# Comparison of Sound Power Prediction Models of Wind Turbines

Eman Zidan, Tamer Elnady, and Adel Elsabbagh

***Abstract*----**Noise of the turbines is a major consideration in determining the acceptance of a wind farm planning application. In this study, the wind turbine noise sources are presented and discussed with the different noise prediction models. The technical characteristics of the turbine model used in this study are defined and used as the input data for the different models. The resulted values from the models have been investigated and an approach for predicting the sound power of wind turbines is proposed in this paper. The results show that the used model should be decided according to the parameter inputs available for the turbine model and also according to the accuracy level needed for the study.

***Keywords*—**Acoustics, Aerodynamics noise sources, Noise modeling, wind turbine.

## I. Introduction

RENEWABLE energy comes from natural resources such as sunlight, wind, rain, and geothermal heat, which are renewable. Globally, the long-term technical potential of wind energy is believed to be five times total current global energy production. Wind turbines can be a great way to utilize the wind energy to convert it into usable electricity. This could require wind turbines to be installed over large areas, particularly in areas of higher wind resources. Utilizing the winds energy with a wind turbine can provide a source of clean and renewable electricity for large or small communities. Wind turbines can be installed as single installations or as part of a wind farm. Some wind farms are capable of providing the entire electricity supply for large villages or small towns and are most effective on high ground where the wind speed is generally higher and more constant than at lower levels.

The purpose of this study is to develop an approach of calculating the sound power emitted by wind turbine blades. This is done through studying the different sources of noise in wind turbines and the models predicting their sound power. This will help urban planners assess the noise impact of new wind farms.

In this study, different wind turbine noise types are defined, and their predictive prediction methodologies and their input parameters are introduced.

Eman Zidan from the Group for Advanced Research in Dynamic Systems (ASU-GARDS), ASU Sound & Vibration Lab, Faculty of Engineering, Ain Shams University, Cairo, Egypt (phone: +20 122 6687374; e-mail: eman.zidan@eng.asu.edu.eg)

Tamer Elnady from the Group for Advanced Research in Dynamic Systems (ASU-GARDS), ASU Sound & Vibration Lab, Faculty of Engineering, Ain Shams University, Cairo, Egypt. (phone: +20 122 3101116; e-mail: tamer.elnady@eng.asu.edu.eg)

Adel Elsabbagh from the Group for Advanced Research in Dynamic Systems (ASU-GARDS), ASU Sound & Vibration Lab, Faculty of Engineering, Ain Shams University, Cairo, Egypt. (phone: +20 100 9205975; e-mail: aelsabbagh@eng.asu.edu.eg)

## II. Noise Sources of Wind Turbines

The noise emitted from wind turbines can be classified to two types of sources: Mechanical noise which is generated from the relative motion of the machinery components of the turbine, and aerodynamic noise which is caused by the air flow around the blades.

### A. Mechanical noise

The main sources of the mechanical noise are mainly the gearbox and generator. The noise emitted from gearbox is structure-borne and air-borne noise, while the noise of the generator is considered only air-borne noise. This is beside the noise emitted from the hub, the rotor and the tower which can transmit the machinery noise.

Table 1 represents the Contribution of individual components to the total sound power level of a 2MW wind turbine which reported by Pinder [1].

TABLE I

Sound Power Levels of Mechanical Noise of a 2MW Experimental [1]

| Element | Sound power level (dB(A)) | Air-borne or structure-borne |
|---|---|---|
| Gearbox | 97.2 | Structure-borne |
| Gearbox | 84.2 | Air-borne |
| Generator | 87.2 | Air-borne |
| Hub(from gearbox) | 89.2 | Structure-borne |
| Blades(from gearbox) | 91.2 | Structure-borne |
| Tower(from gearbox) | 71.2 | Structure-borne |
| Auxiliaries | 76.2 | Air-borne |

### B. Aerodynamic noise

The wind turbine aerodynamic noise is very important to be investigated because of its high emission levels in addition to the difficulty of its control compare with the mechanical noise. The aerodynamic noise can be classified to three types of sources:

