Reducing infrasound and low frequency noise from wind turbine blades and rotors using ANC

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Abstract
The paper constitutes an application of Active Noise Control (ANC) on noise from wind turbine blades and rotors. This study aims at considering the potential of using ANC on wind turbines. To this end, a review was carried out on infrasound and low frequency noise emanating from wind turbines. The basis of human interaction with low frequency noise from wind turbines and its effects are studied, their effects on the environment, past approaches used for their reduction and the potentiality of using ANC. The performance of the system was evaluated by carrying out simulations. The results show that ANC systems are capable of attenuating infrasound and low frequency noise from wind turbines.

Keywords: Active noise control, low frequency noise, infrasound, wind turbines

Introduction
The rapid growth and widespread use of energy from the wind has triggered an increasing concern about the noise it emits and how it affects humans living around it and the environment. Several noise assessments have been carried out to determine the overall sound pressure level and also predictions to determine the various sources of noise. All these are carried out in order to develop technologies for their reduction.

Passive methods work well in reducing high frequency noise but the low frequency noise from the blades cannot be reduced by passive methods; this is because of the large wavelength [1], therefore the need to study the low frequency noise from wind turbines.

This paper focuses on infrasound and low frequency noise emitted from wind turbine rotors and blades and the effect of using Active Noise Control to mitigate it. Low frequency noise can be described as sound which is unwanted and comprising major constituents within an identified frequency range [2]. Extensive research has been carried out on noise reduction using passive methods [3-9], however these methods have worked well in reducing the high frequency components still leaving the infrasonic and low-frequency components a problem. The effects and outcome of low frequency noise are of definite worry not only because of the health and environmental impact but also on the impact it has on the overall efficiency of wind turbines.

Low frequency noise is in the infrasonic and perceptible ranges and has been said to be in the range from about 10Hz-200Hz [10,11], but with range 10Hz-100Hz of most interest [12] and are produced by both rotating and reciprocating machinery. Since atmospheric absorption attenuates high frequencies at a higher rate with distance than lower frequencies, low frequency noise propagates farther and leaves negative effects on individuals residing close to the source. The use of A-weighting was said to be a problem when distinguishing the frequency spectrum of low frequency noise and infrasound from wind turbines because using A-weighting presents the spectrum based on the way humans hear sounds, which completely underestimates the likely influence of infrasonic and low-frequency noise in the ear [13]; infrasound should therefore be measured using G-weighting curve.

Sources and transmission of low frequency wind turbine noise
In a modern horizontal axis wind turbine, the most relevant potential noise sources are trailing edge noise, inflow turbulence noise and tip noise [14,15]. Research on wind turbines have indicated the preponderance of low frequency noise is of increased worry for people who reside in communities where wind turbines have been sited [2]. In the past years, progress has been made on several fronts in the research of wind turbine noise. Most of these studies are experimental and include...
Apart from the blades, low-frequency loading noise can also be generated by machinery, such as helicopter rotors, turbo-machinery, and fans. It was ascertained that swishing is the result of an amplification of broadband noise on wind turbines, which is produced when the rotating blade comes across deficient flow in close proximity to the tower, wakes and sheds from the other blades and wind speed changes. The importance of IT noise is dependent on the structure of the atmospheric turbulence and on the shape of the blades and is triggered by the collaboration of upstream turbulence and the blade and depends on the atmospheric circumstances as shown in Figure 2. IT noise has been studied numerically using synthetic turbulence and Improved Delayed DES (IDDES). The IDDES extension reformulates the length scales so as to resolve part of the boundary layer in unsteady mode. This category of noise is a significant basis of low frequency noise on wind turbines, which is produced when the rotating blade comes across deficient flow in close proximity to the tower, wakes and sheds from the other blades and wind speed changes. Studies by suggested that a key input to the low frequency sound may be the outcome of sudden variation in airflow the blade comes in contact with when it passes the tower however; he explains that this effect hasn’t probably been perceived as significant as the blade passing frequency is considered to be insensitive. The studies also indicate that although infrasound levels from large wind turbines at 20Hz are low and inaudible, they might cause structural elements of buildings to vibrate on the other hand, low frequency inflow turbulence may be capable of being heard by the human ear, it is however loudest at medium to high frequency. Turbulent inflow becomes essential when the length scale of the turbulent eddies is great when compared to the leading predictions [16] and interpretation based on some theoretical considerations (e.g., Amiets, Wigner-Ville spectrum) [17]. Empirical and semi-empirical studies have continued to give insights into the generation and radiation characteristics of wind turbine aerodynamic noise. Some authors have also given an overview of theoretical and computational noise prediction methods. Since wind turbine noise travels faster at night (when temperature transposition is common), it can be concluded that the properties of the ground affects sound propagation, as acoustic impedance changes the reflection-coefficient and phase change at reflection [18]. From his studies, the following sources were depicted for low frequency radiation:

