



**MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES
IN PURE AND APPLIED SCIENCES**



PREDICTION AND IMPROVEMENT OF WIND TURBINE ACOUSTICS FOR AERODYNAMIC NOISE REDUCTION

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Ph.D. THESIS

Department of Mechanical Engineering

Thesis Supervisor

Assoc.Prof. Dr. Emre ALPMAN

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ÖZET

RÜZGAR TÜRBİNİ AKUSTİĞİNİN AERODİNAMİK GÜRÜLTÜ AZALTIMI İÇİN KESTİRİMİ VE İYİLEŞTİRİLMESİ

Rüzgar gücü endüstrisi geçtiğimiz on yıl boyunca büyüyen bir pazar ve olgunlaşan bir teknoloji olmuştur. Artan rüzgar gücünün üretimi rüzgar türbinlerinin montajlarının insanlara ve yaşadığı evlere daha yakın olmasını gerektirmiştir. Bu yüzden, rüzgar türbini gürültüsü ciddi ve tartışmalı bir olgu haline almış ve günümüzde rüzgar gücü üretimi artarken zorlayıcı bir sorun olarak karşımıza çıkmıştır. Bu çalışmanın amacı, iki boyutlu kanat kesitinin akış ve gürültü analiz/simülasyonlarını kullanarak rüzgar türbini kanat gürültüsünün tahminini yapmak ve toplam kanat gürültüsünü elde etmek amacıyla gürültü kaynaklarını birleştirmek için bir yöntem önermektir.

Bu çalışma kapsamında, iki kanatlı NREL Phase VI rüzgar türbini için bir Hesaplı Akışkanlar Dinamiği yazılımı olan ANSYS-FLUENT yardımıyla bazı düzeltmeler uyguladıktan sonra bir takım kabuller altında Kullanıcı Tanımlı Fonksiyonlar kullanarak iki boyutlu akış ve gürültü analizleri yapılmıştır. Analiz sonuçları, Kore Havacılık Araştırmaları Enstitüsü'nün düşük süratli rüzgar tüneline yapılan NREL Phase VI rüzgar türbininin %12 ölçekli modelinin akustik gürültü ölçümleri ile karşılaştırılmıştır. Bu kapsamda, 5.4 m/s, 7.4 m/s, 12.3 m/s ve 13.3 m/s olmak üzere farklı rüzgar hızlarındaki türbin kanadı gürültü ölçümleri, analiz sonuçları ile karşılaştırılmıştır. Belirli rüzgar süratlerinde kanadın uç ve orta kısımlarında makul seviyede uyum sağlanmıştır. İlave olarak, toplam kanat gürültüsünün tahmini için her bir kanat kesitinin gürültüye katkısı hesap edilmiştir.

Mevcut çalışmada, "Rüzgar Türbinlerinin Tasarım Gereklilikleri" hakkındaki uluslararası standart olan IEC 61400-1'e uygun olarak Şiddetli Bora Etkisini (EOG) uygulayarak şiddetli rüzgar durumlarının rüzgar türbinlerinin gürültüsüne etkisi araştırılmıştır. Türbin kanadının uç kısmında ve orta kısmında, EOG'nin gürültüye etkisinin birbirinden farklı olduğu hesap edilmiştir.

Gürültü azaltım çalışmaları NREL Phase VI kanadının büküm açısını değiştirerek yapılmıştır. Beş alternatif büküm açısı daha önceden doğrulanmış gürültü kestirim modeline uygulanmıştır. Tüm kanadın gürültü tahmininin değerlendirilmesi ve kanadın ürettiği torkların karşılaştırılması ile beraber ses basınç seviyelerinin mukayesesi, frekans bazlı gürültü

mukayesesi büküm açısı alternatifleri için yapılmıştır. İki büküm açısı alternatifi, toplam kanat gürültüsünde 2.2 dB ile 3.2 dB arasında, bazı frekanslarda da 4.5 dB üzerinde gürültü azaltımı sağlamıştır. İlave olarak, bu iki alternatifin orijinal kanada göre düşük rüzgar hızlarında daha fazla tork ürettiği hesaplanmıştır.



ABSTRACT

PREDICTION AND IMPROVEMENT OF WIND TURBINE ACOUSTICS FOR AERODYNAMIC NOISE REDUCTION

Wind power industry has been a growing market and maturing technology for several decades. Increasing wind power generation necessitates closer installation of wind turbines to people and their residences. For that reason, wind turbine noise becomes a severe and controversial phenomenon and it is anticipated to become more stringent issue while wind power generation is increased recently. The aim of this study was to propose a methodology to predict the wind turbine blade noise by using two dimensional blade section flows and noise analysis/simulation and combining the noise sources to evaluate the total blade noise with reasonable accuracy.

Within the scope of this work, the purpose was to perform a two dimensional flow and noise simulation for the two bladed NREL Phase VI wind turbine with the aid of a commercially available Computational Fluid Dynamics software ANSYS-FLUENT by using User Defined Functions after applying some corrections under certain assumptions. Analysis results were compared with the 12% scaled model of NREL Phase VI wind turbine acoustic noise measurements conducted in In Korea Aerospace Research Institute at the low speed wind tunnel. Blade noise of the measurements were compared with the analysis results at different wind speeds of 5.4 m/s, 7.4 m/s, 12.3 m/s, and 13.3 m/s. For the tip region and inboard area of the blade, reasonable agreement was achieved at certain wind speeds. Additionally, the summation of the contribution from the each blade section was used to predict the total noise emission.

The effect of extreme wind conditions on wind turbine noise was investigated in the current study by applying Extreme Operating Gust according to the International Standard on "Wind Turbines Design Requirements", namely IEC 61400-1. Dissimilar behavior of EOG effect on noise was predicted for tip section and for mid section of the turbine blade.

Noise reduction studies were performed by changing the twist angle of the NREL Phase VI blade. Five alternative twist angles were applied to the previously validated noise prediction model. Sound pressure levels comparison, frequency based noise comparison were done for the twist angle alternatives along with evaluation of total blade noise prediction and

comparison of generated torques by the blade. Two twist angle alternatives provided noise reduction about 2.2 dB - 3.2 dB in total blade noise, and above 4.5 dB noise reduction in some frequencies. Additionally, it was calculated that these two alternatives generated more torque compare with the original blade at lower wind speeds.



CLAIM FOR ORIGINALITY

Aerodynamic noise radiated from the wind turbine generates discomfort to the neighboring residences due to the closer wind farm installation and 24 hours a day noise generation. In order to reduce the public disturbance, it is essential to perform more research and development in order to make a definition of wind turbine noise generating, control and reduction mechanisms.

Therefore, there is a strong need to develop noise prediction methods and to find noise reducing concepts for wind turbines to be able to further expand wind turbine installation sites.

Initially, a methodology was proposed to predict the wind turbine blade noise under steady conditions by using two dimensional blade section flow and noise analysis/simulations and by combining the noise sources to evaluate the total blade noise with reasonable accuracy.

Additionally, the effect of the extreme wind conditions on wind turbine noise was analyzed. An international standard on " IEC 61400-1 Wind Turbines – Part 1: Design Requirements " was introduced. The purpose of the standard was explained as providing a proper level of integration against accidents generated by dangers during the intended life span. By utilizing extreme wind condition formulation, namely Extreme Operating Gust (EOG), noise values were predicted and presented in the study based on the proposed methodology within the scope of this work.

Finally, the acoustic behavior of the baseline NREL Phase VI Blade geometry was improved. Noise characteristics of the blade were investigated by changing the twist distribution of the blade. Noise results were compared with the baseline configuration in terms of sound pressure level, sound power level vs frequency and total predicted blade noise. Additionally, the effect of changing the twist angle on blade torque was investigated.

SYMBOLS

A	: Projected airfoil area (chord x span) (m^2)
B	: Number of blades
c	: Chord (length) of the airfoil (m)
c_o	: Speed of sound (ms^{-1})
C_l	: Lift coefficient
C_d	: Drag coefficient
C_m	: Pitching moment coefficient
dB	: Decibel
dr	: Radial length of the blade element
dS	: Element of the integration surface area
f	: Function defining location of control surface
f	: frequency (s^{-1})
F_L	: Lift force (N)
F_D	: Drag force (N)
F_N	: Normal force, normal to the plane of rotation (N)
F_T	: Force tangential to circle swept by blade section (N)
$H(f)$	: Heaviside function
I_{ref}	: Expected mean value of the turbulence intensity at 15 m/s.
l	: Airfoil span (m)
L	: Length (m)
L_{Aeq}	: Equivalent continuous level of sound in A scale
L_i	: Local force vector components
L_w	: Sound Power Level (dB)
L_p	: Sound Pressure Level (dB)

L_{10}	: Noise level that is surpassed 10% of the measurement time (dB)
L_{50}	: Noise level that is surpassed 50% of the measurement time (dB)
L_{90}	: Noise level that is surpassed 90% of the measurement time (dB)
M	: Mach number
M_r	: Source Mach number in radiation direction
n_i	: Normal unit vector
p	: Static surface pressure, instantaneous sound pressure (Pa)
p_0	: Reference sound pressure (Pa)
P_{ij}	: Compressive stress tensor (Pa)
p'	: Acoustic pressure (Pa)
Q	: Directivity factor
R	: Rotor radius (m)
Re	: Reynolds number
T_{ij}	: Lighthill stress tensor (Pa)
t	: Observer time (s)
U_i	: Components of vector defined in equation (2.3)
u_i	: Fluid velocity (ms^{-1})
U_{rel}	: Relative wind velocity (ms^{-1})
v_i	: Velocity of control surface (ms^{-1}) in FW-H equation
ν	: Kinematic viscosity of the fluid ($\text{m}^2 \text{s}^{-1}$)
V_{hub}	: Wind speed at the hub of wind turbine (ms^{-1})
V_{ref}	: Reference average wind speed over 10 minutes (ms^{-1})
$V(z)$	: Wind speed as a function of height above the ground, z (ms^{-1})
V_{e1}	: Wind speed with a recurrence period of 1 year (ms^{-1})
V_{e50}	: Wind speed with a recurrence period of 50 years (ms^{-1})
V_{gust}	: Gust magnitude at the hub height (ms^{-1})

- W : Source sound power (Watt)
- W_0 : Reference source sound power (Watt)
- $W(t)$: Resultant velocity (ms^{-1})
- $W_x(t)$: Relative velocity component in x direction
- $W_y(t)$: Relative velocity component in y direction
- x_i : Location of observer (m)
- y_i : Location of source (m)

Greek Letters

- α : Angle of attack (deg)
- μ : Fluid viscosity ($\text{kg m}^{-1} \text{s}^{-1}$)
- ω, Ω : Angular velocity (rad s^{-1})
- θ_p : Blade pitch angle (deg)
- $\theta_{p,0}$: Blade pitch angle at the tip (deg)
- θ_T : Blade twist angle (deg)
- φ : Angle of relative wind (deg)
- λ : wavelength (m)
- λ_r : Local speed ratio
- $\delta(f)$: Dirac delta function
- δ_{ij} : Kronecker delta $\delta_{ij} = 1$ for $i = j$, otherwise $\delta_{ij} = 0$
- ρ : Density of fluid (kg m^{-3})
- σ_1 : Turbulence standard deviation
- Λ_1 : Longitudinal scale parameter

Subscripts

- L : loading component of noise
- n : component in surface normal direction
- Q : quadrupole component of noise

r : component in radial direction

T : thickness component of noise



ABBREVIATIONS

AIAA	: The American Institute of Aeronautics and Astronautics
AWEA	: American Wind Energy Association
CFD	: Computational Fluid Dynamics
EOG	: Extreme Operating Gust
EREC	: European Renewable Energy Council
EWEA	: The European Wind Energy Association
FW-H	: Ffowcs Williams Hawkings
GWEC	: Global Wind Energy Council
HAWT	: Horizontal Axis Wind Turbine
IEC	: International Electrotechnical Commission
IWT	: Industrial Wind Turbine
KARI	: Korea Aerospace Research Institute
NACA	: National Advisory Committee for Aeronautics
NASA	: National Aeronautics and Space Administration
NREL	: National Renewable Energy Laboratory
RNG	: Renormalization Group Method
SPL	: Sound Pressure Level
UAE	: Unsteady Aerodynamics Experiment
UDF	: User Defined Function

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1. INTRODUCTION

Global warming and climate change lead the countries to the development of renewable and green energies. Wind power has been one of the fastest developing energy sources in the last years. Worldwide wind power generation was 6.1 GW at the end of 1996 and 369.6 GW at the end of 2014. 2014 was a record year for the wind industry as annual installations crossed the 50 GW level for the first time. By the end of 2019 it has been forecasted the total wind power generation would exceed 650 GW [1].