1. Low-Frequency Noise, caused by the wind speed change passing through the blades with the tower presence. The most common designs of wind turbines nowadays are upwind designed which has a reduced effect from the tower compare with the downwind type. The low frequency noise becomes not an important noise source when the A-weighting filer is applied to it.

http://dx.doi.org/10.15242/IICBE.C1014154

2. Turbulent Inflow Noise, caused by the atmospheric turbulence and the interacting of the turbulent air with the turbine blades. The characteristics of this noise depend on the atmospheric boundary layer characteristics.

3. Airfoil Self Noise, occurs even if there is no turbulence flow, this noise is caused by the interacting of the air flow with the airfoil surface. The airfoil self noise has a broadband nature and it has different noise mechanisms which are: Turbulent boundary layer trailing edge noise, laminar boundary layer vortex shedding noise, tip vortex formation noise, and trailing edge bluntness vortex shedding noise

## III. Noise prediction models of wind turbines

The wind turbine mechanical noise can be reduced by some simple mitigation measures such as using quitter gearbox, periodic maintenance, changing of some mechanical parts which can affect the emitted noise. That’s why the mechanical noise has been neglected in this study and only the aerodynamics has been considered and investigated.

This section investigates some noise prediction models of the different aerodynamic noise types illustrating the required parameters for each model and how each model can be implemented. Some of the prediction models are simple rules of thumb for the overall levels, and some require complicated inputs and produce the whole frequency range. The different prediction models have been classified according to Lowson [2] into three classes.

TABLE II
Classifications of the noise prediction codes according to Lowson [2]

| Type of code | Description |
|---|---|
| Class I | Predictions giving an estimate of overall level as a simple algebraic function of basic wind turbine parameters |
| Class II | Predictions based on separate consideration of the various mechanisms causing wind turbine noise, using selected wind turbine parameters |
| Class III | Predictions utilizing complete information about the noise mechanisms related to a detailed description of the rotor geometry, and aerodynamics |

Class I models are rules of thumb giving the overall Sound power/pressure levels. These models require simple input parameters, such as rotor diameter, power, and wind speed. Class II models estimate the sound pressure level in a frequency broadband and it requires more complicated input parameters. Class III models includes more refined models describing the noise mechanisms. Up to now, no models of this type have been available for implementation.

### A. Class I noise prediction Models

There are four models for wind turbine noise prediction that can be classified as class I category.

1. Lowson model [2]: Equation (1) has been developed by Lowson as a very simple method to obtain the overall sound power level with simple input parameters.

$$L_{wA} = 10\log_{10} P\mathrm{wT} + 50 \qquad (1)$$

Only one parameter is required as an input for this model which is the rated power of the wind turbine ($PwT$) in Watts.

2. Hau model [3]: Equation (2) is another sound power prediction formula developed by Hau.

$$L_{wA} = 22\log_{10} D + 72 \qquad (2)$$

This model requires only the rotor diameter as an input.

3. Hagg model [4]: Equation (3) is developed by Hagg taking into consideration one more important parameter which is the tip speed at rotor blade ($V_{Tip}$) in m/s.

$$L_{wA} = 50\log_{10} V_{Tip} + 10\log_{10} D - 4 \qquad (3)$$

4. Another model is developed by Hagg [5] taking into consideration more parameters of the turbine characteristics

$$L_{pA} = C_1 \log_{10} V_{Tip} + C_2 \log_{10}(n_B \frac{A_b}{A_r}) + C_3 \log_{10} C_T + C_4 \log_{10} \frac{D}{r} - C_5 \log_{10} D - C_6 \qquad (4)$$

This model has been developed to estimate the overall sound pressure level at a certain distance ($L_{pA}$). The parameters required for this model are the number of blades ($n_B$), blade area ($A_b$), rotor area ($A_r$), axial force coefficient ($C_T$), rotor diameter ($D$), the distance between the rotor hub and the observer ($r$), and a few constants ($C_1$-$C_6$). The values of these constants are listed in the next section.