1. Turbulent Inflow noise—this is a form of aerodynamic low-frequency noise that arises when an airfoil encounters an unsteady flow. Large amounts of this noise produce noise at far distances due to its low frequency nature.
2. Blade vortex interaction—this is related effect and a subset of turbulent inflow noise but most unlikely to take place under ideal conditions and also unlikely to be significant compared to more general turbulent-inflow effects.
3. Effect of non-uniform flow—this is a result in changes in angle-of-attack and directivity. When there is a large variation in the angle of attack, the blades can experience stall which tends to increase sound levels through boundary layer growth and vortex shedding.
4. Dynamic stall—also results if the angle-of-attack variation is large and frequent enough and this poses a higher chance to produce more increase in noise level.
5. Noise produced when counter rotating vortices interact. Apart from the blades, low-frequency loading noise can also be generated from the wind turbine rotor, which is as a result of steady loading being applied to the blades while rotating [16]. The lower frequencies are of infrasound nature and it has both broadband and amplitude modulated pattern in rhythm with the blade passing frequency [19] which may be made audible by interference patterns and other propagation effects [18]. This occurs as a result of fluctuating aerodynamic loading and it is one of the main noise sources of rotating machinery, such as helicopter rotors, turbo-machinery, and fans [19]. In a study to examine the aerodynamic noise which was produced by small wind turbines, numerical predictions and measurement indicated that low frequency broadband noise was generated when atmospheric turbulence is ingested into the wind turbine rotor (i.e., turbulence ingestion noise) [16].

A parametric investigation on the estimation and control of aerodynamic noise from wind turbines has been studied and it was concluded that the blade tower interaction is the main source of low frequency noise [18] and this is shown in Figure 1. In this mechanism of noise generation, the rotating blades come across contained flow deficits as a result of the tower wake [21].

Cyclostational spectral analysis was employed to predict and analyze aerodynamic noise generated by wind turbines and it was ascertained that swishing is the result of an amplitude modulation of the broadband aerodynamic noise which occurs at the blade passing frequency [17].

Inflow turbulence (IT) noise is as a result of the interaction between the leading edge of the airfoil and a turbulent inflow [14], this can also be called Leading Edge noise and it depends on the angle of attack, flow speed, shape of the airfoil and radiation direction [6]. Due to its importance, a lot of research has gone into simulation prediction and modelling IT noise in order to study the different phenomena related to it [7,14,22]. The importance of IT noise is dependent on the structure of the atmospheric turbulence and on the shape of the blades and is triggered by the collaboration of upstream turbulence and the blade and depends on the atmospheric circumstances as shown in Figure 2. IT noise has been studied numerically using synthetic turbulence and Improved Delayed DES (IDDES). The IDDES extension reformulates the length scales so as to resolve part of the boundary layer in unsteady mode [23]. This category of noise is a significant basis of low frequency noise on wind turbines, which is produced when the rotating blade comes across deficient flow in close proximity to the tower, wakes and sheds from the other blades and wind speed changes [4]. Studies by suggested that a key input to the low frequency sound may be the outcome of sudden variation in airflow the blade comes in contact with when it passes the tower however; he explains that this effect hasn’t probably been perceived as significant as the blade passing frequency is considered to be insensitive. The studies also indicate that although infrasound levels from large wind turbines at 20Hz are low and inaudible, they might cause structural elements of buildings to vibrate [2] on the other hand, low frequency inflow turbulence may be capable of being heard by the human ear, it is however loudest at medium to high frequency. Turbulent inflow becomes essential when the length scale of the turbulent eddies is great when compared to the leading
edge radius of an airfoil [14].