The European Countries adopted a target to obtain 20% of electricity from renewable energy until 2020. Additionally, wind power generation will increase from 82 TWh in 2006 to over 477 TWh by 2020 among European Countries based on the projected growth rates [2].

By considering the numbers, wind power industry has been a growing market and maturing technology for several decades. Additionally, wind power is increasing its share in energy industry with installed capacity [1].

Increasing wind power generation necessitates closer installation of wind turbines to people and their residences. For that reason, wind turbine noise becomes a severe and controversial phenomenon and it is anticipated to become more stringent issue while wind power generation is increased.

The wind turbines have become quieter with the advancements in technology in the last decade. Designers showed some effort to reduce noise levels in 1990s and 2000s. This situation was illustrated in the Figure 1.1 as measured sound power levels versus turbine diameter, also rated electrical power.

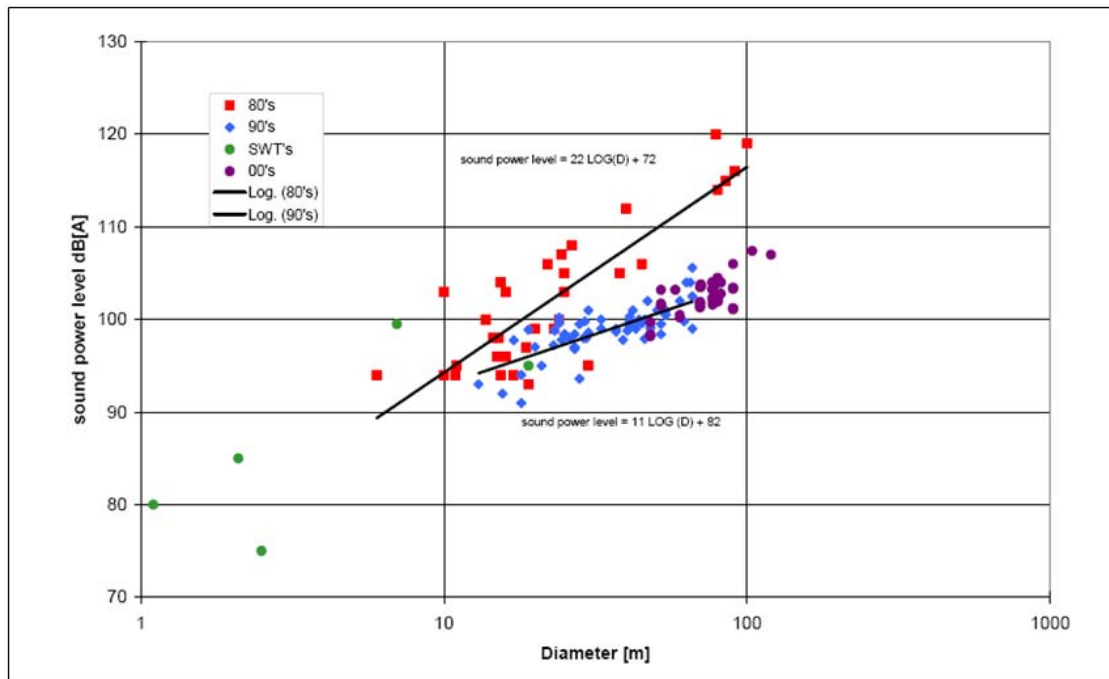


Figure 1.1 Sample Wind Turbine Measured Sound Power Levels [3]

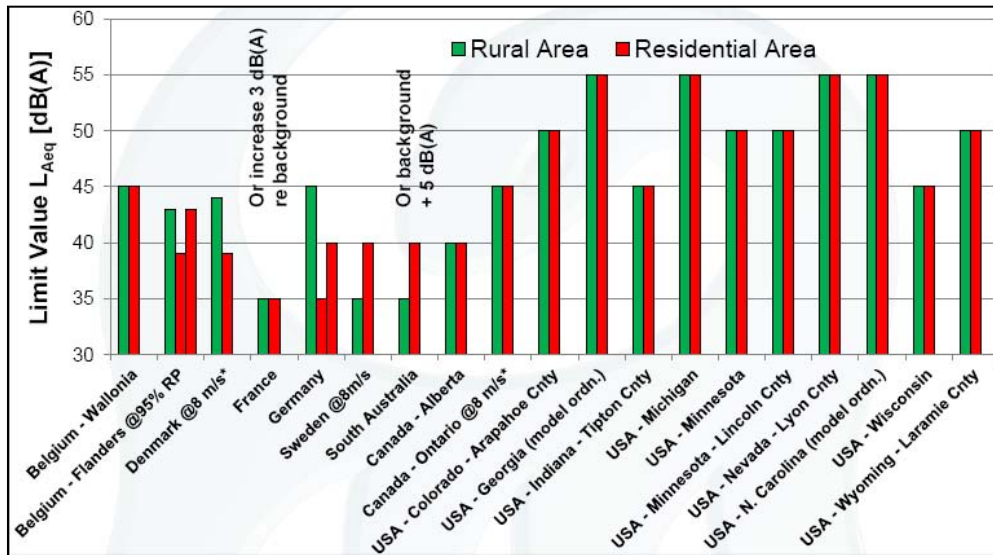
Some of the noise limits in various European countries were shown in **Table 1.1** and night time noise in Europe and North America were demonstrated in **Table 1.2**.

Even though achievements have been noted, noise limits in **Table 1.1** and **Table 1.2**, especially in residential areas shall be considered. Wind turbine noise is still an important issue and need to be considered at the turbine installation site evaluation phase especially when close to residences. There are some studies related to wind turbine noise perception and discomfort issues in the last decade.

Table 1.1 Noise Limits of Sound Power Levels in Various European Countries [4]

Country	Commercial	Mixed	Residential	Rural
Denmark			40 dB(A)	45 dB(A)
Germany				
	65 dB(A)	60 dB(A)	55 dB(A)	50 dB(A)
(night)	50 dB(A)	45 dB(A)	40 dB(A)	35 dB(A)
Netherlands				
		50 dB(A)	45 dB(A)	40 dB(A)
(night)		40 dB(A)	35 dB(A)	30 dB(A)

Table 1.2 Wind Turbine Noise Limit Values of Sound Power Levels (Night-time) in the World [5]



According to Pederson and Waye [6], survey results with people in rural locations showed that annoyance increased with noise levels. Survey also showed that people's annoyance increased more rapidly with wind turbines than other stationary industrial noise sources.

The study of Van Den Berg [7] revealed that noise from a 30 MW wind farm became more noticeable and disturbing to nearby residents at night. According to the study, although the noise was always present, certain aspects of turbine noise was not noticeable during the day, but became very noticeable at night.

In practice, if installation of a wind turbine is proposed within a distance of three times blade tip height to residences or any noise sensitive receptor, a noise study should be done and published [3].

A questionnaire was applied in United Kingdom to compare sleep and general health outcomes between participants living close to Industrial Wind Turbines (IWT) and those living away from them [8]. According to the study, industrial wind turbines' noise emissions disturbed the sleep and caused daytime sleepiness and impaired mental health in residents living in the vicinity of 1.4 km of the two wind turbines installations studied [8].

One of the most comprehensive studies about wind turbine noise and health, was performed during 2013-2014 in Canada and results were published in 2015 [9]. The study provided no linkage between exposure to wind turbine noise and any of the self reported illnesses and chronic conditions about stress and sleep as well. But on the other hand, in the study an association was found between increasing level of noise and individuals reporting to be very or extremely annoyed [9].

In the systematic review of Schmidt and Klokke, a comprehensive literature survey was applied to more than 1200 articles. Finally 36 articles, addressing specific health related results in relation with wind turbine noise exposure, were outlined [10]. According to the study, it was logical to conclude that noise radiation by wind turbines increased the risk of annoyance and sleep disturbance on people in the vicinity. And, tolerable limit of noise was estimated to be around L_{Aeq} of 35 dB according to the study. Additionally, the study indicated that annoyance of noise and sleep disturbance were related to each other and this sleep disturbance possibly could lead to unfavorable health effects [10].

Another systematic review about the effect of the wind turbine noise on sleep and quality of life was published by Onakpaoya et al. [11]. The authors investigated experimental and observational studies about the wind turbine noise. It was concluded in the study that the exposure to wind turbine noise might be associated with increased frequency of annoyance and sleep problems. And, the attitude of individuals toward wind turbines could influence the type of response [11].

In this context, wind turbine noise still a subject of discussion and discomfort. In addition to the fact that there have been some discomfort issues about wind turbine noise, researchers from different countries and different academic institutions keep working on methods for wind turbine noise prediction. Since wind turbine noise is still an important issue especially when sited close to residential areas, numerical methods for noise prediction shall be generated and validated. Then, the proposed models shall be used to alter wind turbine (i.e.airfoil) geometry for wind turbine noise reduction.

In the study of Son et al. [12], flow fields around the wind turbine blade were calculated based on an unsteady vortex lattice method by utilizing potential flow. Tonal noise (low frequency noise) was predicted by Farassat 1A equation; additionally semi empirical formulas were used for the prediction of broadband noise such as airfoil self noise and turbulence ingestion noise.

The properties of noise intensity function were analyzed by Guarnaccia et al. [13] from an analytical point of view, focusing on the slope of intensity function when considering different dependences. Additionally, comparison between the presented model and results of commercial noise prediction software were sketched in the study.

Tadamasa and Zangeneh [14] offered a dual methodology combining commercial CFD solver for calculation of aerodynamic noise sources and Ffowcs Williams-

Hawkings (FW-H) equation for far field propagation calculation. The generated FW-H acoustic codes were used to predict the noise radiated from National Renewable Energy Laboratory (NREL) Phase VI wind turbine blades.

In the the study of Leishman [15], the issues were discussed about the modeling of velocity field at the wake of the turbine, characteristics of dynamic stall, and unsteady behavior of blade sections. According to the inflow turbulence and yaw error directly affects the performance of wind turbines. [15]

Since the performance is related to the pressure distribution over the blades, the acoustic signature of the turbine will also be considerably affected due to those effects. According to the work of Simss et al. [16] performed by NREL, Unsteady Aerodynamics Experiment (UAE) field testing showed that wind turbines operate in very complex environmental conditions. According to the study quickly changing wind velocity, rapidly shifting wind directions, and widely varying levels of turbulence and shear were contributing factors in the environment [16].

In the study of Katinas et al. [17], measurements were performed and noise propagation models were applied. The authors concluded that the biggest change occurred in noise spectrum between 200 Hz and 5000 Hz. Only insignificant changes were observed in infrasound, low frequency (16 - 200 Hz), and ultrasound frequency ranges. Moreover, wind turbine noise was concealed by the background noise above 10 m/s wind velocities according to the study [17].

Airfoil optimization for low noise and high performance was conducted in typical three bladed 10 kW wind turbine considering six different airfoils in the study of Göçmen and Özerdem [18]. The authors used XFOIL as flow analysis tool and semi empirical noise model NAFNoise as self noise analysis tool. The outcomes of the study revealed higher lift to drag ratios and decreased noise emission levels up to 5 dB [18].