5. Models introduced by noise propagation software based on real measurements. Many noise propagation software have a sound emission libraries that provides a pre-measured Sound power levels for different type of sources, the library provides a selection of wind turbine types with specific parameters and their overall sound power levels based on actual measurements, these models can be used as a reference for the estimated sound power levels of different wind turbines if the basic geometric parameters are known. Table 3 shows the different models provided by SoundPLAN software for some wind turbine types at wind speed of 8 m/sec.

TABLE III
SWL of different wind turbine models based on actual Measurements

| Wind Turbine Model | dB(A) | Power (kW) | Hub Height (m) | Rotor Diameter (m) |
|---|---|---|---|---|
| AN Bonus 600 kW/41 | 101.6 | 600 | 50 | 41 |
| DeWind 41 | 99.6 | 500 | 40 | 41 |
| DeWind 46 | 97.9 | 600 | 40 | 46 |
| Enercon E-41 | 99 | 500 | 50 | 41 |
| Euroturbine ET 550/41 | 103.5 | 550 | 42 | 41.5 |
| Husumer Schiffswerft HSW 250 T | 103.5 | 250 | 50 | 28.5 |
| Jacobs Energie GmbH 37/500 | 103.5 | 500 | 40 | 37.5 |
| NEG Micon M 700-225/40 kW | 101.1 | 225 | 36 | 28.8 |
| NEG Micon M 750-400/100 kW | 103.6 | 400 | 53 | 39 |
| NORDEX N29/250 kW | 102.2 | 250 | 50 | 42 |
| NORDTANK 500/41 | 103.2 | 500 | 50 | 41 |
| SEEWIND 52-750-65 | 99 | 750 | 55 | 52 |
| VESTAS V 66/1.65 MW | 103 | 1650 | 60 | 66 |
| Windtechnik-Nord 200/26 | 101 | 200 | 40 | 26 |

*B. Class II noise prediction Models*

In the following models, the turbine blade is divided into segments, each segment has its own chord, span, angle of attack, free stream velocity, and hence each segment has its own contribution on the total sound level emitted. The sound levels of the different blade segments have to be summed producing the sound pressure level of every noise source. The number of blade segments is decided according to the change of the blade geometry along the span.

1. Brooks, Pope, Marcolini (BPM) Model [6]

BPM model studies the airfoil self-noise sources individually. The application of the codes requires noise contributions from all the blade segments to be considered. The codes of the different noise sources are discussed in the following discussion.

The Turbulent Boundary Layer Trailing Edge (TBL-TE) noise has a broad band frequency spectrum; the sound pressure levels are directly proportional to the Reynold numbers. Equation (5) is the main formula for the total sound pressure level of the pressure side, and the same equation will be applied for the suction side with the suction side parameters.

$$\left(L_p\right)_p = 10\log\left(\frac{\delta_p M^5 L D_h}{r_e^{\,2}}\right) + A\left(\frac{St_p}{St_1}\right) + \left(K1-3\right) + \ K_1 \qquad (5)$$

Where $\delta_p$ is the boundary layer displacement thickness of the pressure side which is function in the Reynolds number and the angle of attack, there is a boundary layer thickness value for every segment because of the chord and the velocity change along the span, and hence the Reynolds number varies at each segment, $\alpha$ is the angle of attack which is also varying from point to another along the span, $Re_c$ is the Reynolds number based on chord, $M = U/c_a$ is the Mach number which varies with free stream velocity at each chord, $c_a$ is the speed of sound, $L$ is the length of the segment span, $D_h$ is the directivity, $r_e$ is the observer distance.

$A$ is the frequency spectrum shape which is the responsible factor for obtaining the results in frequency range, $St_p = \left(f\delta_p\right)/U$ is the Strouhal number based on the displacement thickness, $f$ is the frequency, $St_1 = 0.02M^{-0.6}$ and $K_1 = K_1(\Re_c)$.

