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Noise
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3aNSa7. Development of experimental facility for testing human response to ILFN from wind turbines

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The fact that wind turbines produce infrasound continues to draw attention and discussion. Some argue that while the infrasound level produced by wind turbines is quite low, it still may be affecting the vestibular system or the hearing system, particularly via activation of the outer hair cells. Others hypothesize that the infrasound may be inducing whole body, chest cavity, or other human organ resonance. In order to study these hypotheses, it is first necessary to be able to recreate the turbine noise signature in a lab environment. Thus the goal of this work is to create an acoustic system that can produce low-level infrasound. The system requirements include low cost, high fidelity, and imperceptible structural coupling to the lab. In addition, the system must be able to produce a broadband spectrum as well as a single tone. Progress towards the design of this audio system is discussed in this paper.

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BACKGROUND

Recently, much attention is being paid to the noise produced by wind turbines. Interest has risen in this topic due to the proliferation of large-scale wind turbines and the response of neighbors. In 2000, a cross-sectional study was performed in Sweden aimed at determining the intersection of perception and annoyance related to wind turbine noise (Pedersen and Waye, 2004). More recent epidemiological studies include (Pedersen and Waye, 2007, 2008; Pedersen *et al.*, 2009; Shepherd *et al.*, 2011). These studies found correlations between sleep disruptions and wind turbine noise. They also noted that those who saw the turbines were more annoyed that those who did not and those who gained economically from the turbine were less likely to note annoyance.

Concerns still exist and numerous complaints from neighbors continue to be lodged against wind turbines. Some claim that infrasound and low frequency noise emitted by wind turbines is responsible for the negative reaction from neighbors (Pierpont, 2009).

Researchers attempting to better understand the nature of the annoyance and the disturbance have considered the complaints made by those living near wind turbines. C. S. Pedersen *et al.* (2008) followed up with 21 of 203 complainants. Measurements were taken near the homes and the complainants participated in hearing studies. It was shown that the audible noise was responsible for their annoyance not the infrasound and only some of the complainants were actually reacting to the wind turbine noise.

Still, neurophysiologists have noted that there may be a mechanism by which the vestibular system is affected by infrasound and low frequency noise (ILFN) (Salt and Hullar, 2010) and thus a mechanism by which ILFN from wind turbines can be affecting neighbors. They note that the outer hair cells (OHC) do react to infrasound; and, because the OHC serve as amplifiers for the inner hair cells (IHC) (which are responsible for hearing in the audible range), there is the likelihood that if the OHC are altered due to airborne infrasound, then it could disrupt normal hearing and thus make a listener have a reaction similar to other reactions related to disruptions in the vestibular system (motion sickness, headache, etc.). The connection between the OHC, IHC and the organ of Corti in cochlear transduction has been studied previously at BU (Mountain and Cody, 1999). But the question of whether perception is changed in the presence of low-amplitude, low-frequency noise is a new area of interest.

The claims and concerns surrounding ILFN from wind turbines are prompting more studies of human perception of ILFN. In order to conduct research in this field, one must have appropriate experimental equipment and facilities. In particular, one must have a method for generating and measuring IFLN signals and have an appropriate room for conducting human subject testing. The goal of the current research is to create the requisite experimental equipment at a very low cost such that it would be able to be used in several different rooms on campus.

The next section contains a short review of related experiments found in the literature. The facilities and goals of those research studies are described. Finally, the design of the low-cost modular experimental capability being developed at BU will be described.

EXPERIMENTAL TESTING OF HUMAN PERCEPTION OF AND REACTION TO ILFN

Back in 1960, NASA built a low-frequency noise facility. The goal was to generate "intense, chest-pounding sounds of giant Saturn boosters during Apollo launches" (Hallion, 2010, pg. 215). The facility was also used to simulate sonic booms. The facility consisted of a cylindrical test chamber 24 ft in diameter and 21 ft long. An electrohydraulically actuated 14 foot piston produced high amplitude, 1-50 Hz sound waves.

The air force was also concerned about performance of their pilots in the presence of infrasound and they conducted a study at the Aerospace Medical Research Lab (Slarve and Johnson, 1975). They used an electro-hydraulic system to activate a 43 cm diameter piston. They were able to produce 144 dB for 0.5-10 Hz waves and up to 125 dB for 30 Hz waves. They concluded that 144 dB exposures at these low frequencies for periods of time less than 8 minutes were safe. They did not conduct any tests for amplitudes below 120 dB and as such the results are not very relevant to wind turbine noise.