Lee and Lee [19] studied the noise generated by small wind turbine numerically and experimentally. They conducted numerical predictions of turbulence ingestion noise, turbulent boundary layer trailing edge noise, and trailing edge bluntness noise based on previously proposed semi empirical formulae. The prediction results were compared with field measurement data. It was concluded for small with turbine that the trailing edge bluntness noise could be a dominant noise source unless the blades of wind turbine had very sharp trailing edge [19].

The study of Ramirez and Wolf [20] aimed to analyze the effects of trailing edge bluntness over a NACA 0012 airfoil tonal noise for low to moderate Mach numbers. The combined approach was utilized in the study such as direct calculation for near field source computations and Ffowcs-Williams Hawkings (FW-H) equation as the acoustic analogy formulation [20].

As stated in previous works of different research institutes and governmental offices, aerodynamic noise emitted from the wind turbine generates discomfort to the neighboring residences due to the closer wind farm installation and 24 hours a day noise generation. In order to reduce the public disturbance, there needs to be more research and development performed to define how wind turbine noise is generated and how it can be controlled and reduced.

With the aid of the computer technologies, noise source modeling improvement can help in order to gain insight to the correct behavior of the generated noise by the wind turbine.

There is a strong need to develop noise prediction methods and to find noise reducing concepts for wind turbines to be able to further expand wind turbine installation sites. It is expected the more studies for the prediction and the evaluation of noise generated by the wind turbine will be required.

The primary aim of this study is to propose a methodology to predict the wind turbine blade noise under steady conditions by using two dimensional blade section flow and noise analysis/simulations and by combining the noise sources to evaluate the total blade noise with reasonable accuracy.

Additionally, the **secondary aim of this study** is analyzing the effect of the extreme wind conditions on wind turbine noise. An international standard on " IEC 61400-1 Wind Turbines – Part 1: Design Requirements " is introduced. The purpose of the standard is explained as providing a proper level of integration against accidents generated by dangers during the intended life span. By utilizing extreme wind condition formulation, namely Extreme Operating Gust (EOG), noise values were predicted and presented in the study based on the proposed methodology within the scope of this work.

Final aim of this study is improving the acoustic behavior of the baseline NREL Phase VI Blade geometry. Noise characteristics of the blade were investigated by changing the twist distribution of the blade. Noise results were compared with the

baseline configuration in terms of sound pressure level, sound power level vs frequency and total predicted blade noise. Additionally, the effect of changing the twist angle on blade torque was investigated.



2. THEORETICAL BACKGROUND

Noise generated by wind turbine is evaluated using the Lighthill's acoustic analogy and Ffowcs Williams and Hawkings (FW-H) equation.

In acoustic analogy, it is assumed that the acoustic fluctuations are small enough in such a way that they do not have any effect on the mean aerodynamic flow. When this assumption is reasonably satisfied it is possible to perform a combined double analysis; a Computational Fluid Dynamics (CFD) analysis for the mean aerodynamic flow, and an acoustic analysis for acoustic quantities.

2.1. Ffowcs Williams and Hawkings (FW-H) Equation

The FW-H equation is the most common form of the acoustic analogy introduced by Lighthill and it has been utilized to predict the noise generated by complicated arbitrary motions. The original FW-H equation was augmented in 1969 from Lighthill's acoustic analogy [21] by combining the effect of the moving solid body [22].

In FW-H equation the Navier Stokes (momentum) equations are grouped into the form of an inhomogeneous wave equation with monopole and dipole sources on the body surface and with a quadrupole source distribution in the volume nearby the body [23].

The aforementioned equation is originally obtained by representing the blade surface as moving control surface, which introduces discontinuity in the boundless fluid domain. There are two assumptions about the flow. First, the flow inside has the same condition like the undisturbed medium. Second, the flow outside has the real condition including the body influence.

According to reference [24], the FW-H equation is written below as inhomogeneous wave equation,

$$\begin{aligned} \frac{1}{c_o^2} \frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' &= \frac{\partial^2}{\partial x_i \partial x_j} [T_{ij} H(f)] \\ &- \frac{\partial}{\partial x_i} \{ [P_{ij} n_j + \rho u_i (u_n - v_n)] \delta(f) \} \\ &+ \frac{\partial}{\partial t} \{ [\rho_o v_n + \rho (u_n - v_n)] \delta(f) \} \end{aligned} \quad (2.1)$$

$T_{ij} = \rho u_i u_j + P_{ij} - c_o^2 (\rho - \rho_o) \delta_{ij}$ is the Lighthill stress tensor, v_n is the local normal velocity of the integration surface and u_n is the fluid velocity in the direction normal to the

surface $f = 0$. The subscript o was used to denote free stream quantity. P_{ij} is the compressive stress tensor. It is defined as follows for Stokesian fluid [25],

$$P_{ij} = p\delta_{ij} - \mu \left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right] \quad (2.2)$$

According to the study of Brentner and Farassat [24] equation (2.1) can be represented in integral form. New variables U_i and L_i are defined below,

$$U_i = \left(1 - \frac{\rho}{\rho_o}\right) v_i + \frac{\rho u_i}{\rho_o} \quad (2.3)$$

$$L_i = P_{ij} n_j + \rho u_i (u_n - v_n) \quad (2.4)$$

Here, U_i and L_i are the components of vectors defined in equations (2.3) and (2.4), respectively. Considering the previous equations the FW-H equation can be written differential form,

$$\frac{1}{c_o^2} \frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = \frac{\partial^2}{\partial x_i \partial x_j} [T_{ij} H(f)] - \frac{\partial}{\partial x_i} [L_i \delta(f)] + \frac{\partial}{\partial t} [(\rho_o U_n) \delta(f)] \quad (2.5)$$

The solution is comprised of surface integrals and volume integrals. The first term of the right hand side which includes Heaviside function is a quadrupole source out of the control surface. This part can be assumed to be little compared to the quadrupole source in the control surface. For that reason, it can be considered negligible. In the study of Brentner and Farassat [24], an integral representation of the solution can be written as,

$$\dot{p}(\vec{x}, t) = \dot{p}_T(\vec{x}, t) + \dot{p}_L(\vec{x}, t) + \dot{p}_Q(\vec{x}, t) \quad (2.6)$$

where,

$$4\pi \dot{p}_T(\vec{x}, t) = \int_{f=0} \left[\frac{\rho_o (\dot{U}_n + U_n)}{r(1 - M_r)^2} \right] dS + \int_{f=0} \left[\frac{\rho_o U_n (r \dot{M}_r + c_o (M_r - M^2))}{r^2 (1 - M_r)^3} \right] dS \quad (2.7a)$$

$$\begin{aligned} 4\pi \dot{p}_L(\vec{x}, t) = & \frac{1}{c_o} \int_{f=0} \left[\frac{\dot{L}_r}{r(1 - M_r)^2} \right] dS + \int_{f=0} \left[\frac{L_r - L_M}{r^2 (1 - M_r)^2} \right] dS \\ & + \frac{1}{c_o} \int_{f=0} \left[\frac{L_r (r \dot{M}_r + c_o (M_r - M^2))}{r^2 (1 - M_r)^3} \right] dS \end{aligned} \quad (2.7b)$$

In the above equations, the dot over a variable implies source time differentiation of that variable. $L_M = L_i M_i$, and a superscript r or n indicate a dot product of the vector with the unit vector in the radiation direction $\hat{r}$ or the unit vector in the surface normal direction $\hat{n}$, respectively [24].

After sorting the FW-H equation, FW-H equation in differential form is given below with the assumption of not existing fluid flow through the control surface [23].

$$\frac{1}{c_o^2} \frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = \frac{\partial}{\partial t} [(\rho_o U_n) \delta(f)] - \frac{\partial}{\partial x_i} [L_i \delta(f)] + \frac{\partial^2}{\partial x_i \partial x_j} [T_{ij} H(f)] \quad (2.8)$$

In equation 2.8 c_o is the speed of sound in undisturbed medium, p' is the acoustic pressure $p' = c_o^2(\rho - \rho_o)$, U_n is the local normal velocity of the integration surface, p_{ij} is the compressive stress tensor that includes the surface pressure and viscous stress, $L_i = p'_{ij} n_j$ is the local force vector components applied by the surface on fluid, $T_{ij} = \rho u_i u_j + p_{ij} - c_o^2 \rho \delta_{ij}$ is the Lighthill stress tensor. $\delta(f)$ and $H(f)$ are the Dirac delta and the Heaviside functions, respectively.

The first term on the right hand side of the Equation (2.8) denotes the noise source which is proportional to the local mass rate insertion into the boundary of control surface. This type of source can characterize thickness (monopole) noise, because of the disturbance in the flow generated by the rotating blade [26].

The second term denotes the noise source that is proportional to the local force intensity. This type of source can represent the loading (dipole) noise, because of the disturbance in the flow caused by associated pressure field [26].

Loading noise is generated by the accelerating force on the fluid caused by moving rotor blade surface. Blade vortex interaction noise and broadband noise are important types of loading noise. Blade vortex interaction noise is due to a shed vortex after interacting with a subsequent blade [23].

The third term denotes quadrupole type source. The third term is frequently assumed negligible, because of the complexity of volume integral calculation. For that reason, the original FW-H equation fails to predict the quadrupole noise term. The quadrupole source term models the nonlinearities due to both local sound speed variation and the finite fluid velocity near the blade [26].

Thickness and loading terms are surface distribution sources as indicated by the presence of delta function. On the other hand, quadrupole term is a volume distribution of sources indicated by Heaviside function.

As a summary, the three source terms on the right hand side of FW-H equation are known as the thickness, loading and quadrupole source terms, respectively. This terminology is proper if only data surface corresponds to a solid (impermeable) surface [23]. The computation of the quadrupole contribution requires volume integration of the entire source region and can be difficult to implement. The details of each source terms were given in the studies of Tadamas and Zangeneh [26], and Filios et al.[27].

It is known that the quadrupole sources are responsible for distortion of the acoustic wave form, hence noise generation. The studies of Di Francescantonio [28], Brentner and Farassat [24] showed that the surface source terms of the FW-H equation account for the nonlinear quadrupole terms surrounded by a permeable integration surface. The most intense quadrupole sources were in the vicinity of the blades.

In the study of Brentner and Farassat [24] it was shown that if surface surrounds the blade and the volume of intense quadrupole sources in the FW-H method, then the level of acoustic pressure could be correctly calculated. The weaker quadrupole sources, which are distant from the blade surface, make smaller distortion of the acoustic wave form. For that reason, the external quadrupole sources might be ignored when the integration surface is quite close to the noise generating surface.

One of the recent studies done by Rahier et.al. [29] provided insight to the additional terms for the use of FW-H surface integrals. The study specified the links between the surface and volume integrals. Additionally, the writers defined a new expression of additional surface terms that could represent an estimate of the missing volume integral [29].

2.2. Wind Turbine Blade Aerodynamics and Blade Element Theory

Airfoils are utilized to generate aerodynamic forces by the airfoil's relative dynamics and an enclosing fluid. The airfoil shape cross sections constitute the wind turbine blades and the wind turbine blade dimensions are determined based on the required aerodynamic performance, the airfoil properties, the highest required turbine power, and strength requirements [30].

The terminology related to airfoils is presented in **Figure 2.1**.

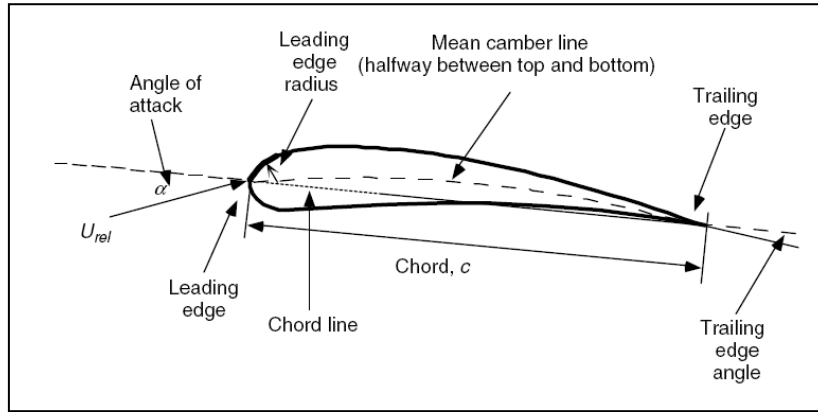


Figure 2.1 Airfoil Terminology [30]

Additionally, the airfoil span indicates the extent of the airfoil at 90 degree to its cross section. The radius of leading edge, trailing edge angle, maximum thickness, mean camber line, and airfoil thickness distribution are the other parameters affecting the aerodynamic properties of the airfoil [30].

