulated noise; low-frequency noise

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1. INTRODUCTION

Power production by renewable wind energy has risen sharply in recent years, and during the last 20 years, it has evolved successfully all over the world. This energy source has the highest growth rate of all renewable sources, with an increase of installations greater than 20% annually.[1] Most 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, and these larger turbines are louder and potentially more annoying to people living nearby.

Broadband aerodynamic blade noise is the dominant noise source of modern large-scale wind turbines. Wind turbine noise (WTN) measurements using a linear microphone array outdoors have shown that the noise is mainly generated when the blades go downward and in the outer 25% of the blade span.[2,3] Therefore, a number of research studies have been dedicated to the design and testing of highly efficient and low-noise airfoils for wind turbine applications.[4] More recently, active flow control to manipulate the boundary layer features has also been suggested as a potential technology to reduce trailing-edge noise.[5] A comprehensive review of some trailing-edge noise prediction models may be found in the work of Kamruzzaman *et al.*[6] On the other hand, outdoor noise emissions from isolated wind turbines and farms have been predicted from propagation models based on ray tracing that simulates the ground and air effects.[7] In addition, the effect of resonant conditions in modern large-scale wind turbines has recently been studied by Tibaldi *et al.*,[8] who reported that aero-elastic modes might be excited, depending upon the wind turbine operational external excitations.

Broadband aerodynamic blade noise is responsible for the amplitude modulation (AM) observed mainly in large turbines, that is, a pulsating broadband sound.[2,3,9] This AM, commonly referred to as 'swishing', 'whooshing' or 'pulsating' noise, is currently considered to be the main cause of annoyance for residents living near wind farms.[10,11] Recently, infrasound from wind turbines has also received significant attention.[11,12] However, the generation of this noise component is not well understood and cannot easily be quantified, since a limited number of conclusive measurements are available.

Turbines are not typically as loud as other sources of industrial or transportation noise at a similar distance. The AM characteristic is what makes WTN more annoying than other types of noises at the same sound pressure level (SPL). Very quiet rural communities that lack the masking of nighttime traffic noise are particularly affected. AM noise is perceived as more annoying than a constant amplitude sound containing the same spectrum and average noise level.[13,14] Therefore, WTN is commonly more aggravating than other industrial and community noise sources.[14–16] For example, it was found that 10–20% of residents are annoyed outdoors (of them 6% are very annoyed) by AM WTN at A-weighting equivalent emission levels between 35 and 40 dBA.[11] This is about twice the annoyance rate for industrial noise at the same levels.[15]

Broadband AM noise is typically defined by the modulation depth (ΔL), defined as the difference between the peak and trough SPLs, 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, that is, the turbine blade passing frequency. The swishing AM sound of wind turbines is stronger in the mid-frequency range (from 400 to 1000 Hz) and in the downwind direction.[17,18]

Despite the fact that SPLs decrease with distance, the modulation depth does not until background noise levels begin to reach the WTN levels. This effect has been demonstrated in several noise measurement studies.[17–19] When AM is present at lower frequencies (20 to 300 Hz), it is often described as a thumping noise.

In psychoacoustics, sounds with modulation frequencies below 20 Hz cause a hearing sensation of fluctuating sound strength. Moreover, modulation frequency of about 4 Hz matches the normal speaking rate of four syllables/second.[13] The perception of amplitude modulated sound can be quantified using the fluctuation strength metric, which was developed to measure the human perception of AM in sounds.[13]

Several metrics have been suggested for assessing WTN annoyance.[18] In one of the first reported studies, indoor annoyance from low-frequency WTN (less than 160 Hz) was determined using six weighted overall noise levels, including the conventional A-weighting.[20] In this study, it was confirmed that people definitely perceive and are annoyed by low-frequency WTN. The results suggested the use of low-frequency sound level or C-weighting and to establish 67 and 76 dBc 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.[21] The standard establishes that G-weighted SPLs below 90 dBG will not be significantly important for either human perception or disturbance. Even more stringent are the Danish guidelines that establish a limit of 85 dBG using this metric.[22] Although fluctuation strength was originally developed to quantify perception, it has recently been investigated for outdoor WTN annoyance in several studies,[17–19,23,24] which found good correlation between fluctuation strength and annoyance. However, these studies cannot be applied to indoor WTN, because the contextual and attitudinal aspects are completely different.[25]

A few European countries, such as the Netherlands and Denmark, have regulations for WTN. Danish regulation for WTN establishes an outdoor noise limit of 44 dBA at a wind speed of 8 m/s no more than 15 m from dwellings.[26] However, Swedish and Dutch studies have reported that about 20% of people were very annoyed at WTN levels of 40–45 dBA.[16] This again confirms the inadequacy of A-weighting for WTN.