An equivalent expression is developed for the suction side.

$$SPL_s = 10\log\left(\frac{\delta_S M^5 L D_h}{r_e^{\,2}}\right) + A\left(\frac{St_S}{St_1}\right) + \left(K1-3\right) \qquad (6)$$

Where $(L_p)_s$ is the sound pressure level from the suction side. The total sound pressure level from turbulent trailing edge noise is then found from:

$$\left(L_p\right)_{TBL-TE} = 10\log\left(10^{\left(L_p\right)_\alpha/10} + 10^{\left(L_p\right)_s/10} + 10^{\left(L_p\right)_p/10}\right) \qquad (7)$$

$(L_p)_a$ is the sound pressure level when the angle of attack is not equal to zero

$$SPL_\alpha = 10\log\left(\frac{\delta_S M^5 L D_l}{r_e^{\,2}}\right) + B\left(\frac{St_S}{St_2}\right) + K_2 \qquad (8)$$

Equations (7) & (8) are used when angle of attack $\leq 12.5^o$. At attack angles above $12.5^o$, equation (9) is used:

$$SPL_\alpha = 10\log\left(\frac{\delta_S M^5 L D_l}{r_e^{\,2}}\right) + A'\left(\frac{St_S}{St_2}\right) + K_2 \qquad (9)$$

Where A' is the curve A with a value of $Re_c$ equals three times the actual value, and in this case $SPL_s$ & $SPL$ will equal $-\infty$. $K_1$ and $K_2$ are the amplitude functions where $K_2$ is function of Mach number and $K_1$. The laminar boundary layer vortex shedding (LBL-VS) noise can be calculated from

$$\left(L_P\right)_{LBL-VS} = 10\log\left(\frac{\delta_p M^5 L D_h}{r_e^{\,2}}\right) + G_1\left(\frac{St'}{St'_{peak}}\right) + G_2\left(\frac{\Re_c}{\left(\Re_c\right)_o}\right) + G_3(\alpha) \qquad (10)$$

The first term in equation (10) is the same of the previous code which was for the turbulent boundary layer trailing edge noise. $G_1$, $G_2$, and $G_3$ are the spectral shape functions. For $G_1$, *St'* is the Strouhal number, $St'_{peak} = St'_{peak}(\alpha)$ is the peak Strouhal number and function of the angle of attack. For $G_2$, $\left(\Re_c\right)_o = \left(\Re_c\right)_o(\alpha)$ is the is the reference Reynolds number and it is calculated from the angle of attack. $G_3$ needs only the angle of attack values.

The Trailing Edge Bluntness Vortex Shedding (TEB-VS) noise depends on the shape and thickness of the airfoil's trailing edge. Only in the cases of large trailing edge thickness, this source can be dominant in the overall noise. So there is a trend to use smoother sharp trailing edges wind turbine blades to reduce noise levels. Equation (11) is the main formula for this model.

$$\left(L_P\right)_{TEB-VS} = 10\log\left(\frac{hM^{5.5} L D_h}{r_e^{\,2}}\right) + G_4\left(\frac{h}{\delta_{\ avg}}, \Psi\right) + G_5\left(\frac{h}{\delta_{\ avg}}, \Psi, \frac{St'''}{St'''_{peak}}\right) \qquad (11)$$

The new parameters here in this model are $h$ which is defined as the trailing edge gab or the trailing edge thickness, the expression that usually used to define this parameter is $h/c$ which is the ratio between the TE thickness and the chord length, $\delta_{avg}$ is the average displacement thickness for the suction and pressure side, $\Psi$ is the solid angle between the sloping surfaces upstream of the trailing edge or it can be called the trailing edge angle. $G_4$ is the peak level spectrum and $G_5$ is the shape of the spectrum. $G_4$ is function of the thickness ratio $St = h/\delta$ and the trailing edge angle $\Psi$. $G_5$ is function of the same parameters of $G_4$ in addition to the Strouhal number and the peak Strouhal number.