2.2.1. Flow around airfoil

Before proceeding to the definition of forces on airfoil, the basic definitions shall be discussed. Basically, the pressure distribution on the surface of the airfoil and the friction involving the airfoil and the air generates the lift and drag forces, thus pitching moment. The air velocity changes cause the pressure variations and this phenomenon can be explained by the principle of Bernoulli. That principle defines that the summation of static pressure and dynamic pressure are constant under the assumption of frictionless flow [30].

$$p + \frac{1}{2} \rho v^2 = \text{constant} \quad (2.9)$$

here, p defines the static pressure. v defines the local velocity on the surface.

The pressure drops when the air flow accelerates around the leading edge and later on negative pressure gradient is observed. When the air flow gets close to the trailing edge, the flow decelerates, in the meanwhile pressure of surface increases. Thus, a positive pressure gradient is observed. A net lift force is generated if the air flow of the upper surface speeds up more than the lower surface of the airfoil for the given airfoil design and angle of attack [30].

The friction between the airfoil and the air flow and pressure distribution over the airfoil generates drag force. Net pressure distribution generates drag due to pressure in air flow direction. On the other hand, the drag force component generated by friction depends on the

fluid viscosity and this component emits energy into the environment [30].

Two different regions of the flow are developed due to drag. The first region is far from the airfoil surface. In the region, the effects of friction are insignificant. The second is the boundary layer, just around the airfoil surface. In this region, effects of friction dominate and the flow velocity increases from zero to the undisturbed flow velocity outside the boundary layer. The boundary layer thickness may differ from a millimeter to tens of centimeters on a wind turbine blade. Laminar flow and turbulent flow may be developed in the boundary layer. Generally, the boundary layer flow becomes turbulent due to effects of viscosity and inertial forces at some point downstream [30].

2.2.2. Forces on airfoil

Lift and drag forces acting on generic airfoil section, chord and angle of attack are presented in **Figure 2.2**.

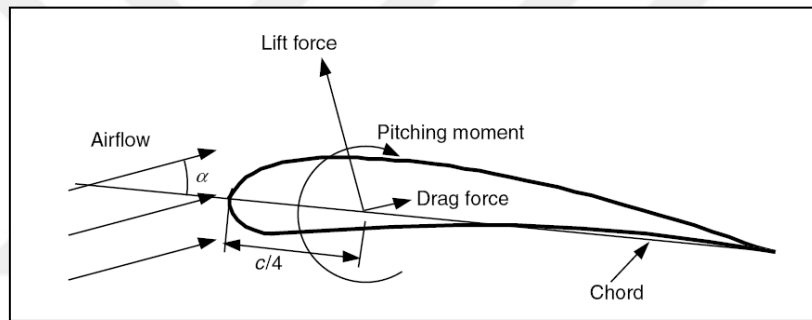


Figure 2.2 Forces and Moments Acting on Generic Airfoil Section [30]

Distribution of forces is generated by air flow over airfoil. Lift force is generated as result of uneven pressure on the lower and upper surfaces of the airfoil. And, lift force is perpendicular to the direction of incoming airflow.

Drag force is generated by two reasons. First, by the friction forces on the airfoil surface, and second, by the uneven pressure on the airfoil surfaces in front of the incoming flow and the opposite.

Another important term related to airfoil flow to define features of flow behaviour is the Reynolds number, Re . It is a non dimensional parameter and the ratio of the inertial forces to viscous forces. And, Reynolds number is defined by,

$$Re = \frac{\rho v L}{\mu} = \frac{\rho v L}{\mu} = \frac{\text{Inertial Force}}{\text{Viscous Force}} \quad (2.10)$$

Here, L is the characteristic length, v is the velocity of the fluid, ρ is the fluid density, μ is the fluid viscosity and $\nu = \mu / \rho$ is the kinematic viscosity of the fluid. In our case, L is the chord length of the airfoil, c .

The other important non dimensional coefficients related to the flow are two dimensional lift coefficient C_l , and two dimensional drag coefficient, C_d [30].

$$C_l = \frac{L/l}{\frac{1}{2}\rho v^2 c} = \frac{\text{Lift force per length}}{\text{Dynamic force per length}} \quad (2.11)$$

$$C_d = \frac{D/l}{\frac{1}{2}\rho v^2 c} = \frac{\text{Drag force per length}}{\text{Dynamic force per length}} \quad (2.12)$$

Here, l is the airfoil span.

2.2.3. Blade element theory

According to Blade Element Theory, the forces on the wind turbine blades might be defined as dependent on lift coefficient, drag coefficient, and angle of attack. In the analysis, the assumption of dividing the blade into N sections is illustrated in Figure **Figure 2.3** [30].

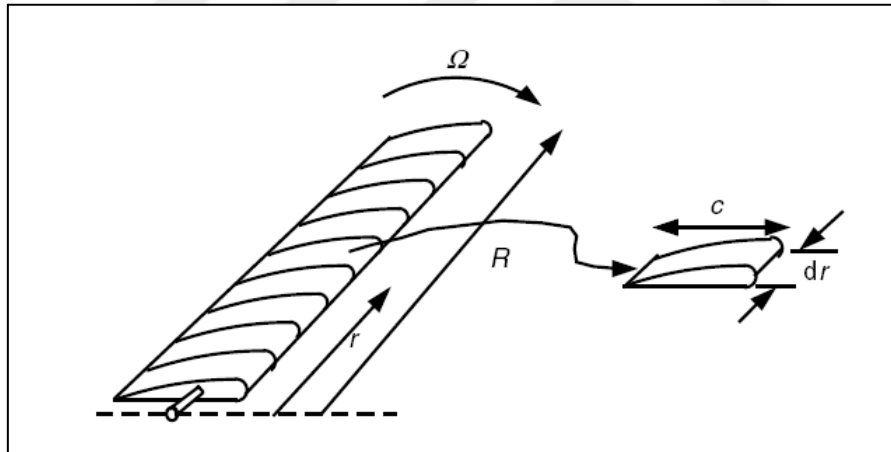


Figure 2.3 Illustration of Blade Elements [30]

Here, c , is the chord length, dr is the radial length of the element, r is the radius, R is the radius of rotor, and Ω is the angular velocity of rotor. The main assumptions are; first, there is not any interaction between elements. In other words, there is no radial flow. Second, the forces on the blades are resolved only by the lift and drag forces of the airfoil sections through the blade [30].

The lift and drag forces are perpendicular and parallel to relative wind, respectively. The vector summation of the wind velocity at the rotor, $U(1-a)$, and the wind velocity because of blade rotation is the relative wind. The mentioned rotational velocity component is the vector

summation of the blade section velocity, Ωr , and the induced angular velocity at the blades from conservation of angular momentum, $\omega r/2$. The expression is as follows [30],

$$\Omega r + (\omega/2)r = \Omega r + \Omega d r = \Omega r(1 + d) \quad (2.13)$$

The overall flow presentation of a horizontal wind turbine is shown in **Figure 2.4**.

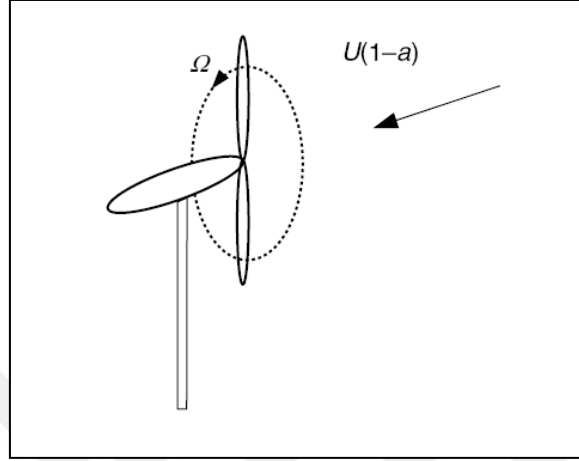


Figure 2.4 Overall Geometry of a Horizontal Wind Turbine Analysis [30]

The blade geometry with affecting forces, angles, and the velocities at the blade are presented in **Figure 2.5** by looking down from the blade tip.

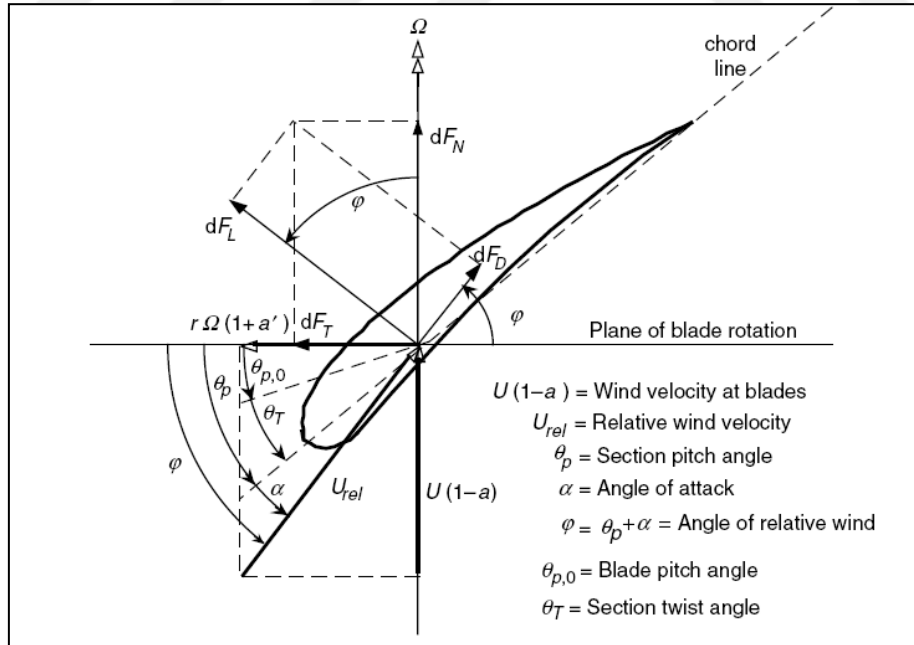


Figure 2.5 Detailed Blade Geometry of a Horizontal Wind Turbine [30]

Here, θ_p is the sectional pitch angle and indicates the angle between the plane of rotation and

the chord line. $\theta_{p,0}$ is the blade pitch angle at the tip and θ_T is the blade twist angle. α is the angle of attack and defines the angle between the relative wind and the chord line. φ is the angle of relative wind and it is the summation of section twist angle and angle of attack for zero pitch angle. U_{rel} is the relative wind velocity.