Studies carried out by [22] proposed an improvement to the adaptation of the analytical model by Amiets theory. One of these proposals was an empirical airfoil thickness correction in the turbulent inflow noise model which included Doppler effects for rotating blades. The model for turbulent inflow noise by [26] is given as:

\[ L_n = 10 \log \left[ \frac{\rho_0 c_0}{\gamma} \frac{\mathcal{L} \Delta L \rho_0^2}{\eta^2 M^2 I_k^3 (1 + k^2)^{2/3}} \right] + 58.4 + 10 \log \left( \frac{K_c}{1 + K_c} \right) \quad (1) \]

Where:
- \( \mathcal{L} \): Turbulence length scale
- \( \Delta L \): Blade segment semi-span
- \( K_c \): Low frequency correction

The dimension of the turbulence length scale (\( \mathcal{L} \)) and the square of the turbulence intensity (\( I^2 \)) is essential in the investigation of IT noise. For WT, the inflow turbulence may be due to atmospheric boundary layer turbulence or wakes from upstream turbine [15,23]. The properties of the incoming turbulence are highly reliant on the characteristics of inflow turbulence. Because the frequency of the radiated sound is given as: \( f = \frac{U}{\lambda} \), the spectrum of inflow turbulence noise is related directly to the spectrum of the incoming turbulence and atmospheric turbulence which is of a natural nature, is expected to cause broadband noise for frequencies up to 1000Hz [15].

Another source of low frequency noise on wind turbine blade is separation stall noise. This occurs when the flow begins to separate from the suction side of the airfoil as a result of increase in the angle of attack and this appears to be radiated from the trailing edge. Even though this source of noise is considered to be of modern pitch-controlled wind turbine, they are a source of low frequency noise radiation from airfoils [15].

**Problems and the negative Impact of low frequency wind turbine noise**

Low frequency noise in wind turbines have obviously received less concern, however they mask higher frequencies, cross greater distances and is has the ability to bring about resonance in human body [2]. Contrary to belief that infrasonic noise and some low-frequency noise are inaudible [2,19], it has been established that hearing doesn't stop at 20Hz, as humans can hear infrasound up to 1Hz [11]. Infrasonic and low-frequency sounds which are perceived as inaudible can influence the function of the human ear as it is likely to have more effect on the structures of the inner ear [13].

The authors went on to state the three main processes prompting the sensitivity of the human ear to low-frequencies. Several researchers have carried out subjective and experimental studies on the outcome of low frequency noise on sleep and work output in humans while sleeping at night and during work hours. This was done to characterize work efficiency and quality [27]. Reviewed the consequence of low frequency noise up to 100Hz on some physiological parameters, performance and subjective complaints, which was validated by carrying out laboratory experiments and field studies related to the threshold of hearing. It was concluded that there was no systematic confirmation for an connotation between A-frequency-weighted sound pressure level and the biological effect, there was also no substantial differences in medical or psycho-social symptoms [28]. There was a distinct dependence on frequency of the hearing threshold in the low frequency range with a steep slope when likened to the middle frequency range.