Many WTN complaints relate to indoors at night, when background levels are lower.[19] As recently reported, indoor noise has the potential to cause sleeping disorders.[11,13,16–19,27] The problem of WTN indoors is more complicated because of the effect of 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. However, at frequencies below 200 Hz, the system resonances can result in an increase in indoor noise levels, as compared with outdoors.[11] Although some recent studies have shown that indoor noise levels from wind farms comply with guidelines, they concluded that there could be low-frequency WTN problems in some cases.[11] Some people prefer to sleep with the windows open or slightly open, and the World Health Organization has recommended that noise regulations should allow for this contingency.[28,29] Denmark took this recommendation into account and established that for the low-frequency noise regulation, measurement should be made with open windows when the complainant asks for it.[28]

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, it becomes more urgent to define proper guidelines and standards. As stated in the New South Wales Wind Farm Guidelines,[30] 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 manufacturers, regulators and operators to predict and avoid the harmful effects of WTN. Studies on human annoyance response to AM WTN have mainly focused on the outdoor case, where a large amount of measured data is available. This is not the case for indoors, where it is much more difficult to gather data. Thus, there is a need to understand and accurately predict the transmission of AM WTN into dwellings and to develop indoor annoyance metrics.

In this article, a fluid-structural computational model is presented to predict the indoor acoustic response due to AM WTN. This numerical model was previously developed to investigate the transmission and to assess indoor annoyance caused by sonic booms from future commercial supersonic aircrafts into typical residential structures.[31] It is proposed to use this code for the study of indoor annoyance from AM noise produced by wind turbines and wind farms. The accuracy of this code for the AM WTN application is presented here. Using an outdoor AM WTN recording and a realistic structure, a series of computer simulations for indoor noise predictions were made. Because AM WTN is mainly below 1000 Hz, the simulations were performed for frequencies between 0 and 1000 Hz. The indoor predictions were then processed to compute several conventionally used metrics for WTN, for example, spectral content and modulation depth. These predicted metrics were compared with 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 previously developed for the vibro-acoustic response of structures subjected to aircraft-generated sonic booms. The code is referred to as vibro-acoustic response of buildings to sonic booms (VARS).[32] The computer program has the capability to solve the exterior-to-interior transmission of sound through three-dimensional, thin-walled elastic structures over a frequency range from 0 to 6000 Hz. 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 Svensson.[33,34] There are several orders of diffraction, depending on the number of edges that 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 modeling methods for low and high frequencies, respectively. These predictions are then mixed together using digital filters. Details and validation of the model can be found in the works of Remillieux *et al.*.[35,36]

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 into the in vacuo normal modes of the structure. The sound pressures inside the rooms are decomposed into the normal acoustic modes of the cavities, assuming perfectly reflecting surfaces, that is, acoustically rigid boundaries. The structural modes are computed with the finite element 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, for example, plaster-wood walls, windows and doors. Acoustic modes were computed analytically assuming a rectangular domain with rigid boundary conditions. Using the structural and acoustic modes, the modal vibro-acoustic responses are solved by numerical integration and then transformed to the physical domain.[31]

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 with the dimensions of the structure, and the structure will not exhibit individual low-global modal behavior because of the high-modal density. In other words, the responses of individual modes of vibration are not seen because of 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 modeled as a distribution of equivalent monopole sources. To accomplish this, the exterior loaded surfaces transmitting sound into the interior rooms of interest are divided into a number of elements (referred as high frequency mesh). 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. Reflections were taken into account and computed using the pyramid tracing algorithm. The commercial pyramid tracing software package, RAMSETE, is used to predict the interior acoustic response.[37]

For validation purposes, the code predictions were compared with real measurements for four test structures subjected to simulated and real sonic booms.[31] The accuracy of the predictions is shown here from results obtained in the National Aeronautics and Space Administration Interior Effects Room.[38] 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 proximity to the exterior walls. The arrays, containing 52 subwoofers and 52 midrange speakers, have a usable bandwidth of 3 to 5 kHz and sufficient power output to allow study of sonic boom noise. Specific details on the exact location of the loudspeaker arrays can be found in Klos *et al.*[38] The vibration of the building components also induces nonlinear 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 Interior Effects Room facility is the capability to isolate the linear vibro-acoustic responses.

Criteria for assessing the accuracy of the predictions were defined by National Aeronautics and Space Administration for the case of sonic booms as (i) for time domain signals (dominated by the low-frequency components), the ratio of measured-to-predicted time-domain maximum absolute responses should be in the range 1.5 to 0.666 and (ii) for spectra, the SPL difference in one-third octave bands averaged across all bands should be less than 10 dB. The validation cases [31] showed that the time domain criterion was met better than the spectral criterion.