Incremental forces are shown as dF_L for lift, dF_D is for drag. dF_N is the incremental force normal to the plane of rotation and this force component contributes to thrust. dF_T is the incremental force tangential to the circle swept by the rotor and this component of force creates useful torque. Additionally, θ_T blade twist angle is defined relative to the blade tip where $\theta_{p,0}$ is the blade pitch angle at the tip [30].

$$\theta_T = \theta_p - \theta_{p,0} \quad (2.14)$$

When θ_p changes of the position of the blade, $\theta_{p,0}$, changes, even though the twist angle is a function of the blade geometry. Additionally, the relative wind angle is the summation of the angle of attack and section pitch angle [30].

$$\varphi = \theta_p + \alpha \quad (2.15)$$

In case of zero blade pitch angle, the angle of relative wind is as follows,

$$\varphi = \theta_T + \alpha \quad (2.16)$$

Following equations can be determined considering **Figure 2.5** [30].

$$\tan \varphi = \frac{U(1-a)}{\Omega r(1+a)} = \frac{1-a}{(1+a)\lambda_r} \quad (2.17)$$

$$U_{rel} = \frac{U(1-a)}{\sin \varphi} \quad (2.18)$$

$$dF_L = C_l \frac{1}{2} \rho U_{rel}^2 c dr \quad (2.19)$$

$$dF_D = C_d \frac{1}{2} \rho U_{rel}^2 c dr \quad (2.20)$$

$$dF_N = dF_L \cos \varphi + dF_D \sin \varphi \quad (2.21)$$

$$dF_T = dF_L \sin \varphi - dF_D \cos \varphi \quad (2.22)$$

If the rotor has B number of blade, the total normal force on the section at distance, r , from the center is given by following equation [30],

$$dF_N = B \frac{1}{2} \rho U_{rel}^2 (C_l \cos \varphi + C_d \sin \varphi) c dr \quad (2.23)$$

The differential torque generated by the tangential force operating at a distance, r , from the

center is given by following equations [30],

$$dQ = BrdF_T \quad (2.24)$$

and,

$$dQ = B \frac{1}{2} \rho U_{rel}^2 (C_l \sin \varphi - C_d \cos \varphi) cr dr \quad (2.25)$$

The equations (2.23) and (2.25) provide the definition of normal force (thrust) and tangential force (torque), respectively by way of utilizing blade element theory. These forces are defined in terms of the corresponding section of rotor as a function of airfoil characteristics and flow angles compare to the blades [30].

2.3 Sound and Noise

2.3.1. Sound and noise fundamentals

Sound is generated by rapid pressure fluctuations and sound waves are described by their speed of sound, c , frequency, f , and wavelength, λ . These three terms related to each other as follows [30]:

$$c = f\lambda \quad (2.26)$$

The speed of sound is a function of the medium that sound travels. The sound travels about 340 m/s speed in atmospheric air at room conditions and it generally moves quicker in higher density media. Sound frequency determines the note or in other words the pitch that a person hears. On the other hand, an octave indicates the frequency band between one frequency sound and sound with two times of that frequency. The human can generally hear the frequencies between 20 Hz and 20 kHz.

Basically, noise is unwanted sound. Perception of people sound as noise relies on some subjective factors. For instance, sound level and duration of the sound. The major factors related to the potential environmental impact of wind turbine noise are presented in **Figure 2.6** [31].

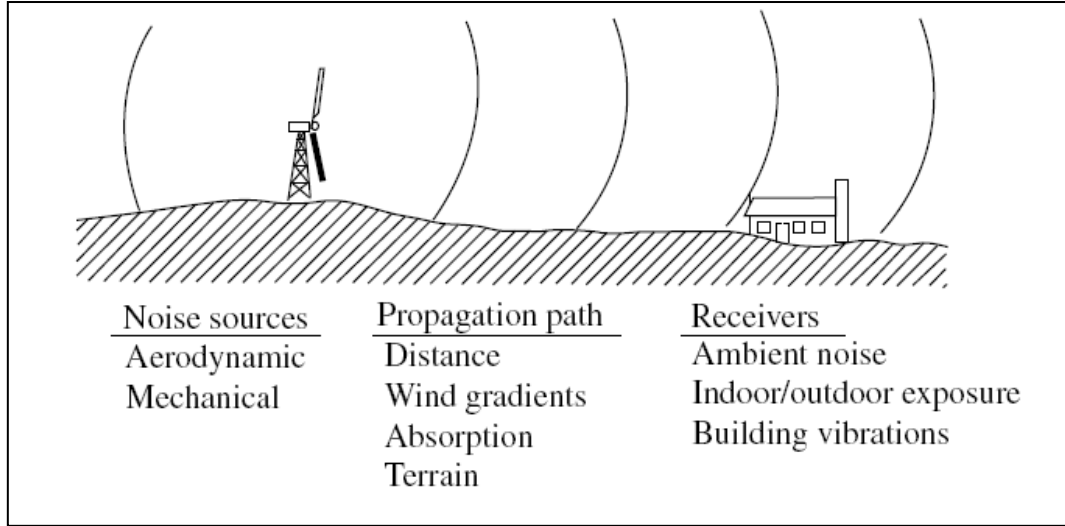


Figure 2.6 Wind Turbine Noise Assessment Factors [31]

There is a clear distinction between levels of sound power and sound pressures. Sound power level is attributed to the sound source; hence it provides the total acoustic power emission of the source. But on the other hand, sound pressure level is attributed to the sound itself at a defined location and sound pressure level can be determined by a microphone. In applications, the magnitude of an acoustical magnitude is defined in logarithmic scale and it is represented in level of decibels (dB) compared with a zero reference level.

Sound power level of a source, L_w , in units of decibels (dB) is expressed by the following equation [30],

$$L_w = 10 \log_{10}(W/W_0) \quad (2.27)$$

Here, W is the source sound power and W_0 is a reference sound power, which is generally 1×10^{-12} W. The sound pressure level of a source, L_p , in units of decibels (dB) is expressed by the following equation [30],

$$L_p = 20 \log_{10}(p/p_0) \quad (2.28)$$

Here, p is the instantaneous sound pressure and p_0 is a reference sound pressure, that is generally 20×10^{-5} Pa.

Vibrations in low frequencies are characteristically classified as low frequency sound and infrasound. Low frequency sound is named for the frequencies between 10 - 100 Hz, and *infrasound* is named for below 20 Hz, the general human perception limit. Infrasound has always been present in the surroundings. It is generated by various sources; such as ambient atmospheric turbulence, traffic, airlines, constructions, other digging, drilling machineries.

Infrasound propagates longer distances than higher frequencies because of having lower atmospheric absorption rate. The basic features of human perception of low frequency sound and infrasound are outlined as follows [30];

- Infrasound and low frequency sound are recognized as a combination of auditory and discernible sensation.
- Lower frequencies of sound shall have a bigger magnitude in dB to be perceived. Because, the threshold of hearing is roughly 100 dB at 10 Hz, at the same time the threshold is 40 dB at 50 Hz.
- Tonality of sound cannot be distinguishable below approximately 18 Hz.
- Due to long wavelength of infrasound, it may not be a sound emitted from a specific location.

According to Manwell et al. [30], annoyance is the main human response to infrasound with side effects as consequence. Some factors affect the level of annoyance; such as intensity of sound, deviations respect to time, highest level and period of sound. Annoyance of infrasound prevails based on three effects; general sensation of static pressure, clattering of windows and doors due to strong low frequency elements, and masking effects in certain frequencies like medium and high frequencies periodically [30] [31].

Examples of different sound pressure levels in pressure scale and in decibel scale are presented in **Figure 2.7**. The threshold of pain is approximately 200 Pa for human ear as sound pressure, and this value is equal to sound pressure level of 140 dB.

The logarithmic decibel scale has the following characteristics [30],

- A 1 dB change in sound level cannot be distinguished other than laboratory ambient,
- A 3 dB change in sound level is regarded as a hardly perceptible difference outside of laboratory.
- A 5 dB sound level change will usually cause an obvious public response.
- Sound level increase of 10 dB is individually heard as almost double in loudness and generally causes unfavorable public reaction.

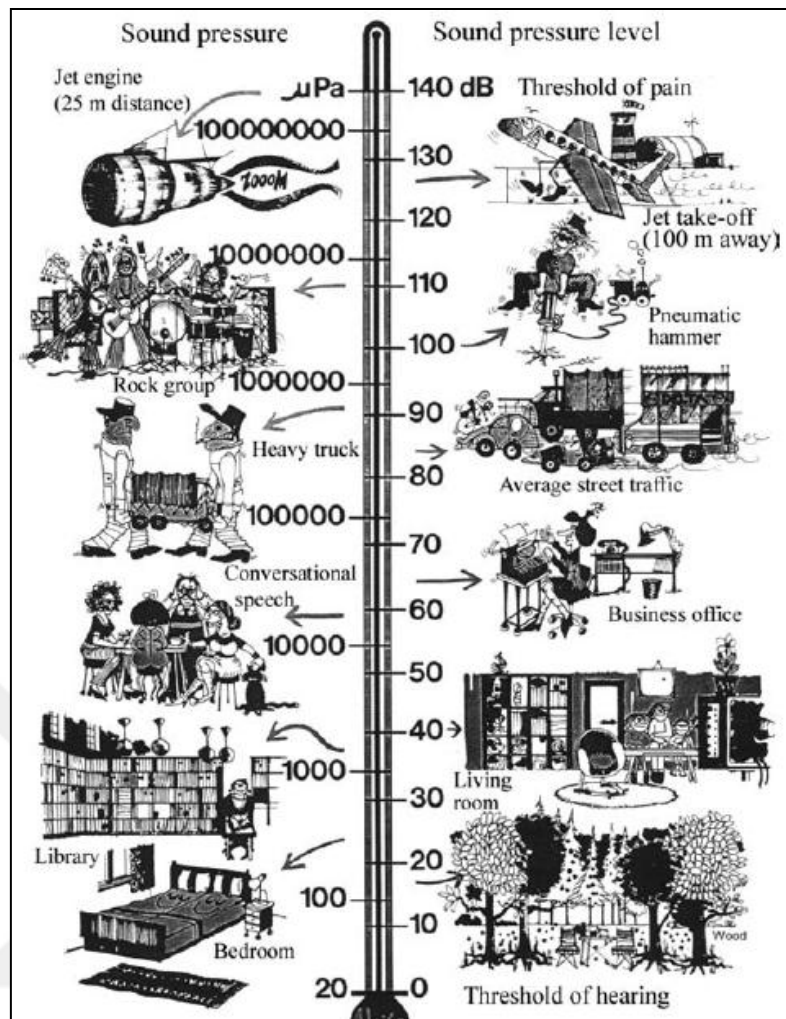


Figure 2.7 Sound Pressure Level (SPL) Examples [30]

Sound level meters are usually applied some filters which provide degradation to lower frequencies in order to determine reaction of human ear. These filters, in other words weighting scales are named A, B, and C scale and presented in **Figure 2.8** [32]. Additionally, there is G weighting scale and it is mainly designed for infrasound. Generally, A scale is utilized for environmental noise measurements, and measurements made by this filter are designated in units of dB(A).

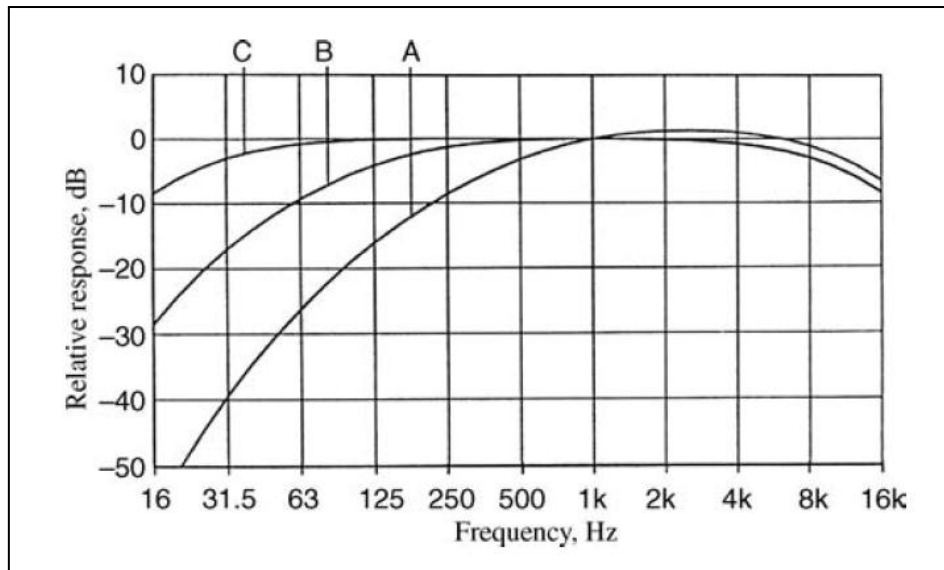


Figure 2.8 Curves for A, B, and C Frequency Weighting Scales [32]

After the measurement of A weighted scale for a period of time, measurements can be utilized different purposes. They can be used to determine some statistical explanation and to clarify the sensitivity of night time noise levels. General noise descriptions are as follows [30],

L_{10} , L_{50} , L_{90} : These descriptions stand for the A weighted noise levels that are surpassed by 10%, 50%, and 90% of the measurement time, respectively. L_{90} is generally considered as the background noise level.