The Strouhal number is defined by the TE thickness instead of the boundary layer thickness parameter that was used in the previous codes $St = fh/U$. The peak Strouhal number is function of the trailing edge angle and the thickness ration and it varies according to the thickness ratio value.

The Tip Vortex Formation (TIP-VF) Noise is caused by the interaction between the tip vortex and the trailing edge. The tip noise is not significant compared to the turbulent trailing edge noise. Equation (12) only requires the parameters of the tip segment.

$$(L_P)_{Tip} = 10\log\left(\frac{M^2 M_{max}{}^5 l^2 D_h}{r_e{}^2}\right) - 30.5\log(St'' + 0.3)^2 + 126 \quad (12)$$

$M_{max} = M_{max}(\alpha_{tip})$ is the maximum Mach number, $l = l(\alpha_{tip})$ is the spanwise extent of the separation zone, $St'' = fh/U_{max}$ is the Strouhal number, $h$ is the trailing edge gab, $U_{max}$ is the maximum velocity in the vicinity of the tip vortex. This model could not be applied due to the difficulty of getting some parameter inputs for the turbine model used for the study.

2. Lowson's Model [2]

Turbulent Inflow noise: As mentioned previously, the inflow noise is caused by the interaction of the turbulent air and with the blade.

Equation (13) is the main formula for the high frequency levels which will be corrected later for the low frequency ranges.

$$(L_p)^H{}_{INFLOW} = 10\log\left(\frac{\rho_o^2 c_o^2 l d}{r_e{}^2} M^3 u^2 I^2 K^3 \left(1+K^2\right)^{-7/3}\right) + 58.4 \quad (13)$$

Where $\rho_o$ is the air density, $l$ is the length scale of the atmospheric turbulence, $u$ is the mean wind speed, d is the segment length.

I is the turbulence intensity, and it is assumed to be 1% for low turbulence, 5% for medium, 10%--20% for high turbulence. Here it is assumed that it's a medium turbulence flow with 5% turbulence intensity.

$k = \pi fc/U$ is the wave number. Equation (14) estimates the total sound pressure level for the segment.

$$(L_p)_{INFLOW} = (L_p)^H{}_{INFLOW} + 10\log\left(\frac{\mathrm{LFC}}{1+\mathrm{LFC}}\right) \quad (14)$$

Where $LFC$ $LFC$ is the low frequency correction factor which is calculated from equation (15)

$$LFC = 10 S^2 M K^2 \beta^{-2} \quad (15)$$

Where S is called the compressible shears function and is obtained from equation (16)

$$S^2 = \left[\frac{2\pi K}{\beta^2} + \left(1 + 2.4\frac{K}{\beta^2}\right)^{-1}\right]^{-1} \quad (16)$$

And .

Trailing-Edge Noise: this prediction uses a re-analysis of the BPM model measured data.

$$L_{P,TBLTE} = 10\log\left(\frac{\delta\ M^5 s}{r^2}.G_6(f)\right) + 128.5 \quad (17)$$

$$G_6(f) = \frac{4\left(\frac{f}{f_{peak}}\right)^{2.5}}{\left[1+\left(\frac{f}{f_{peak}}\right)^{2.5}\right]^2} \quad (18)$$

Where $f_{beak}$ is obtained from $f_{peak} = \dfrac{0.02\ U\ M^{-0.6}}{\delta}$

3. Grosveld's Model [7]

Inflow-Turbulence noise: this model considers that the noise source is represented as a point located at the turbine hub and it is only valid for low frequencies, where turbulence length scale is large compared to the blade chord. The Sound pressure level is given by:

$$L_p = 10\log_{10}\left(\frac{w^2 U^4 C R n_B \sin^2(\varphi)\rho^2}{r^2 c_0^2}\right) + K_1(f) + C_1 \quad (19)$$

This model couldn't be applied due to the difficulty of getting some parameter inputs for the turbine model used for the study.