Investigations of human response to ILFN for reasons beyond space and defense missions have been carried out since the 1980's. In 1984, Andresen and Moller presented their equal annoyance contours for the infrasonic range related to human perception. The experiments were conducted at Aarlborg University in Denmark where they have highly specialized acoustic facilities. They produced infrasound in a 16 cubic meter pressure chamber. They used 16 loudspeakers driven by a B&K 2712 amplifier. The loud speakers were behind a screen. Tones in the infrasonic range were used together with a 1000 Hz octave-filtered pink noise (Andresen and Moller, 1984). The annoyance levels in the infrasound range that they found exceed the levels produced by modern wind turbines. Now, researchers at Aarlborg are considering the properties of noise that determine if the low-frequency noise will be particularly annoying. They note this is dependent upon the relative balance between the low and high frequencies.

Landstrom and Bystrom (1984) considered threshold levels for physiological effects of infrasound. In particular, they monitored wakefulness using EEG-analysis, eye movement measurement and pulse monitoring. The tests were done in a pressure chamber. Eight loudspeakers placed on opposite walls of the chamber produced tones with amplitudes above and below the hearing threshold level. B&K microphones were used to measure the signal at the position where the test subject's head would be located. They found that exposure levels above the hearing threshold affected wakefulness, while those below the hearing threshold did not.

Waye and Ohrstrom (2002) used samples from recordings of wind turbines to try to determine if the audible part of the spectrum from a turbines could elicit more annoyance even though it has the same equivalent noise level as another turbine. The study was conducted in a semi-reverberant 4 x 5 m, sound-insulated room with two loudspeakers in the corners at the end of the room opposite the door. The speakers were hidden by a curtain. The sound pressure levels for frequencies below 160 Hz were below the threshold of normal hearing. In the end, none of the psycho-acoustics parameters such as sharpness and loudness were responsible for the differences in annoyance response. Their study also indicated that the "swishing" could be the actual annoying feature as opposed to the low frequency noise.

Physical response to infrasound including changes in respiration, blood pressure, etc. have been considered. A research group in Poland constructed specialized infrasonic cabin for their testing (Damijan and Wiciak, 2005). The cabin had 6 speakers of roughly 12 in diameter mounted on the top. The cabin is roughly 11 ft high, 6 ft wide and 4 ft deep. With their setup they produced 120 dB tones at 7 and 18 Hz. At 120 dB they found instant changes in the EEG. Again these levels are a bit high compared to normal wind turbine signals.

In 2010 researchers at the University of Salford conducted further human subject experiments to ascertain the effect of wind turbine noise (von Hunerbein *et al.*, 2010). They used an ambisonic system with 8 loudspeakers (which is an advanced surround sound system) supplemented with 4 subwoofers. All of the speakers were positioned outside of a circular curtain. The listening room consisted of an inner room floating on a bed of compressed mineral wool. The room was 6.6 x 5.5 x 3 m^3 and the test circle was 4 m in diameter. The emphasis of the work was to determine the sensitivity to low frequency tones from 30 to 400 Hz. They showed that low frequency tones with the same prominence as tones of higher frequency are not more annoying. They showed that sound from small and large wind turbines evoke similar annoyance responses in realistic indoor and outdoor settings.

Currently Tachibana et al. (2012) in Japan are conducting further human subject tests. The lab consists of a reverberation room and anechoic room side-by-side with a wall of 16, 40-cm woofers between the rooms. An additional speaker is located in the middle of the wall. This speaker is used to produce sound above 224 Hz. The listeners sit in the anechoic room which has a volume of 210 m^3. However, the room is not anechoic at the lower frequencies and as such the subject is placed carefully within the room based on room acoustic measurements. As a first step, the hearing threshold levels in the low frequency range were measured. The results support the previously found levels. Now they are using high pass filtered recordings of wind turbines to gauge audibility and annoyance as compared to other sounds.

NEW EXPERIMENTAL CAPABILITY

The threshold for low frequency noise and the perception of low frequency noise associated with wind turbines has been studied as described above. Many of the tests indicate that the main issue with wind turbine noise is not related to the low frequency portion of the spectrum but rather with the higher frequency audible swishing. It is still of interest though to consider whether the ILFN is playing a role in neighbor reaction and in particular if it is perceived by humans in the method that Salt has suggested (Salt and Hullar, 2010). In order to pursue the answer to this question, a method for reproducing the ILFN is needed. The requirements on the design of the system that will be used at Boston University included: 1) it must be built on a very small budget and 2) it must be usable in several different rooms on campus because a final testing facility has not been identified.