L_{eq} (equivalent noise level): The average A weighted sound pressure level that provides the identical total energy while the changing sound level during the measurement period.

L_{dn} (day and night noise level): This descriptor represents the average A weighted noise level in 24 hours. By adding 10 dB to the noise measurements between 10 pm and 7 am, this descriptor can be calculated.

2.3.2. Noise mechanisms of wind turbines

2.3.2.1. Types of noise

During the operation of wind turbine, basically four types of noise are generated. They are tonal, broadband, impulsive, and low frequency and their descriptions are written below [30].

Tonal Noise. It is the noise at separate frequencies. This type of noise is generated by wind turbine parts like connected gears, by vortex shedding from trailing edge bluntness, by unstable behavior of boundary layer related to turbine blade, irregular flows over gaps or cracks on the blade.

Broadband Noise. This noise is distinguished by a constant sound pressure distribution. The sound pressure frequencies are bigger than 100 Hz in broadband noise. It is usually generated when wind turbine blades interact with environmental turbulence. Moreover, it is known as "whooshing" or "swishing" sound.

Impulsive Noise. This noise type is characterized by short acoustic impulses and thumping sound which change in amplitude in time. The cause of this type of noise can be the interaction of turbine blades with the effected air flow around the downwind turbine tower, and/or the unexpected use of tip breaks or actuators.

Low Frequency Noise. This type of noise is described in frequencies between 20 Hz and 100 Hz and it is generally essential to downwind turbines. Mainly, it is generated when the turbine blades meet local flow deficiencies generated by the flow around a turbine tower and due to the wakes shed by other blades.

2.3.2.2. Aerodynamic noise

Primarily, noise emitted from wind turbines can be divided into two categories. First, aerodynamic noise, the later is mechanical noise. The major sources of mechanical noise are the generator and gearbox. And, it is transmitted through the turbine structure and dissipate by it surfaces. Mechanical noise is not in the scope of this work.

Aerodynamic noise is generated by the flow on the blades. Schematic of flow around a turbine blade is presented in **Figure 2.9**. A big number of complicated incidents generate this type of noise. The various aerodynamic noise mechanisms are divided into three main groups [33]. They are grouped as low frequency noise, airfoil self noise, and inflow turbulence noise.

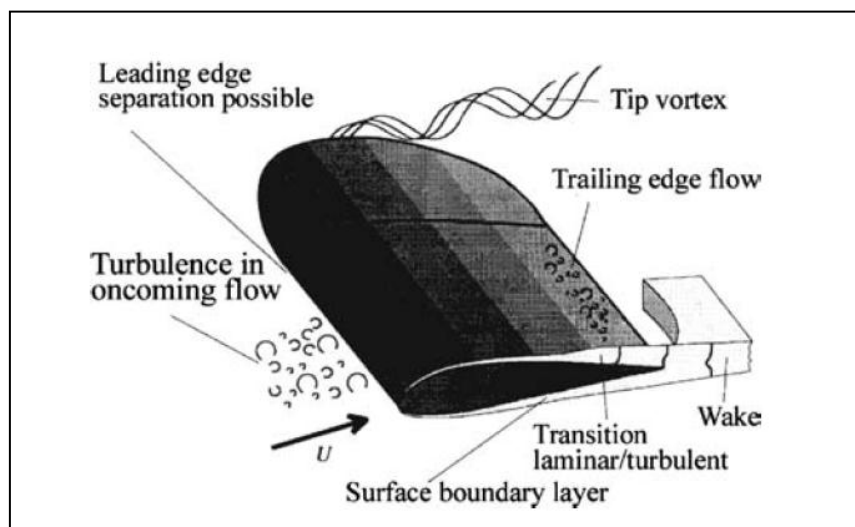


Figure 2.9 Schematic Presentation of Flow Around a Rotor Blade [33]

Low frequency noise

This sound is produced when the rotating blade meets local flow deficiencies. These deficiencies may be caused by changes in wind speed, surrounding flow of the tower, or shedding of wakes the other blades [33].

Steady thickness and loading noise is generated by the rotating of the blade due to the rotation of lifting surfaces. In this type of noise, frequency is related to blade passing frequency.

Unsteady loading noise is caused by passing of the blades through tower speed deficit or turbine wakes. Frequency is also related to blade passing frequency as well. This type of noise contributing of total noise is possibly bigger in case of wind farms [33].

Inflow turbulence noise

This sound depends on the atmospheric turbulence. Local force or local pressure fluctuations around the blade generates atmospheric turbulence [33].

According to the study of Son et al. [12] turbulent inflow noise is generated by inflow turbulence. Yet, turbulence causes unsteady loading distribution on the blades. Spectrum of turbulent inflow noise relies on size of the eddies. If the eddy size is bigger than the airfoil chord length, it produces the low frequency noise. When the eddy size is a lot smaller than the chord length, it generates the high frequency noise [12].

Inflow turbulence sound is also known as leading edge interaction noise. Unsteady loading distribution causes unsteady lift by the blade when the blade interacts with the turbulent eddies. The unsteady lift generates sound like a dipole source which is located at the leading edge of blade. This sound has directivity pattern like dipole source [34].

Airfoil self noise

This group sound is produced by the air flow by the side of the surface of the airfoil. This sound is generally broadband and it is related to the boundary layer on the blade surface. Conversely, tonal noise components may generate because of trailing edge bluntness, flow over gaps and holes [33].

Airfoil noise emission is caused by the instabilities in boundary layer or interaction of eddies with the airfoil surface in the boundary layer. Some mechanisms that generate airfoil self noise as follows: trailing-edge noise, laminar boundary layer noise, tip noise, stall separation noise, blunt trailing edge noise, noise from blade surface imperfections.

Airfoil self noise generation occurs on the blade itself due to turbulence. Turbulence is

generated inside the boundary layers either attached or separated because of the random pressure variations on the blade. Tip vortex formation noise, trailing edge noise, and laminar vortex shedding noise are the other self noise sources [23].

Trailing edge noise: Because of the presence of viscous shear between the air and the blade, a boundary layer is developed. This boundary layer will generally transit to a turbulent state when air reaches the trailing edge, especially on large wind turbine flow conditions. When turbulent eddies go by the trailing edge of a wind turbine blade, the acoustic waves due to turbulence are strengthened by the diffraction at the edge. This phenomenon is called as trailing edge noise [34].

The directivity pattern of trailing edge noise is different than a monopole or a dipole source. Most of the sound is radiated to the forward direction of the blade in the direction of the rotation that is why less value of the sound is radiated behind. This is known as cardioid directivity pattern. Boundary layer turbulence going by the trailing edge of the blade is the fundamental mechanism of this type of noise [34].

Airfoil tip noise: Flow over the blade tip produces airfoil tip noise and this noise is prevalent in the trailing edge vortex system. This type of noise generation is like trailing edge noise, because the turbulence interacts with an edge. Its directivity pattern is cardioid and interacting turbulence with rotor tip vortex shedding is the basic mechanism [34].

Airfoil tonal noise: Strong tonal noise is generated because separate vortices appear either in boundary layer or at the wake. Tonal noise occurs at low to moderate Reynolds numbers, for that reason it is not usually a problem for large wind turbines that operate at high Reynolds numbers. Small wind turbines which generate power less than 10 kW may operate at conditions where tonal noise comprises majority of the noise source. This type of noise has cardioid directivity pattern, furthermore vortex shedding or feedback loop in resonance on rotor blade boundary layer is the mechanism of this type of noise [34].

Graphical representation of airfoil self noise generating mechanism is shown in **Figure 2.10** [35].

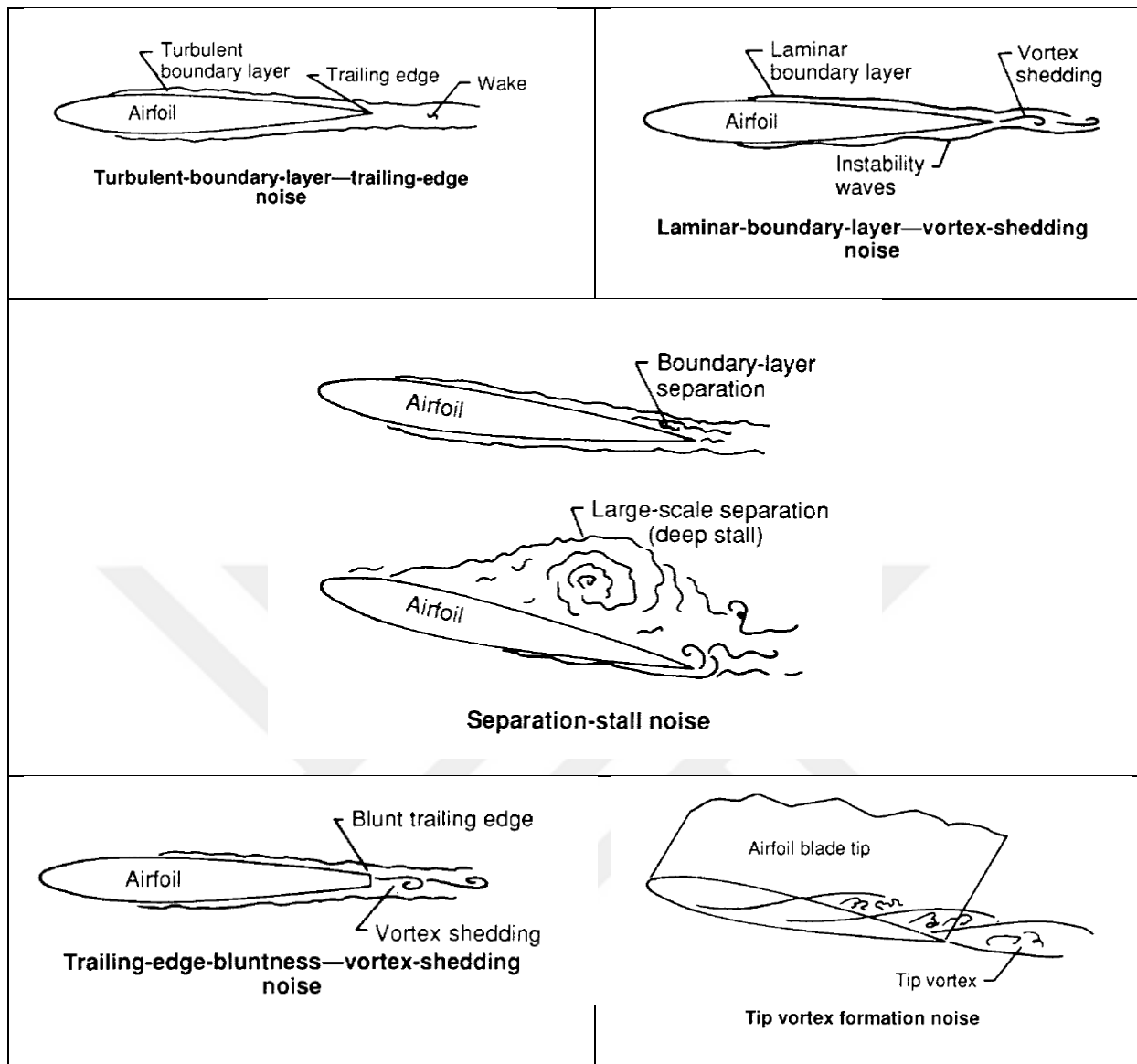


Figure 2.10 Flow Conditions Producing Airfoil Self Noise [35]

Blade tower interaction noise: Additionally, another type noise mechanism due to blade and tower interaction is worth to discuss. The interaction of the turbine blade with the tower can be an significant noise generating mechanism. Nowadays, blade tower interaction noise is eliminated since the modern horizontal axis wind turbines are upwind turbines and the rotor is placed to the upstream of the tower [34]. On the other hand, the blades still pass through an area of disturbed flow upstream of the tower, this situation generates unsteady lift and consequently it generates noise [33].