The consequences of exposure to moderate levels of low-frequency noise and a flat-frequency noise was studied by [29] in which a comparison was made to determine whether low frequency noise could result in performance impairment during work. The tasks carried out were picked to be sensitive to exhaustion and enthusiasm. Pearson's correlation Analysis was implemented to ascertain relationships between the following: performance results, subjective reports and subjective sensitivity while also analyzing the correlation between cortisol levels and the stress and energy reported. At the end of the study, a connection was found between motivation and concentration for the noise conditions studied. Noise irritation as a result of low frequency was the positively correlated to absence of attentiveness, fatigue and eardrum pressure which led to an overall rise in annoyance, while these relationships were not found for the flat-frequency noise condition. A conclusion was reached that low frequency noise had an undesirable effect on monotonous and routine type character which resulted in tiredness and routine type character.

A study by [30] investigates the influence of adding another sound to Low frequency noise. Paired comparison test was used to evaluate the combination of Low frequency noise with pink noise; Frequency modulated pure tones and Natural sounds. The Bradley-Terry model was used to obtain the subjective annoyance value (SAV). The psychoacoustic annoyance value (PAV) was also calculated and its correlation with SAV analyzed. When pink noise of 250-1000Hz was added to the LFN, the SAV declined, and then ascended linearly. When
natural sound and FM sounds was added, the SAV increases with increasing SPL of the combined sound. The studies suggested there was a preferable correlation between the SAV and the fluctuation extent of FM pure tones.

The amplitude modulation frequency of a 31.5Hz tone and the balance of high and low frequencies in a Low frequency noise were interactively varied with the objective to create a more pleasant or less unpleasant LFN using subjects who were allowed to adjust the LFN to their desired levels [10]. The results advocated that a higher or lower modulation frequency as opposed to the original LFN. The combination of a low frequency noise with both a pleasant frequency balance was rated as less needed to be changed and as somewhat less annoying.

Turbines in a wind park experience a wind that is more constant over greater distances and they may cause structural elements of buildings to vibrate [2,25]. The World Health Organization (WHO) recognizes the special place of low frequency noise as an environmental problem and the annoyance associated with it originates from acoustical signals which are not compatible with, or which disturbs these psychological functions [12]. The results of the study carried out on mental performance by [31], indicates that low-frequency noise at moderate levels might adversely affect visual functions, concentration, continuous and selective attention.

### Low frequency noise reduction procedure

Results from studies conducted by [22] shows that increase in airfoil leads to a reduction in turbulent inflow noise, however, the thickness correction did not seem significant when the atmospheric turbulent length scale is very large.

Passive control methods also rely heavily on structural resonance; membranes and plates have been used in many cases and their main effects have been the mass required to achieve such low frequency resonance [32].

Active control should be considered as a viable option since it requires little space to be installed and is effective in the low frequency range [33]. Modern active noise control is generally achieved through the use of analog circuits or digital signal processing. Adaptive algorithms are designed to analyze the waveform of the background aural or non-aural noise, then based on the specific algorithm, generates a signal that will either phase shift or invert the polarity of the original signal. This inverted signal is then amplified and a transducer creates a sound wave directly proportional to the amplitude of the original waveform, creating destructive interference. This effectively reduces the volume of the perceivable noise.

### Past research and works carried out on active noise control systems and its potentiality

An important reason why active noise control is more important than passive noise control at low frequencies [34,35] is that ANC uses a digital signal processing (DSP) system as the canceler, which can execute complicated mathematical operations with enough speed and precision in real time [36]. An in-depth review of the various ANC systems in the last seven and half decades was carried out by [38] with emphasis on non-linear techniques. ANC systems have the advantage of being small, compact, environmentally adjustable, and they are cost effective [39]. The success of an ANC system depends mainly on fulfilling two main criteria: the anti-noise waveform must closely match the shape and frequency of the noise waveform and the wave must be precisely 180° out of phase with respect to the original noise waveform, when reached to the target area [39,54], or else a second acoustic noise is generated. For a highly effective cancelling system, the source of noise must be nearly stationary in relation to the speaker emitting the anti-noise waveform; secondly, the noise source should be located very close to the ANC system and for the best result, the target noise should be dominantly radiating in one direction [39].