Illustrative validation results in both time domain and one-third octave bands are shown in Figure 1 for an accelerometer mounted on the window and a microphone near the center of the room. The predictions in the time domain, which are dominated by the low-frequency components, show very good agreement. One-third octave band spectra show good accuracy in the predictions at frequencies below 500 Hz. In general, errors are more important for frequencies above 500 Hz, and they increase with frequency. Note that at higher frequencies, the excitation boom did not have significant energy content, which potentially contributes to poorer agreement.[31] 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.

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

3. 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[39] at about 50 m 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

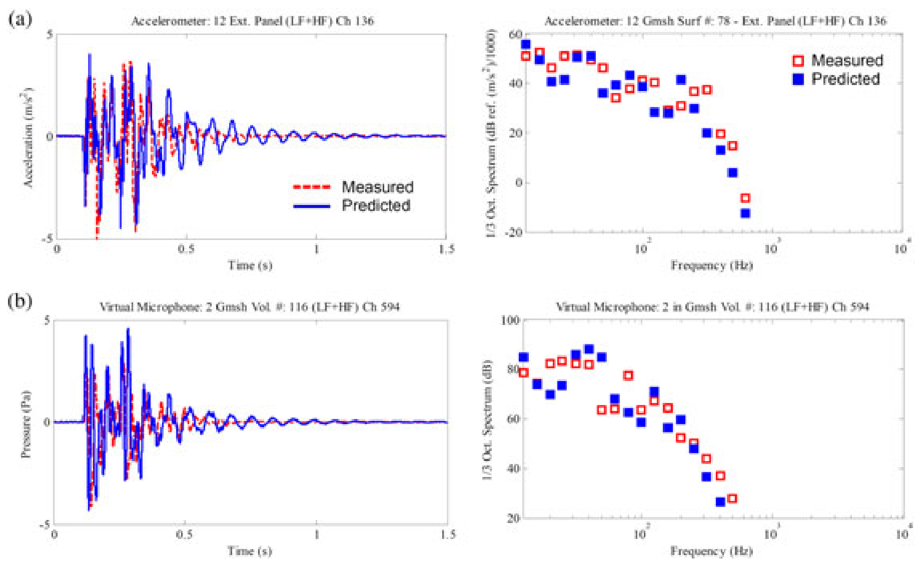

Figure 1. Illustrative comparison of predicted and measured vibro-acoustic responses for a sonic boom excitation. (a) Acceleration at the window and (b) interior pressure near the center of the room.

in the simulations was 10 s, corresponding to the second half of the original recording. For the sake of consistency, the AM WTN input signal was adjusted to have an equivalent A-weighted SPL of 45 dBA. This level was selected as it has the highest proportion of annoyance, as shown in the Swedish and Dutch studies.[16] Since the structural analysis is linear, any gain applied to the input signal applies equally to the interior acoustic responses. Because the AM is most dominant at low frequencies and the structure provides significant transmission loss at higher frequencies, the simulations were limited to the lower part of the spectrum, i.e., below 1 kHz.

As modulation frequency and depth have been used to describe AM WTN,[18] they are computed here for both the input and indoor responses. The modulation frequency and depth were calculated using the approaches described by Lundmark[40] and Cooper and Evans.[41] The overall A-weighted and C-weighted SPLs, L_{Aeq} and L_{Ceq}, were obtained for 125 ms time windows, selected so as to be comparable with the integration time of the human ear. To determine the equivalent levels, a Hanning filter was applied to the 125 ms time windows, the narrowband spectrum was computed using the fast Fourier transform (FFT) with no overlap applied; and subsequently, the spectral energy was added. The magnitude of the spectrum of $L_{Aeq}(t)$ and $L_{Ceq}(t)$ is then obtained by taking a single FFT of the entire signal. This spectrum is referred to as the AM spectrum. From this spectrum, the frequency of the dominant peak indicates the modulation frequency, f_{mod}, and the peak level is the modulation depth, ΔL, averaged 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 maxima and minima in $L_{Aeq}(t)$ or $L_{Ceq}(t)$ and computing the difference between the mean maximum and minimum levels.[41] Both approaches to compute modulation depth yielded very similar results for the outdoor input signal. To gain insight into the frequencies showing AM, the average narrowband and one-third octave band spectra corresponding to the maximum and minimum were also computed.

The signal processing described earlier was applied to the input signal, and the results are shown in Figure 2. The input time signal is shown in Figure 2(a) where the AM is evident. The A-weighted equivalent 125 ms time signal, $L_{Aeq}(t)$, is plotted in Figure 2(b) with local maxima (red) and minima (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 approximately 0.8 Hz. Figure 2(c) shows the C-weighted average one-third octave band spectra for the maxima, minima and all 125 ms 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 one-third octave bands with a maximum modulation depth of 14.3 dB at 160 Hz.