Trailing-Edge noise: Grosveld's model [7] uses the results of Schlinker and Amiet [8] that was developed for helicopter noise.

$$L_{p,TBLTE} = 10\log_{10}\left(\frac{\delta s U^5 D_1}{r^2} n_B\right) + K_2(f) + C_2 \quad (20)$$

The required parameters for this model are already presented and discussed in previous models in this paper, only the frequency dependent scaling function has to be defined in equation (21)

$$K_2(f) = 10\log_{10}\left\{\left(\frac{St'}{St_{max}}\right)^4 \left[\left(\frac{St'}{St_{max}}\right)^{1.5} + 0.5\right]^{-4}\right\} \quad (21)$$

Where the maximum Strouhal number $St_{\max}$ equals 0.1

## IV. Numerical Example

In this section, some results are illustrated using different noise prediction models in order to propose an appropriate approach for predicting the sound power of wind turbines. The values of the input parameters used for this study are presented and the numerical results obtained from the different models are investigated. The turbine considered in this study has a rated power of 55 kW and rotor diameter of 15.5 m.

### A. Class I models

1. Lowson model [2]

Equation (1) requires only one parameter which is the turbine rated power $PwT$ in Watts. The rated power of the used model equals to 55 kW. The calculated overall sound power level obtained from this model equals 97 dB(A).

2. Hau model [3]

Equation (2) requires only the rotor diameter which is equal to 15.5 m, the overall sound power level obtained from this model equals 98 dB(A).

3. Hagg model [4]

Equation (3) which is developed by Hagg [4] requires also the rotor diameter in addition to the tip speed $V_{Tip}$ which is equal to 58.6 *m/s*. This model estimates a sound power level of 96 dB(A). The other model that is developed by Hagg [5] estimates sound pressure level at a certain distance, the following input parameter are used for this model: The number of blades $n_B$ is 3, the rotor diameter $D$ equals to 15.5 m, the blade area $A_b$ is equal to 5 m$^2$, the rotor area $A_r$ is equal to 754 m$^2$, and the axial force coefficient $C_T$ equals to 0.7258. The constants $C_i$ have the following values:

TABLE IV
CONSTANTS OF EQUATION (4) ACCORDING TO HAGG [5]

| Constant | Value |
|---|---|
| $C_1$ | 63.3 |
| $C_2$ | 11.5 |
| $C_3$ | 2.5 |
| $C_4$ | 20 |
| $C_5$ | 10 |
| $C_6$ | 27.5 |

$r$ is the distance from the rotor hub to observer which is assumed to be 1 m. Since this model estimates sound pressure level, it cannot be directly compared to other models which estimate the sound power levels. The sound power level is estimated from the overall sound pressure level using equation (22) [10]

$$Lw = Lp + 10\log r^2 + C \tag{22}$$

$C$ is the summation of some correction factors depending on the medium of the source, these factors depend on directivity, source characteristics (whole, half, or quarter sphere), distance effect, air absorption, ground and meteorological effects, attenuation by surrounding areas, screening, addition by reflection, correction by the running time or other (tonality, impulsiveness).

Assuming some values for these factors, C is taken equal to 11. Hence, the sound power level of this model equals to 88 dB(A). Table 5 concludes and presents the A-weighted overall sound power levels obtained from class I models.

TABLE V
OVERALL SOUND POWER LEVELS OBTAINED BY CLASS II MODELS

| Model implemented | $L_{wA}$ dB(A) |
|---|---|
| Model (1) by Lowson [2] | 97 |
| Model (2) by Hau [3] | 98 |
| Model (3) by Hagg [4] | 96 |
| Model (4) by Hagg [5] | 88 |

*B. Class II models*

Class II models presented in this section estimate the sound pressure level at one meter distance from the hub. Since the frequency input values are defined in third octave bands, the the output is the sound pressure level at third octave bands. The sound pressure level is converted to sound power level using equation (22), and A-weighting curve is applied to the results.