ANC systems can be broadly classified into feed-forward and feedback control [38], or a combination of hybrid ANC [40,41]. Depending on the noise signal and environmental characteristics, they both have their advantage and disadvantages [41,42].

An ANC has to be adaptive due to environmental changes, system component degradation and noise source alteration [42], and are generally designed on the basis of a mathematical description and its linearized model [42]. Acoustic delay is also a factor that must be sufficiently dealt with in a noise cancelling system [39].

In this paper, a single-channel feed-forward ANC system with one reference microphone and one error microphone will be used.

The applications of ANC is seen in a high-speed elevator in which various transfer paths of noise are transmitted from motor and rope to cabin interior. A model of multiple-input and single-output (MISO) with respect to transfer paths of a high-speed elevator on conditions of stationary and driving states was built. A modified algorithm was developed and applied to the elevator system in order to improve the active noise control performance. A noise reduction of 8dB was achieved in the cabin at ear level [43].

ANC was also applied to impulsive noise which occurs in channels which suffer from switching, manual interruptions, ignition noise and lightning, for example Digital Subscriber Line systems (DSL) and digital TV [44], and the focus of the author was on removing additive impulsive noise from a lowpass signal. An iterative method where the initial detection of the impulsive noise locations is performed using an adaptive threshold-holding technique [45].

An investigation on the effect of using an ANC system on a radial fan was carried out by [35]. Sound levels at different positions were measured and a suitable position was selected. Their investigations included power spectral density measurements, sound pressure level measurements and octave band measurements. A single channel feed-forward ANC system
was used and effective on the studied ventilation system using duct with an airflow speed of 4-5m/s, noise reductions between 20-30dB for the tonal components and 5-10dB for broadband noise in the frequency range of around 100Hz and around 200Hz was achieved.

The control noise from cooling fans of engines in free-field was studied by [49], the study constituted the use of A single-input single-output (SISO) adaptive feed-forward controller. The validity of the model of fan noise that was used for the study existed only when the greatest radiating modal constituent of the flow is taken into account. The performance of the system was assessed through the use of global control metrics. The results showed the capability of the ANC system to meaningfully decrease the BPF and its initial harmonics in free field and noise was attenuated by up to 28 and 18dB.

Hybrid passive-active approach which has been used for noise reduction in fan noise placed in ducts was studied by [48], using a characteristic adaptive feed-forward control. The types of reference sensors used are: microphone infra-red device. In other to match their efficiency, one reference device was used at a time. Using the infra-red as a reference device disregarded the short-comings of acoustic feedback and guaranteed the stability of the system. The aerodynamic pressure utilized by fan blades can be broken down into an axial component (z) and a circumferential component based on thrust and drag respectively (Figure 3).

The time Fourier series is given by [46] as:

\[
f_z(t; r_1, \phi_1) = \sum_{n=-\infty}^{\infty} A_n \left( \tau_1 \right) e^{-i\omega_0 n (t - \frac{z}{c})} = f_z^a(\tau_1) \sum_{n=-\infty}^{\infty} A_n \left( \tau_1 \right) e^{i\theta_n} e^{-i\omega_0 n} \tag{2}\]

Where:
- \(f_z\) Axial pressure component acting on the rotor
- \(t\) Time [s]
- \(r_1, \phi_1\) Polar co-ordinates of the rotor plane
- \(A_n\) Acoustic area [m²]
- \(r\) Radial elements
- \(\phi\) Radial components
- \(\Omega\) Angular velocity of rotor [rad/s]
- \(f_z^a\) Circumferential average value of \(f_z\)
- \(N\) Number of blades
- \(\alpha\) Time Fourier coefficient
- \(\omega\) Blade passage angular frequency

Conclusions were then reached that the broadband component of fan noise can be lessened by using passive control and the high level of low frequency discrete fan noise can be globally attenuated by using ANC. An overall noise reduction of about 6dB was achieved.