An important consideration in the estimation of the modulation depth in Figure 2(b) is that the signals were A-weighted, which considerably reduces the impact of low frequencies. However, in WTN, the majority of the modulated sound occurs at low frequencies, as shown in Figure 2(c). This fact, in concurrence with the unsuitability of the A-weighting to assess annoyance,[20] potentially indicates that modulation depth as computed is not an appropriate metric, in particular for indoor

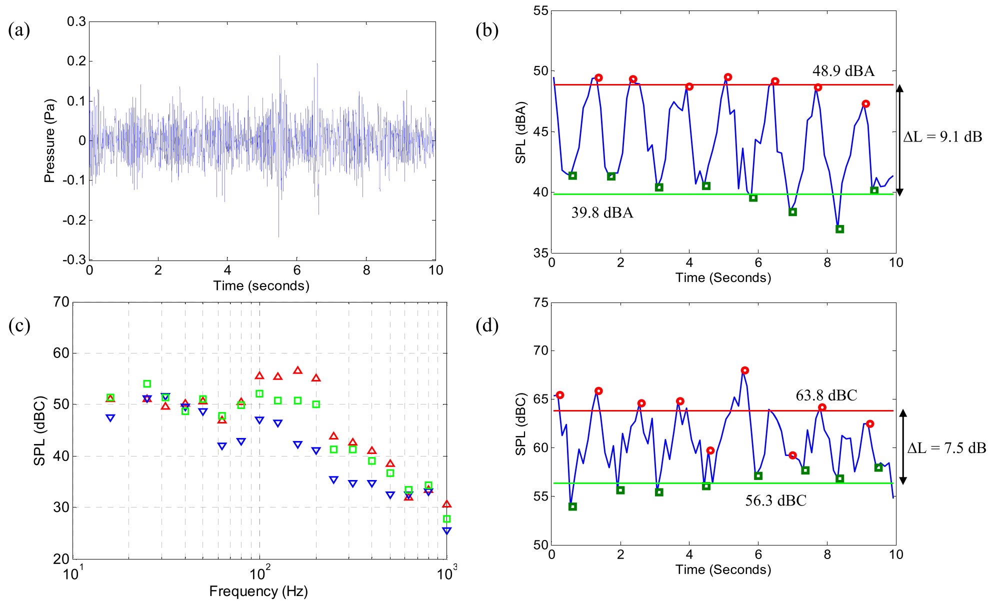

Figure 2. Amplitude modulated wind turbine noise (WTN) input signal used in simulations.[31] (a) Time history; (b) A-weighted equivalent 125 ms time signal; (c) C-weighted one-third octave band spectra for WTN signal of maxima, minima and all 125 ms time windows; and (d) C-weighted equivalent 125 ms time signal $L_{Ceq}(t)$.

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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 2(d). The average and maximum modulation depth using C-weigthed sound levels is 7.5 and 14.1 dB, respectively. The average noise level is 61.6 dBc.

3.2. Structure

The structure employed for the simulations was a wood frame construction typically used in dwellings in the USA.[31] The structure consisted of a single room made of a 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 $2.7 \times 4.8 \times 2.7\,m^3$. This structure is shown in Figure 3(a) and is referred to as the 'VT single room structure'. As shown in Figure 3(b), 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 structure 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.[32] The signals from all sensors were recorded simultaneously with a sampling frequency of 50 kHz.