1. Brooks, Pope, Marcolini (BPM) Model

Three codes of three noise sources are applied for this model which are: turbulent boundary layer trailing edge (TBL-TE) noise, laminar boundary layer vortex shedding (LBL-VS) noise and trailing Edge Bluntness Vortex Shedding (TEB-VS) Noise.

The first BPM model for the (TBL-TE) noise which is represented by equations (6), (8) and (9) is applied with the following input parameters:

Boundary layer displacement thicknesses of the pressure and suction side values $\delta_p$ and $\delta_s$ are equal to [0.3328, 0.05317, 0.04885, 0.0479, and 0.0455] and [0.0134, 0.0268, 0.0292, 0.0295, and 0.032], respectively as provided by aerodynamic analysts. The five segments are taken at the chord lengths of [0.92, 0.9, 0.78, 0.62, and 0.42 m]. The relative velocities $U$ at these chords are equal to [10.18, 17.5, 25.2, 32.99, and 40.76 m/s]. The angles of attack $\alpha$ of the five segments are [16.73, 4.4,2, 1.54, and 0.28 degrees].

Speed of sound $c_0$ = 343, density of air at 20$^o$C, $\rho$ =1.2041, viscosity of air at 20c equals 1.83*10$^{-5}$, span length of each segment equals to 1.4 *m*, directivity $D_h$ is assumed to be 1 to exclude its effect, distance to the receiver is assumed to be 1. The total sound level of the five segments are summed to give the total sound pressure level for one blade, then the sound pressure level of the three blades is calculated using equation (23) [10].

$$Lp(Total) = 10\log(10^{Lp1/10} + 10^{Lp2/10} + .......) \tag{23}$$

The second BPM model is for the laminar boundary layer vortex shedding (LBL-VS) noise. It is represented by equation (10). The input parameters for this model are almost the same ones used in the TBL-TE of BPM code.

The third and final model applied by BPM is for the trailing edge bluntness vortex shedding (TEB-VS) noise which is represented by equation (11). The parameters, different from previous models, required for this one are: The trailing edge thickness *(h)* is defined as a ratio of the chord length $h/c$ and is assumed to be 0.005. The trailing edge angle $\Psi$ is 10.

2. Lowson model

Two codes for two noise sources are applied for this model. The first is the turbulent inflow noise which is modeled using equations (13), (14), (15) & (16). The different parameters needed for this model are the length scale of the atmospheric turbulence $l$ which set to be 10, mean wind speed $u$ which is assumed to be 8 m/s, the turbulence intensity $I$ which is assumed to be 5% corresponding to medium turbulence. The second code is for the TBL-TE noise which is represented by equations (17) & (18). This code requires the same parameters of the TBL-TE done by BPM model.

3. Grosveld model

Only one code for one noise type is applied in this model which is the TBL-TE noise code represented by equations (20) and (21). The only different parameter required for this code is the maximum Strouhal number $St_{\max}$ which is defined by 0.1. The overall sound power levels of all noise types from each model is 91 for Lowson model, 84 for BPM model, and 108 for Grosveld model. Table (6) concludes the A-weighted overall sound power levels calculated from the outputs of class II models. Fig. 1 concludes the A-weighted third octave sound power levels.

TABLE VI
OVERALL SOUND POWER LEVELS OBTAINED BY CLASS II MODELS

| Model implemented | LwA dB(A) |
|---|---|
| Lowson [2] | 91 |
| BPM [5] | 90 |
| Grosveld [7] | 108 |

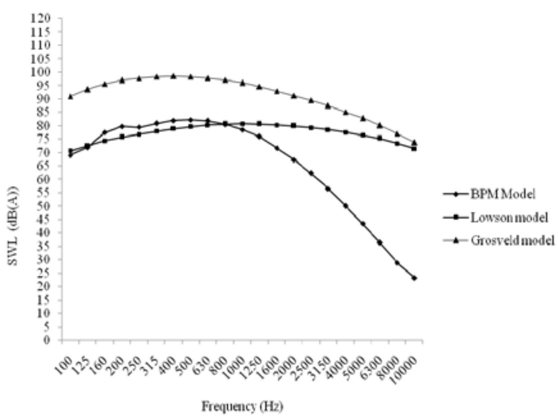


Fig. 1 Third Octave sound power levels obtained by class II models

After investigating the overall sound power levels of the different prediction models, it is obvious that there exists a considerable deviation between the results of the first three simple models which are included to class I and the rest of models which require more parameters to be applied.