The reduction of tonal noise from large-diameter spray dryer exhaust stacks was carried out by [50], using sufficient in-duct control sources and error sensors. The effect of location of the error sensors on the active control of tonal noise was evaluated by locating the control speakers optimally. The use of experiments showed that ANC can always provide cancellation at the error sensor location. When the error sensors are optimally located, the far-field noise is also reduced as a consequence of minimization of the sound field at the error sensor location. The results showed that the tonal noise emitted from the exhaust stack was reduced almost to the background noise level using the optimized ANC system.

Investigation for turbofan engine noise using ANC was carried out by [51] where a special fan rig called “Advanced noise control fan” was built and used in a wide range of experiment. The actuators to carry out the noise control were mounted in fan duct walls and inside stator vanes. Tests carried out have shown single and multiple duct mode cancellation from the inlet and exhaust of the fan duct. The author went on to state that he saw lesser need to concentrate on Active Noise Control of Turbofan engine noise because newer engine cycles are becoming less tone dominant except they are methods for reducing broadband noise.

[52] researched the use of Active Noise Control used to reduce noise in a discrete-frequency axial flow fan. Here the fan itself is used as the source of the anti-noise. This was achieved by driving the entire fan unit axially with an electro-dynamic shaker, which converts the fan into a crude loudspeaker. A Feed-forward FXLMS algorithm was used and an excellent global noise reduction was achieved. The fundamental blade-passage frequency sound pressure level at the location of the error sensor is reduced by 20dB while the second and third harmonic levels are reduced by 15dB and 8dB respectively. A simplified block diagram of an ANC system is shown in Figure 4.

**Methods**

An FXLMS feed-forward control system was used for this study. It involves a set-up in which the source for the disturbance can be sensed beforehand and used as a reference for control signal generation [52] which leads to the removal of the non-zero restriction on the error signal [53]. Many of the electronic systems used in feed-forward control systems derive control inputs via modified adaptive signal processing/ architecture combinations. Adaptive signal processing is a field which developed due to modern telecommunications systems requirements, where signal filtering is essential and needful, thereby extracting it from contaminating noise. In this context, a digital signal processor will be employed to
filter the background surrounding noise from the wind turbine noise. Feed-forward control system is made up of two parts, the ‘physical’ control system (actuators and sensors) and the ‘electronic’ control system [53], and it was further explained that the feed-forward modifies the zeroes of the system in which it is being applied. The equations of motion for a case in which the control input is introduced to cancel out a primary noise or disturbance is given as:

\[ x(t) = Ax(t) + bu(t) + w(t) \]
\[ y(t) = c(t) \]

Where \( w(t) \) is an \((n \times 1)\) primary disturbance vector and it is equal to \((which is the transfer function between the input sinusoid r(t) and w(t))\) given as:

\[ w(t) = mr(t) \]

If the feed-forward control input’s objective is to cancel the primary disturbance at the error sensor, it can be shown that:

\[ c[mr(t) + Nb(t)] = 0 \]

Substituting for Eq. (5) into Eq. (4), and representing the result in frequency domain, output between the output \( y \) and reference signal \( r \) is:

\[ \frac{y(s)}{r(s)} = c(sI - A)^{-1}(Nb + m)r(s) \]

From Eq. 5, it follows that:

\[ \frac{y(s)}{r(s)} = 0 \]

This shows that the controller for a feed-forward system places zero transmission at the reference signal frequency.

The feed-forward ANC structure is able to handle both narrowband noise and broadband noise, but the hybrid structure presented by [41], which consists of a feed-forward structure, was used to estimate the noise path and a feedback structure used to cancel the feed-back acoustic noise.