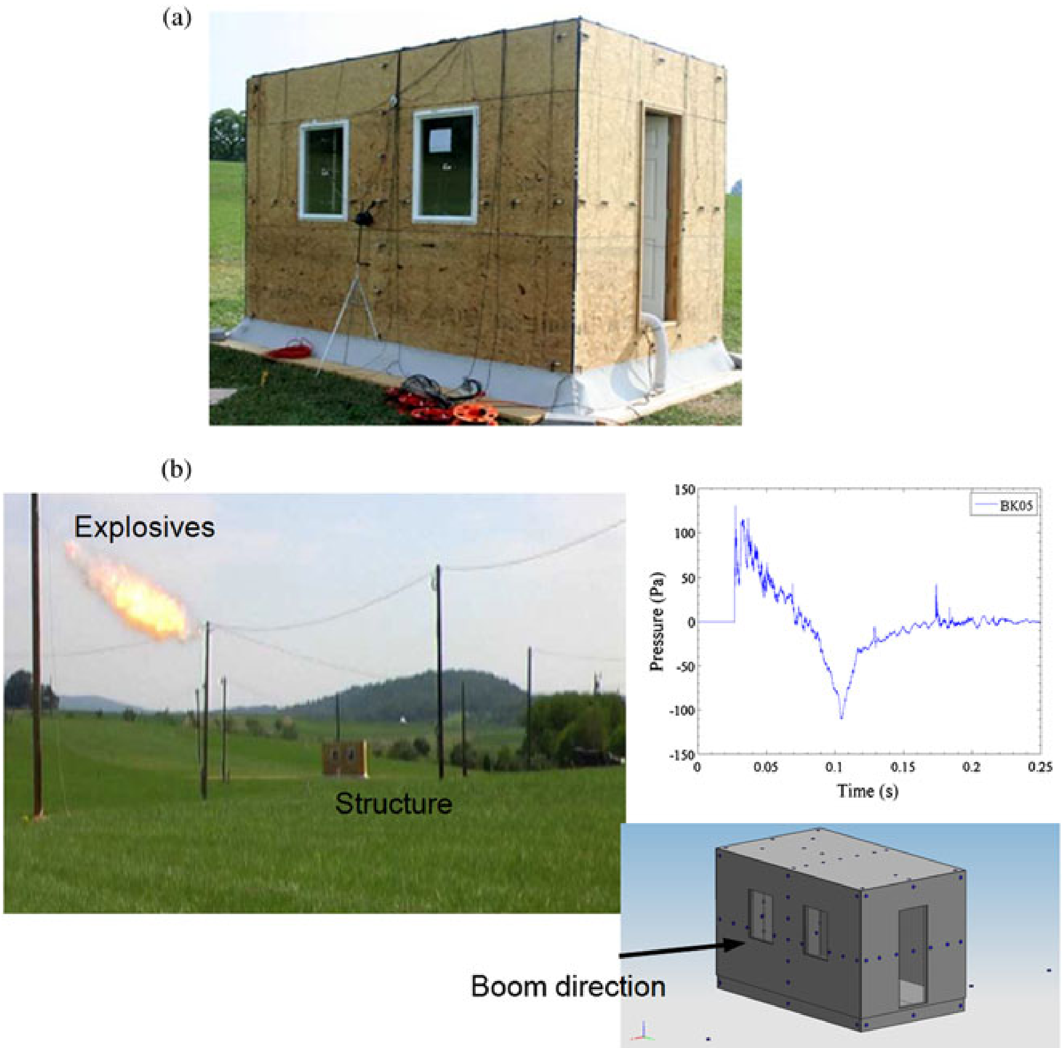

Figure 3. (a) Structure used for interior acoustic response to the amplitude modulation wind turbine noise (AM WTN) signals and (b) explosives technique used to simulate the sonic boom input.

Figure 4(a) 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 from 0 to 738 Hz. The fundamental frequency of the structure is 12.3 Hz. Modal damping ratios of 5% are assumed to be the same for all modes. 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 defining 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 4(b). A total of 594 monopoles were used to model the interior sound field. The high-frequency and low-frequency predictions were combined using high-pass and low-pass filters with cutoff frequency at 500 Hz.

Both structural and interior pressure monaural and binaural time responses were obtained as outputs. In this study, only the monaural responses were used for the 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 AM WTN.

3.3. 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, the measured indoor response of the structure is needed, but unfortunately, it does not exist. To obtain 'empirical' 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 sound pressure produced by the WTN in the absence of the structure (but accounting for ground reflection) at the sensor located where the structure is. As a result, the exterior microphone used to compute the transfer functions was located on

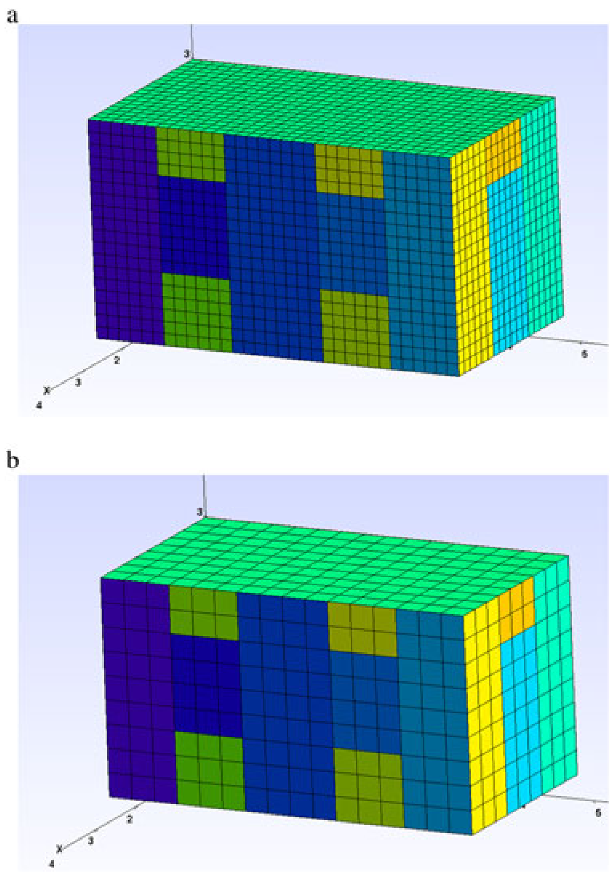

Figure 4. (a) Finite element mesh for the low-frequency predictions and (b) mesh to define monopole sources for interior noise predictions at high frequency.

the ground at a distance of 30 m 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 corrected measured exterior 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 provided the experimentally determined impulse response functions that were then convolved with the AM thumping noise input signal described in Section 3.1. 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 5–9. Figure 5 shows the time history of the interior microphone pressure over a second duration for easy comparison of 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 (1 Hz) spectra are compared in Figure 6. In this plot, the spectrum for the exterior microphone is also shown for 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 test revealed that the resonance at 22.3 Hz is associated with the first mode of the wall with windows. The resonance at 37.6 Hz corresponds to the first acoustic cavity mode (Figure 6). The second acoustic cavity mode is at 65 Hz, and the fundamental frequency of the structure is 12.3 Hz. 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 incorrect damping values in the model.