The potential facilities for the planned tests are not anechoic in the low frequency range. As such, a low-cost, reliable measurement system must also be designed in order to characterize the final sound field in the room. In this section, both the speaker and measurement system designs are described.

Speaker and Measurement System Design

All of the experimental facilities described in the previous section use some sort of speaker array to produce the ILFN. Following this trend, a speaker array was designed for use at BU. Researchers had access to several 12 in woofers so these were chosen for the design. A simple theoretical calculation using Boyle's Law was performed to determine the potential static pressure level that could be generated in an ideal room. An Ideal room here refers to one in which no structural deflection will occur for pressure changes up to 20 Pascals and in which there are no air leaks and no absorption. Boyle's Law states that pressure times volume will remain constant. A single 12 in diameter speaker displaced 7 mm will create a volume change of 0.00051 m^3. For one of the potential testing rooms with volume 13.5 m^3, following Boyle's Law, the ratio of new volume to original volume leads to a change in pressure of 3.8 Pa. A fluctuation of 3.8 Pa referenced to 20 μPa leads to an SPL (sound pressure level) of 105.5 dB.

A loudspeaker baffle that will fit in a standard 36 by 84 inch commercial door frame was selected. The use of the standard door frame mount will enable various rooms with unique acoustic properties to be tested. Because the baffle will cover access to the room, a small door was included in the baffle. The remaining area was covered with speakers which allowed for the placement of 8 woofers in the end. The selection of 8 speakers ensures the amplitude of the hearing threshold at a frequency of 2 Hz (~ 130 dB) can be achieved and surpassed even when there are losses in the room. The nonsymmetric pattern of placement is viewed positively because it will cut down on the propensity for natural resonances between the speakers. The schematic of the loudspeaker baffle is shown in Figure 1.

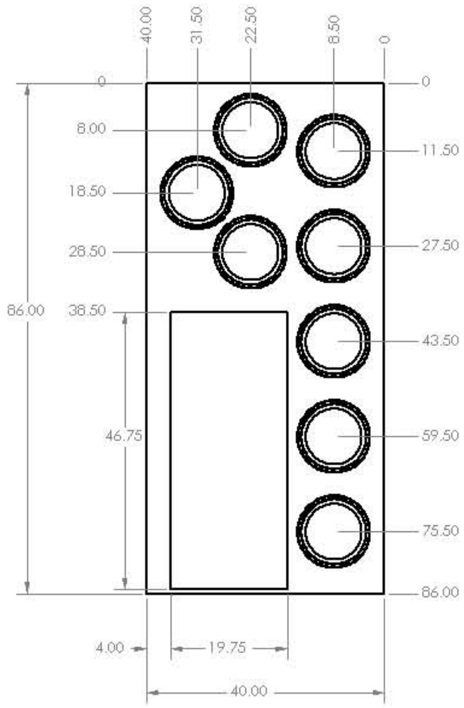

FIGURE 1: Placement of door and woofers in baffle. All lengths are given in units of inches.

As mentioned above, the ideal test room is small in volume and nearly airtight. The small volume and long wavelengths of the infrasound will prevent standing wave formation. However, wall, ceiling and floor bending modes are likely to be present. A Laser Doppler Velocimeter in conjunction with a low frequency microphone will be used to measure structural modes. A suitable room will have a minimum of modes and the experimental stimulus frequencies will be selected to avoid the modes.

The loudspeaker compliance and mass in conjunction with the test room air compliance will likely cause an acoustic resonance to develop. The dimensions of the adjacent room and its air losses will also factor into the frequency response of the system. We propose to flatten the frequency by employing a closed loop control system that senses the pressure near the test subject and corrects for deviations.

The stimulus playback and sound pressure control system will be implemented using a National Instruments data acquisition board in a PC computer. A C++ routine will be used to control the card in real time. There will be controls put in place in the event of loss of stability to prevent subject exposure to high pressure levels. The pressure sensor will be a combination of a Bruel and Kjaer microphone and absolute pressure sensor. Their outputs will be individually conditioned and digitized. The National Instruments DAC output will be filtered by an 8th order butterworth filter to prevent audible noise from being generated by imaging. The loudspeaker array will be driven by a pair of Hafler DH 500 stereo power amplifiers that have been modified for ultra low frequency operation.

The subject will have a keyboard to input their responses to stimuli. The keyboard inputs will be logged in a database along with the stimuli and pressure data. Schematics of the overall control system and the room are given in Figures 2 and 3.