**Determination of the masking noise levels \( L_{pn,IT} \)**

The 12 sound pressure levels of the masking noise \( L_{pn} \), according to Swift-Hook (1989) are defined as follows:

\[ L_{pn} = L_{pn,avg} + 10 \log \left[ \frac{\text{critical bandwidth}}{\text{effective noise bandwidth}} \right] \]

Where: \( L_{pn,avg} \) is the energy average of the spectral lines identified as masking.

**Determination of the tonality \( \Delta L_{tn} \)**

The tonality \( \Delta L_{tn} \) is the difference between the sound pressure level \( L_{pt} \) and the level \( L_{pn} \), the 12 \( \Delta L_{tn} \) are then energy averaged to one \( \Delta L_{tn} \).

**Declaration of sound power level, sound pressure level and tonality levels of wind turbines**

The sound power level of a source, \( L_w \), in units of decibels (dB) is given by:

\[ L_w = 10 \log_{10} \left( \frac{P}{P_0} \right) \]

With \( P \) equal to the sound power of the source and \( P_0 \), a reference sound power (usually \( 10^{-12} \) Watts).

The declared sound power levels for a wind turbine can be determined from \( n \) measurements results \( \{L_i\} = \{L_i\} \) obtained by performing one measurement at each of \( n \) individual turbines of the same type. The \( n \) measurements results in a mean value \( L_w \) and a standard deviation \( s \) is defined as follows:

\[ L_w = \frac{1}{n} \sum_{i=1}^{n} L_i \]  
\[ S = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (L_i - L_w)^2} \]

The standard deviation of production can be estimated from:

\[ \sqrt{(s^2 - \sigma_p^2)} \leq \sigma_p \leq s \]

An estimate of the standard deviation of reproducibility \( \sigma_p \) is 0.9dB [56].

The standard deviation used for the declaration (including the standard deviation \( \sigma_p \) and \( \sigma_p \)) from the \( n \) existing measurements and the standard deviation and of verification measurement is then determined by:

\[ \sigma = \sqrt{\frac{1}{n} \left( \sigma_p^2 + \sigma_p^2 \right)} \]
\[
\sigma = \sqrt{\frac{1}{n} \left( \sigma_x^2 + \sigma_p^2 \right)}
\]  
(14)

With \( \sigma = 0.9 \text{dB} \) and \( \sigma_p = s \)

The declared sound power level is calculated from:

\[
L_{w_{\text{d}}} = L_w + k = L_w + 1.645 \sigma
\]

(15)

The sound power level shall be declared by dual power noise-emission values reporting both \( L_w \) and \( k \). \( k \) represents a certain confidence level and \( k = 1.645 \). \( \sigma \) represents a probability of 5\% that a sound power level measurement result made according to (IEC 61400) performed at a turbine of the batch exceeds the declared value.

Sound level meters are the instruments used to measure Sound Pressure Levels. They are recorded on a meter and make use of a microphone that converts pressure variations into a voltage signal [4]. The sound pressure level (SPL) of a noise, \( L_p \), in units of decibels (dB), is given by:

\[
L_p = 20 \log_{10} \left( \frac{P}{P_0} \right)
\]

(16)

With \( p \) equal to the effective (or root mean square, rms) sound pressure and \( P_0 \) a reference rms sound pressure (usually 20\times10^{-5}).

Broadband energy is created by the interaction of turbulence with the leading and trailing edges. Turbulence leading-edge interaction noise is dominated by the spectrum of the inflow turbulence in the atmospheric boundary layer. The peak energy for this type of noise is contained at a frequency. The frequency of the peak energy is given as [36]:

\[
f_{\text{peak}} = \frac{StV_{\text{tip}}}{h - 0.7R}
\]

(17)

With:
- \( St \): hub height (m)
- \( V_{\text{tip}} \): rotor tip speed (rpm)
- \( R \): blade radius (m)

And the first order Blade Tower Interaction (BTI) interaction noise source strength is given as [37]:

\[
\frac{LD_T}{V_{\text{tip}} q_{\text{cl}}} = 2\pi \alpha \frac{D_T}{V_{\text{tip}}}
\]