The measured and predicted interior responses were also analyzed in the same manner as the input signal to uncover the AM characteristics of the interior response. Figure 7(a),(b) show the predicted and measured C-weighted equivalent 125 ms time history, $L_{Ceq}(t)$. Again as reference, the exterior microphone time C-weighted equivalent 125 ms time history is shown

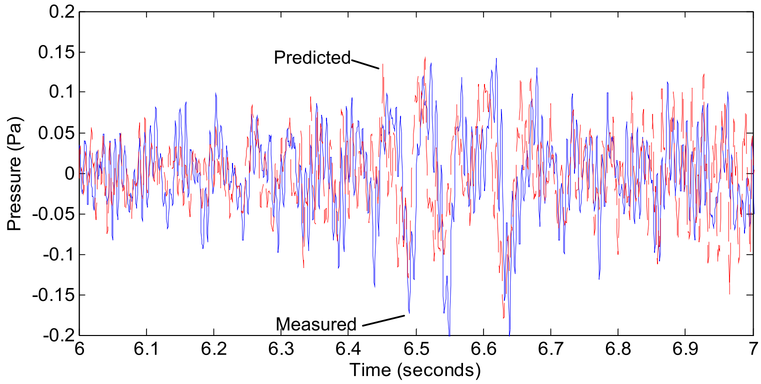

Figure 5. Predicted and measured interior acoustic response for microphone near room center.

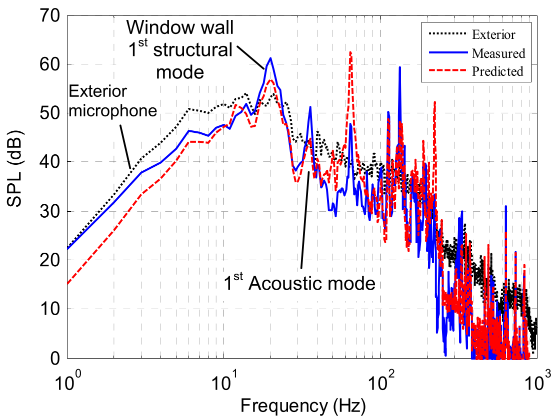

Figure 6. Predicted and measured average narrowband unweighted spectra of exterior and interior (near center of the room) microphones.

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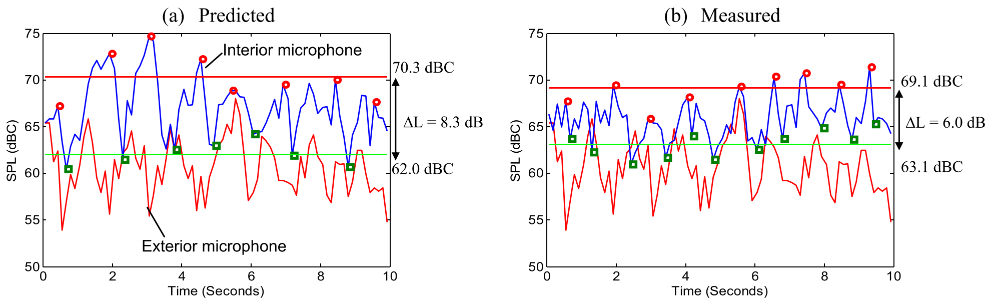

Figure 7. Predicted and measured $L_{Ceq}(t)$ time history for interior microphone 4 and exterior microphone. Average amplitude modulation: predicted = 8.3 dB and measured = 6.0 dB. Maximum amplitude modulation: predicted = 14.2 dB and measured = 10.5 dB.