CONCLUSION

A low-cost, mobile, speaker system to produce infrasound and low-frequency noise has been designed and is now built. The accompanying measurement system has also been designed. Once the full waveform generation and data acquisition systems are complete, preliminary tests will be run in two different rooms at BU. The results of these initial tests will be described in the conference presentation. Once the proof of concept is complete, the necessary approvals will be obtained to perform human subject testing. A study is planned that will focus on determining if there are changes in normal hearing when low frequency tones are present. In addition, the study will consider whether changes in normal hearing occur due to low frequency broadband noise such as that produced by a wind turbine.

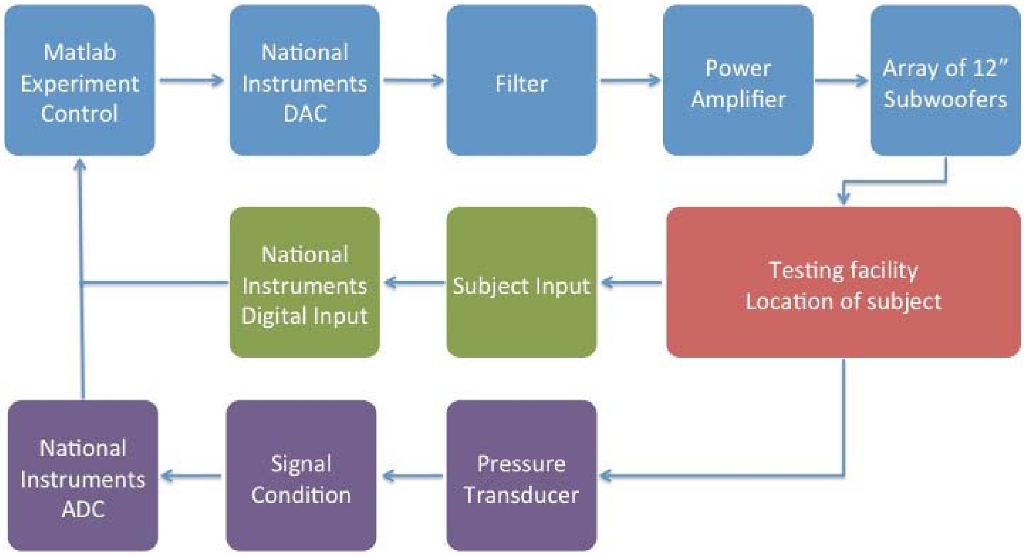

FIGURE 2: Block diagram for acoustic waveform generation and data acquisition.

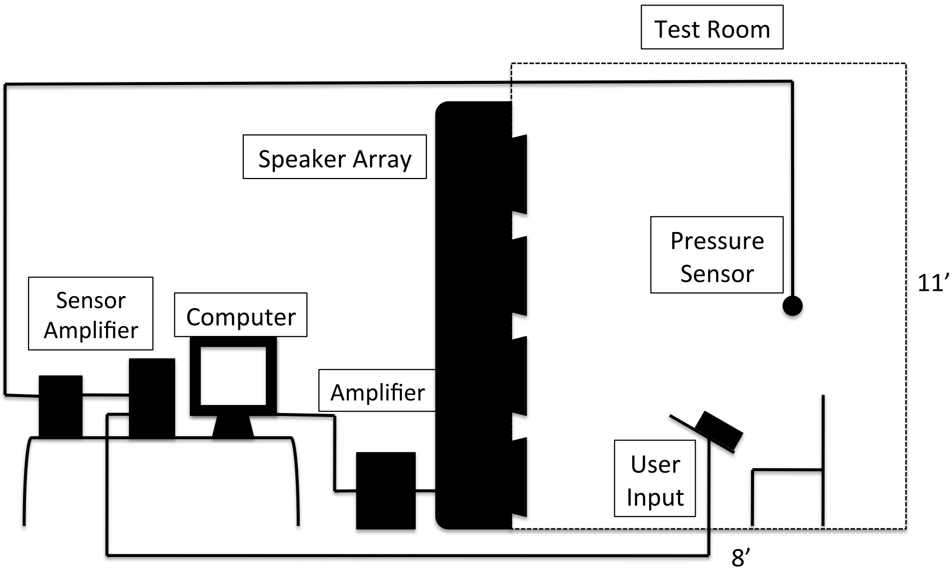

FIGURE 3: Block diagram for acoustic waveform generation and data acquisition.

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