It is obvious that estimated sound power levels by class I models are close except for the model by Hagg [5]. This may be attributed to the assumption of a correction factor to predict the sound power level from the sound pressure one. Class I models are easy to implement and the needed information including the turbine power and rotor area are quite simple. However, the estimated sound power levels are overall values and no frequency dependence can be calculated.

On the other hand, the results of different class II models show large deviations which may be attributed to the different noise sources considered and the inaccurate estimation of some parameters. It is obvious that class II models are much more difficult to implement because of the amount of information needed. However, they are able to predict the frequency bands of the produced noise which is often needed in noise control.

In conclusion, class I models can be used as a preliminary estimation of noise expected from wind turbines. However, detailed studies investigating the effect of specific design parameters on the noise produced by the wind turbine necessitate applying class II models.

## V. CONCLUSION

The increased use of Wind Turbines develops the need to assess their impact on the environment where they are going to be installed. One of the important aspects of Wind Turbines environmental impact is its noise. In order to assess their noise impact, the sound power of the individual wind turbine needs to be estimated. There are a number of research and models dealing with this issue. The models are reviewed in this paper. Class I models are simple compared to class II ones. Some deviations are quite considerable. An example Wind Turbine was considered and its sound power was calculated using all the models. An engineer can choose which model to use based on the amount of details (overall levels vs. frequency bands) he/she needs and also based on the amount of information available about the wind turbine.

## REFERENCES

[1] Pinder, J. N., “Mechanical Noise from Wind Turbines,” Wind Engineering, Vol. 16, No. 3, pp. 158-168, 1992.
[2] Lowson, M. V., “Assessment and Prediction of Wind Turbine Noise,” Flow Solutions Report 92/19, ETSU W/13/00284/REP, pp. 1-59, December 1992.
[3] Hau, E., Langenbrinck, J., Palz, W., “WEGA Large Wind Turbines,” Springer-Verlag, Berlin, pp. 1-143, 1993. http://dx.doi.org/10.1007/978-3-642-52129-4
[4] Hagg, F.; van der Borg, N. J. C.M. ; Bruggeman, J. C.; et al.,” Definite Aero-Geluidonderzoek Twin,” Stork Product Engineering B.V., SPE 92-025, April 1992.
[5] Hagg, F., “Aerodynamic Noise Reduced Design of Large Advanced Wind Turbines,” ECWEC'90, Proc. of the European Community Wind Energy Conference, Madrid, Spain,pp. 384-388, September 1990.
[6] Brooks, F. T.; Pope, D. S.; Marcolini, M. A. ,“Airfoil Self-Noise and Prediction,”. NASA RP-1218, pp. 1-137, July 1989.
[7] Grosveld, F. W., “Prediction of Broadband Noise from Horizontal Axis Wind Turbines,” Journal of Propulsion and Power. Vol. 1, No. 4, pp. 292-299, July 1985. http://dx.doi.org/10.2514/3.22796
[8] Schlinker, R. H.; Amiet, R. K., “Helicopter Rotor Trailing Edge Noise,” NASA CR-3470, pp. 1-145, November 1981.
[9] Glegg, S. A. L.; Baxter, S. M; Glendinning, A. G., “The Prediction of Broadband Noise from Wind Turbines,” Journal of Sound and Vibration, Vol. 118, No. 2, pp. 217-239, 1987. http://dx.doi.org/10.1016/0022-460X(87)90522-0
[10] Royster, L.H.; Doswell, J., ” The Noise-Vibration Problem-Solution Workbook,” American Industrial Hygiene Association: 1-8 Fairfax, 2002.