(18)

Where:
- \( L \): Time derivative of lift
- \( D_T \): Tower diameter (m)
- \( q \): Dynamic pressure of the flow approaching the blade tip (N/m²)
- \( c \): Blade chord
- \( L \): Span wise region of the blade
- \( \alpha \): Time derivative of the blade angle of attack

The anti-noise signal made by the adaptive filter should pass through several compartments such as the D/A converter, reconstruction filter, amplifier and speaker. As this signal will be sampled by the error microphone, it has to pass again through an acoustic path from speaker to the error microphone, anti-aliasing filter, pre-amplifier and A/D to be received by the controller. This indicates how much the secondary path is important. The secondary path is measured by a sensor or microphone placed in the path to measure the impulse response.

The filter coefficients which describe the impulse response of the secondary path from the controller to the error microphone are shown in Figure 5. The accuracy of the secondary path impulse response is given in Figure 6. The plot shows the coefficients of both the true and estimated path. The residual error does not significantly harm the performance of the system during operation.

**Results**

The performance of FxLMS algorithm in reducing low frequency and infrasound noise from wind turbines is given in...
this section. The sampling frequency used is 44.1KHz and a low-pass filter with a cut off frequency of 200Hz was used to filter out high frequency components leaving behind the low-frequency noise. The reference signal is noise measured from an 80m high, 850KW Wind turbine and at a wind speed of about 5-6m/s.

The simulation combines the noise generator, the FXLMS filter and a primary path filter. The simulation was done in three stages:

1. Importing of the noise into MATLAB workspace
2. Processing of the noise through a primary filter
3. Processing the output through an FXLMS filter

The frequency-domain representation of the signal which shows its magnitude and phase at each frequency is shown. The wind turbine noise is given in Figure 7 while the magnitude and phase response of the low frequency noise spectrum which shows the magnitude and phase is plotted in Figure 8. The magnitude response shows the strength of the frequency components while the phase shows how all the frequency components align in time.

The secondary propagation path is the route the noise produced the secondary loudspeaker takes to get to the error microphone. A secondary propagation path generated for 0.1seconds is shown in Figure 9 and the primary path impulse response in Figure 10, while Figure 11 shows a plot of the original and attenuated noise in the time domain.

The power spectrum of the signal gives a plot of the portion of the signals power or energy per unit time with 200Hz. Figures 12 and 13 shows the power spectrum with and without ANC. A reduction of about 10dB can be seen from Figure 13 which was measured at the error microphone. The error microphone measures the extent to which noise is reduced at the receiver position.

**Conclusions**

A brief review on wind turbine low frequency noise and
infrasound has been carried out. This was done because low frequency noise and infrasound has been found to be the major source of annoyance to people living close to wind turbines.

Various sources of the noise have also been studied. Using Active Noise Control has shown to be an efficient method in attenuating low frequency noise from wind turbines blades and rotors. The simulated cancellation result is obvious, and the system reacts very fast to this simulated noise, however there was an observed delay which is as a result in complexities from the reference noise.

This is a simulated work and future work will focus more on building the real-life model. This approach can be used on wind turbine blades for reducing low frequency noise and infrasound being emitted from wind turbine blades and rotors, and it can also be used for reducing noise in fans radiating in free field.

Competing interests
The authors declare that they have no competing interests.

Authors’ contributions

| Authors’ contributions | GA | LTEN | FI |
|------------------------|----|------|----|
| Research concept and design | ✓ | -- | -- |
| Collection and/or assembly of data | ✓ | -- | -- |
| Data analysis and interpretation | ✓ | -- | -- |
| Writing the article | ✓ | -- | -- |
| Critical revision of the article | -- | ✓ | ✓ |
| Final approval of article | -- | ✓ | ✓ |
| Statistical analysis | ✓ | -- | -- |

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