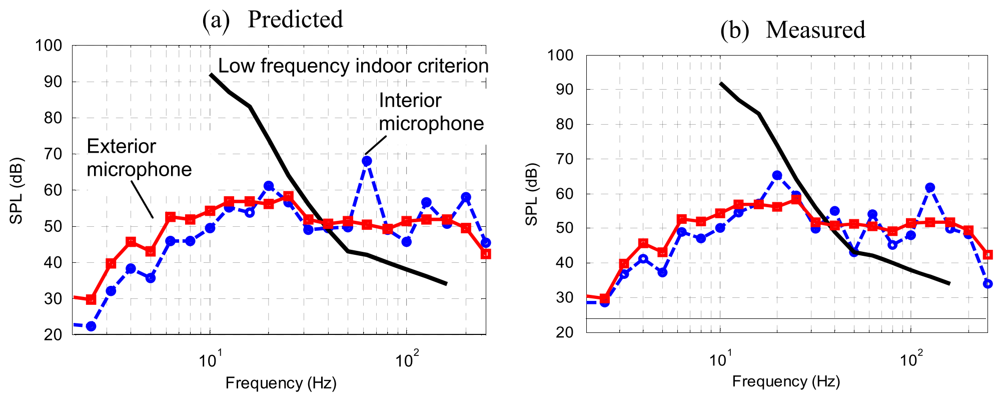

Figure 8. Predicted and measured Z-weighted indoor average one-third octave band spectra and comparison with the reference curve for low-frequency noise indoor annoyance.[35] Z-weighted outdoor average one-third octave band spectrum is also shown.

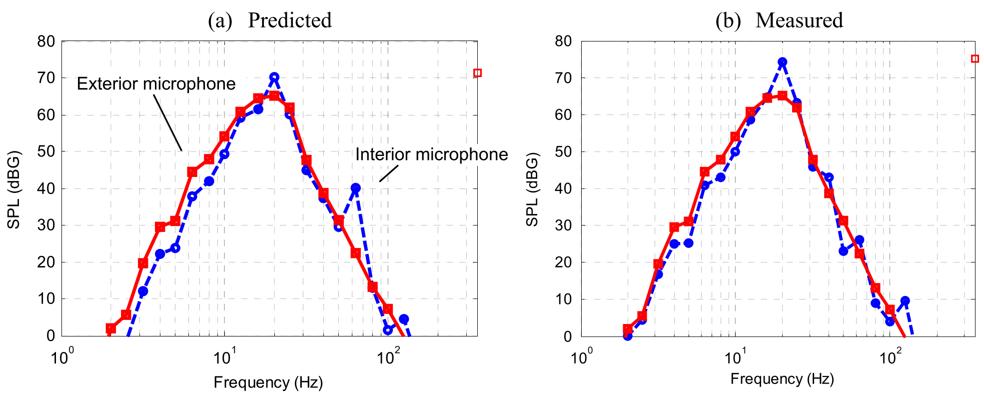

Figure 9. (a) Predicted and (b) measured average one-third octave band G-weighted spectra (typically used for infrasound studies). G-weighted outdoor average one-third octave band spectrum is also shown.

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 s.

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 four microphones located inside the room. The average of these values was also computed. The results are shown in Table I. 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 dBc, predicted and measured, respectively) are higher than the outside overall level of 61.6 dBc.

Since indoor WTN is mainly a low-frequency noise problem, specific noise metrics were suggested to quantify annoyance. A one-third octave band criterion curve was suggested for low-frequency noise indoor annoyance assessment.[42] This criterion basically compares the average indoor spectrum taken during a period when the noise is present to this curve. For unsteady noise, SPLs that are 5 dB below the reference curve could be audible. If the low-frequency noise exceeds the reference curve this noise would be assessed as one which could cause disturbance. This criterion is recommended as guidance to determine if there is low-frequency noise that might be expected to cause disturbance. Thus, the predicted and measured average one-third octave band spectra were computed and compared with this criterion as shown in Figure 8(a),(b). The results show reasonably good agreement between the predicted and measured results.

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. Although the indoor infrasound is not the primary goal of this study, it was decided to compare the predicted and measured indoor G-weighted spectrum commonly used to assess low-frequency noise problems. Figure 9(a),(b) show the average G-weighted spectra for the indoor and outdoor responses. The overall G-weighted results for four indoor microphones (and the average for the room) are shown in Table II. Again the predicted results agree well with the measured data. In general, the predicted overall G-weighted levels are slightly lower than the measured ones.

3.4. Predictions for the open-window case

As mentioned in the introductory section, the regulation in Denmark considers the case of open windows in the assessment of WTN impact. Therefore, to illustrate the capabilities of the numerical tool, a simulation was carried out for the case where one of the windows was open. Figure 10 shows the results for this case. The average narrowband spectrum in Figure 10(a) reveals a very strong resonance at approximately 7 Hz where the indoor levels 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 a wavelength larger than the window dimensions. Thus, the open window not only does not provide meaningful transmission loss but also creates a new detrimental dynamic (resonance) in the infrasound frequencies. These results demonstrate the significant role played by the structural dynamics at low frequencies. Figure 10(b) shows the predicted C-weighted equivalent 125 ms time history, $L_{Ceq}(t)$. Again as reference, the exterior microphone time C-weighted equivalent 125 ms time history is shown in the same figure. The maximum modulation amplitude is in this case 12.6 dB (69.2–56.6 dBc). Finally, Figure 10(c),(d) shows the one-third octave band spectrum versus the low-frequency noise

Table I. Predicted and measured C-weighted average SPL and modulation depth for four indoor microphones.