The directivity pattern of blade tower interaction noise is dipole. The noise generating mechanism is turbine blade passing through flow disturbed by tower. Since the turbine blade passes through this disturbed flow region, the angle of attack varies on the blade and this

change induces a variation in lift force. This variation in lift force radiates sound with a time scale connected to the size of the disturbed flow area at the upstream of the tower [34].

2.3.3. Noise propagation from wind turbines

The propagation of sound waves should be considered in order to calculate the sound pressure level from a source, where sound power level is known, to a specified location. In the study of Beranek and Ver [32], the details of sound propagation are presented.

Under spherical spreading assumption, sound pressure level can be calculated for a single wind turbine. Pressure level is decreased by 6 dB when the distance is doubled for spherical spreading. If the source of noise is located on perfectly flat and reflecting surface, the spreading may be assumed hemispherical. And, in hemispherical spreading assumption, sound pressure level is decreased by 3 dB when the distance is doubled [30].

The atmospheric absorption and the ground effect depend on noise frequency and distance between the source and observer. The absorption coefficient graphic is presented in **Figure 2.11** [31]. Additionally, effect of the ground is basically, a function of height of the emission point and the coefficient of the ground reflection.

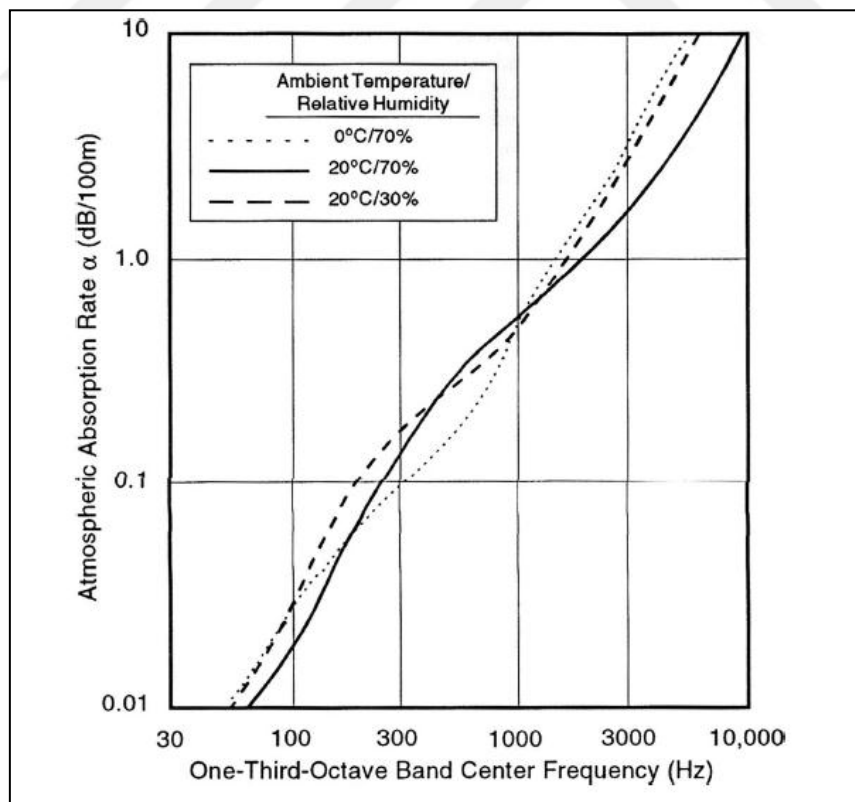


Figure 2.11. Standard Rate of Atmospheric Absorption [31]

Considering hemispherical noise propagation on a reflective surface, a simple formulation is defined below with air absorption [30].

$$L_p = L_W - 10 \log_{10}(2\pi R^2) - \alpha R \quad (2.29)$$

Here, L_p is the sound pressure level in units of dB at a distance R from a noise source that has a sound power level, L_W in units of dB. And, α is the sound absorption rate which is based on frequency and humidity.

2.3.4. Threshold of hearing

The threshold of hearing curve exhibits that the required sound intensity to be heard is different for audible frequency range of human. The intensity of sound is required to be 60 dB at 30 Hz to be heard. On the other hand, the maximum sensitivity is about 2000 to 5000 Hz according to the **Figure 2.12** [36].

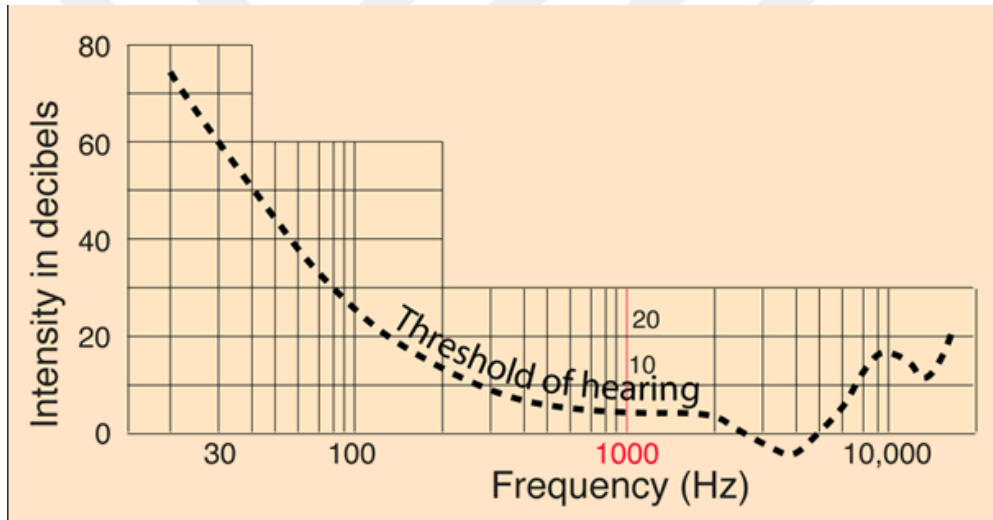


Figure 2.12 Threshold of Hearing [36]

Furthermore, equal loudness curves shall be noted. After examination of these curves, it can be stated that there is considerable difference between response of ear at different sound levels. This phenomenon is illustrated in **Figure 2.13** [36]. As presented in the figure, the same sound intensity may result different human response based on the frequency that the noise generated.

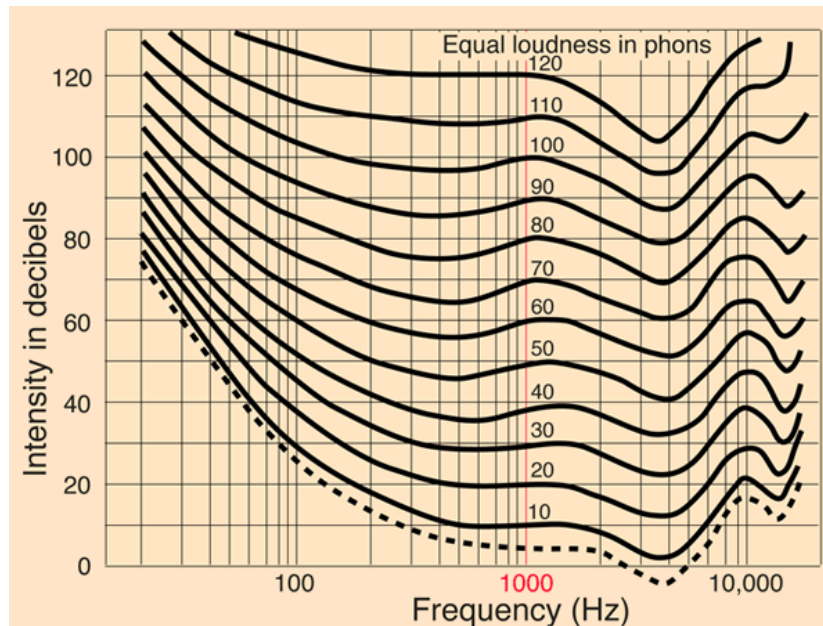


Figure 2.13 Equal Loudness Curves [36]

In the **Table 2.1**, estimated community response to noise is presented. The differential amount by which received noise exceeds threshold level (dB) describes the reaction of community according to [31].

Table 2.1 Estimated Community Responses to Noise [31]

Amount by which received noise exceeds threshold level (dB)	Estimated community response	
	Category	Description
0	None	No observed reaction
5	Little	Sporadic complaints
10	Medium	Widespread complaints
15	Strong	Threats of community action
20	Very Strong	Vigorous community action

2.4. Extreme Operating Gust (EOG), Unsteady Extreme Conditions

International Standard on " IEC 61400-1 Wind Turbines – Part 1: Design Requirements " was prepared and published by International Electrotechnical Commission (IEC). The principle of this standard is specifying necessary design requirements to guarantee the engineering completeness of wind turbines. According to the IEC, aim of the standard is to provide a proper level of integration against accidents generated by dangers during the intended life span [37].

There have been some studies about the aforementioned International Standard in literature. The study of Ishihara, T. et al. examined the characteristics of the standard deviation of the offshore wind by observation of measurements in Eastern Seas of Japan [38]. The study of Freudenreich and Argyriadis demonstrated the effect of the overall load level and discussed the resulting problems [39]. The work of Jonkman [40] published by NREL developed a comprehensive simulation tool in order to model the dynamic response of offshore floating wind turbines. American Wind Energy Association published a report about Large Land Based Wind Turbine Support Structures [41]. In the report, extreme operating gust was considered in fault conditions during power production, start-up and shut-down.

Considering the previous works of academicians, institutes, and associations; EOG was considered in researches and wind turbine design efforts for structural analysis purposes.

International Standard defines extreme wind conditions including wind shear events, peak wind speeds due to storms and rapid changes in wind speed and direction. These wind conditions were formulated based on parameters such as wind turbine classes, turbulence scale parameter, and extreme wind speed and so on. One of the extreme conditions that the wind turbine can encounter is the Extreme Operating Gust that is defined in the IEC 61400-1 [37].

In the IEC 61400-1, external conditions are defined since they shall be evaluated in wind turbine design. According to the standard, the normal external conditions mainly related to regular structural loading conditions, as the extreme external conditions stand for uncommon external design conditions. The normal and extreme conditions are given in this context [37].

The considered external conditions depend on the proposed location or type of location for wind turbine installation. Wind turbine classes are described with regard to turbulence parameters and wind speed and presented in **Table 2.2**. Wind turbine Class S means the required values shall be defined by the designer if special safety issues are required [37].

Table 2.2 Basic Parameters of Wind Turbine Classes [37].

Wind turbine class	I	II	III	S
V_{ref} (m/s)	50	42.5	37.5	Values specified by the designer
$A \quad I_{ref}$ (-)	0.16			
$B \quad I_{ref}$ (-)	0.14			
$C \quad I_{ref}$ (-)	0.12			

All parameters are at hub height and V_{ref} is the reference average wind speed over 10 minutes, A designates the class for higher, B designates the class for medium and C designates the class for lower turbulence characteristics. I_{ref} is the expected mean value of the turbulence intensity at 15 m/s.

2.4.1. Normal wind speed model

According to the IEC 61400-1 [37], the expression "turbulence" denotes random variations in 10 minutes average wind speed. Random wind speed field for the turbulence models shall meet the turbulence standard deviation, σ_1 , and the longitudinal scale parameter, Λ_1 . The longitudinal scale parameter at hub height, z , defined as follows:

$$\Lambda_1 = \begin{cases} 0,7 z & z \leq 60 \text{ m} \\ 42 \text{ m} & z \geq 60 \text{ m} \end{cases} \quad (2.30)$$

The turbulence standard deviation, σ_1 , is defined for the wind speed at the given hub height,

$$\sigma_1 = I_{ref}(0,75 V_{hub} + b) \quad ; \quad b = 5,6 \text{ m/s} \quad (2.31)$$

The reference values for the turbulence standard deviation, σ_1 , and the turbulence intensity σ_1/V_{hub} are presented in **Figure 2.14.** and **Figure 2.15**, respectively.