Microphone	Predicted		Measured	
	Average SPL dBc	Modulation depth, ΔL dB	Average SPL dBc	Modulation 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

Outside microphone overall C-weighted SPL is 61.6 dBc.
SPL, sound pressure level.

Table II. Predicted and measured overall G-weighted sound pressure level (SPL) for four indoor microphones.

Microphone	Predicted dBG	Measured dBG
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

Outside microphone overall G-weighted SPL is 69.7 dBG.

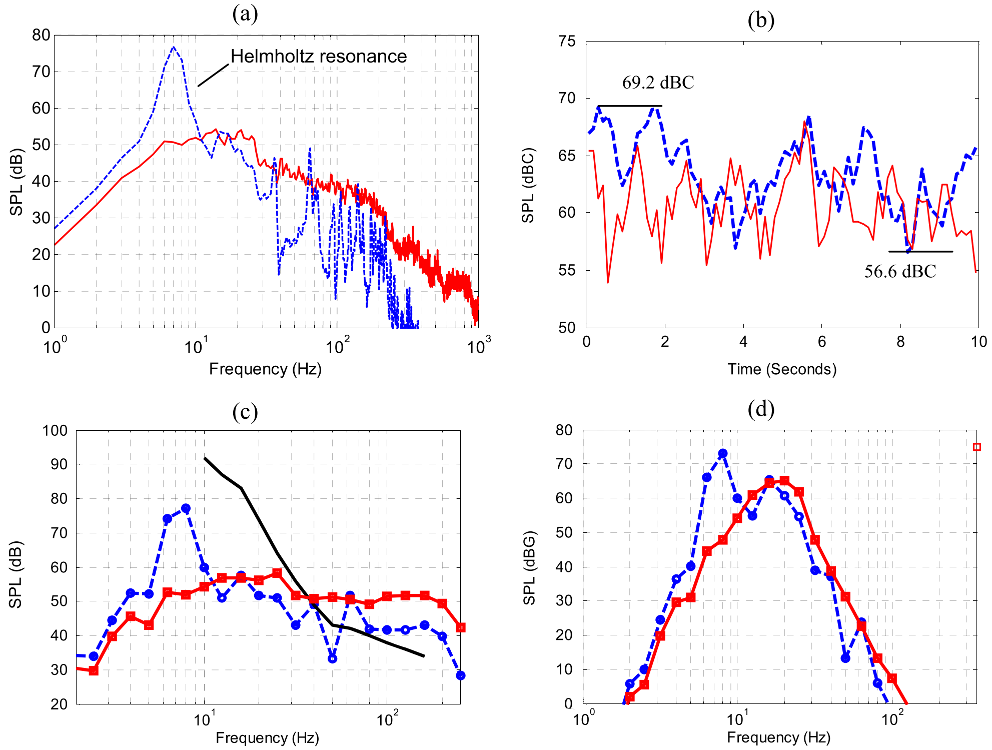

Figure 10. Indoor and outdoor responses: (a) average narrowband Z-weighted spectrum, (b) $L_{Ceq}(t)$ time history, (c) Z-weighted indoor average one-third octave band spectrum and comparison with the reference curve for low-frequency noise indoor annoyance[42] and (d) average one-third octave band G-weighted spectra (typically used for infrasound studies) for the case of the structure with one window open.

indoor annoyance criterion[42] and the average G-weighted spectrum for the indoor and outdoor responses, respectively. The indoor G-weighted level is 74.9 dBG, that is, 5.2 dB louder than outdoors.

4. CONCLUSIONS

A numerical tool for the prediction of indoor AM WTN was presented. This numerical model was originally developed to investigate the sound transmission and to assess indoor annoyance because of impulsive sonic booms from future commercial supersonic aircrafts into typical residential structures.[43] It is proposed to use this code for the study of indoor annoyance caused by 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 were carried out in terms of time histories, spectra and typical noise metrics used to assess annoyance such as modulation depth, overall C-weighted and G-weighted levels. The results show that the code captures the interior response reasonably well in terms of both 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 show that the indoor noise levels are higher than outdoor noise levels even though the structure tested offers significant transmission loss (doors and windows are closed). The increase in indoor levels is primarily at the fluid–structure resonance frequencies below around 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 the infrasound region. The increase in levels at this Helmholtz resonance is very significant (25 dB approximately) relative to the outside level. Typically, this situation is ignored and not considered in indoor environmental assessments. These results could potentially explain the reported higher annoyance for indoor AM WTN.

The future application of this tool is twofold. First, the tool may be used for predicting WTN stimuli 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 to the indoor problem. Second, the tool may be used to evaluate the environmental impact of future wind farm projects, predicting potential 'worst-case' scenarios.

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