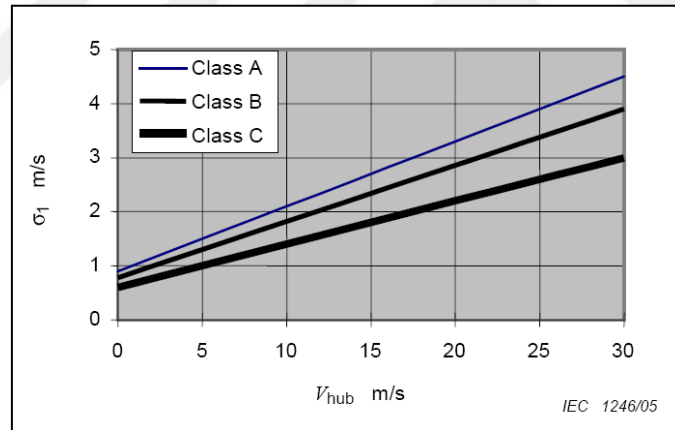


Figure 2.14 Turbulence Standard Deviation, σ_1 , for the Normal Turbulence Model [37]

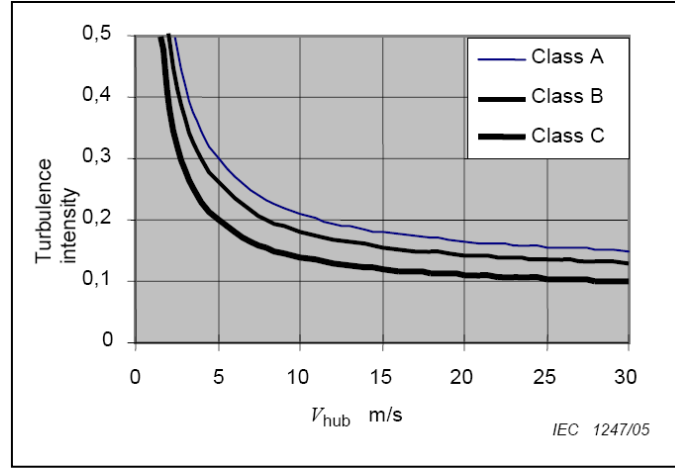


Figure 2.15 Turbulence Intensity for the Normal Turbulence Model [37]

$V(z)$ is the wind profile and indicates the average wind speed as a function of height above the ground, z . The normal wind speed profile is given by the power law as follows. Here, α , is the power law exponent and it is assumed to be 0.2.

$$V(z) = V_{hub} \left(\frac{z}{z_{hub}} \right)^\alpha \quad (2.32)$$

2.4.2. Extreme wind speed model

For the steady extreme wind model, two different extreme wind speed are computed. The first one is V_{e50} , with a recurrence period of 50 years, the second is V_{e1} , with a recurrence period of 1 year. These two extreme wind speeds are calculates as a function of height, z , by following equations:

$$V_{e50}(z) = 1,4 V_{ref} \left(\frac{z}{z_{hub}} \right)^{0,11} \quad (2.33)$$

$$V_{e1}(z) = 0,8 V_{e50}(z) \quad (2.34)$$

The other important parameter for Extreme Operating Gust formulation is the gust magnitude, V_{gust} , at the hub height. It can be computed with the following formulation [37];

$$V_{gust} = \left\{ 1,35(V_{e1} - V_{hub}) ; 3,3 \left(\frac{\sigma_1}{1+0,1\left(\frac{D}{\Lambda_1}\right)} \right) \right\} \quad (2.35)$$

where σ_1 , turbulence standard deviation is given in equation (2.31), turbulence scale parameter, Λ_1 , is given in equation (2.30), D is the rotor diameter, extreme wind speed, V_{e1} is given in equation (2.34).

Then, wind speed is calculated in Extreme Operating Gust (EOG) condition as follows [37],

$$V(z, t) = \begin{cases} V(z) - 0,37V_{\text{gust}} \sin(3\pi t/T)(1 - \cos(2\pi t/T)) & \text{for } 0 \leq t \leq T \\ V(z) & \text{otherwise} \end{cases} \quad (2.36)$$

$V(z)$, the normal wind speed profile is given in equation (2.37) and T is equal to 10.5 second. In the IEC 61400-1 [37], an example of Extreme Operating Gust is shown in **Figure 2.3** for the following input conditions; $V_{\text{hub}} = 25$ m/s, Class I_A, and $D = 42$ m.

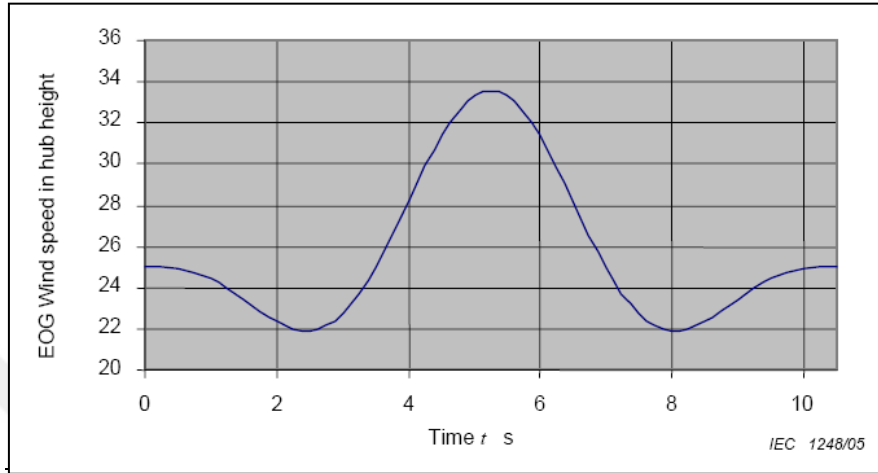


Figure 2.16 An Example of Extreme Operating Gust [37]

3. METHODOLOGY

Wind Tunnel Test Configurations were performed and published by National Renewable Energy Laboratory (NREL) in Unsteady Aerodynamics Experiment (UAE) Phase VI [42]. The results of these experiments have been one of the most comprehensive tests about wind turbine aerodynamics. Therefore, a series of wind tunnel tests were carried out in Korea Aerospace Research Institute (KARI) for the study of the scaled effect of wind turbine model. In KARI, 12% scaled model of NREL Phase VI wind turbine was tested at the low speed wind tunnel. Also, KARI conducted acoustic noise measurement with 144 channel microphone array. The wind turbine was operated at a constant rotating speed of 600 rpm to match the tip Mach number of real model test at NASA Ames wind tunnel [43].

Within the scope of this work, the purpose was to perform a two dimensional flow and noise simulation for the two bladed NREL Phase VI wind turbine with the aid of a commercially available Computational Fluid Dynamics (CFD) software ANSYS-FLUENT [44] by using User Defined Functions after applying some corrections under certain assumptions.

Numerous two dimensional simulations were made to gain information about different aspects of the noise generating mechanism of the flow around NREL Phase VI [42] turbine blade. Primarily, numerical/simulation results were compared with the NREL Phase VI experimental data [43] for validation; second, observations were made to draw some conclusions to check the sufficiency of the numerical results.

3.1. Turbine Geometry

The turbine had a stall regulated rotor and had a rated power of 19.8 kW with two twisted and tapered blades based on the S809 airfoil [45] with a diameter of 10.1 m. Rotor rotated at an angular speed of 72 rpm. The turbine rotor was supported with 0.4 m diameter tower at a hub height of 12.192 m and rotor overhang was 1.401 m (yaw axis to blade axis). This UAE configuration was mounted in the NASA Ames wind tunnel [42].



Figure 3.1 Two Bladed Wind Turbine Rotor in NASA Ames Wind Tunnel [42]

Blades had S809 airfoil cross section from 0.25R to the tip at all span locations. The blade taper distribution started at 0.25R ($r = 1.257$ m) with maximum blade chord as 0.737 m and ended at the tip ($r = 5.029$ m) with blade chord as 0.356 m. The blade twist decreased from 20.04° at 0.25R to -1.815° at the tip. The blade twisted about an axis located at 30% chord aft from the leading edge. Blade planform dimensions of Phase VI were shown in **Figure 3.2**.

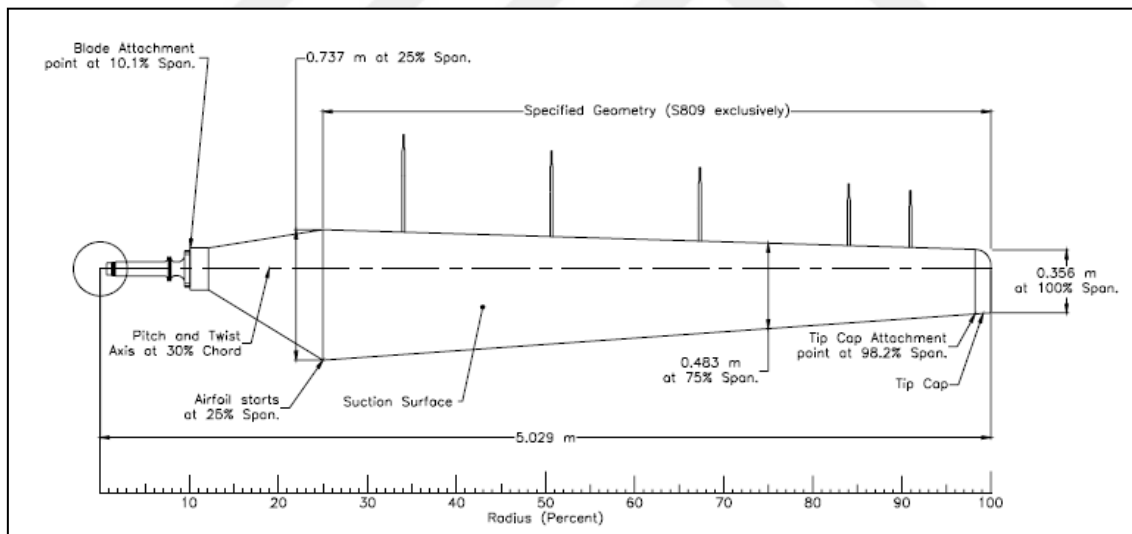


Figure 3.2 Blade Planform Dimensions [42]

The blades of the NREL Phase VI had S809 airfoil cross section [45] which was presented in **Figure 3.3**. Wind turbine detail configuration, physical properties of the blades and aerodynamic performance results were presented in the study of Hand and et al. [42].

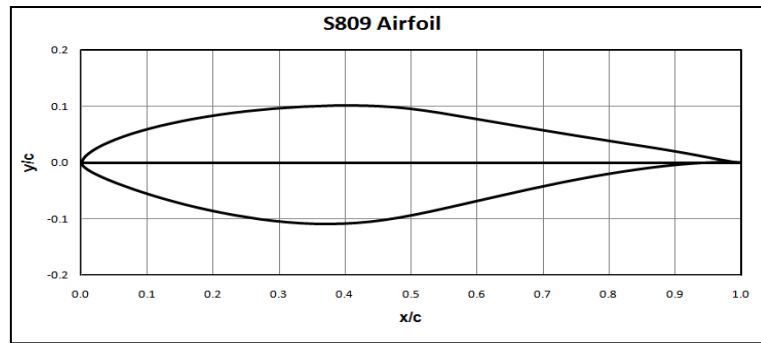


Figure 3.3 NREL S809 Airfoil Profile [45]

3.2. Computational Domain and Grid

Two dimensional S809 airfoil model and mesh was generated by using GAMBIT mesh generator, the interface of GAMBIT mesh generator was shown in **Figure 3.4**.

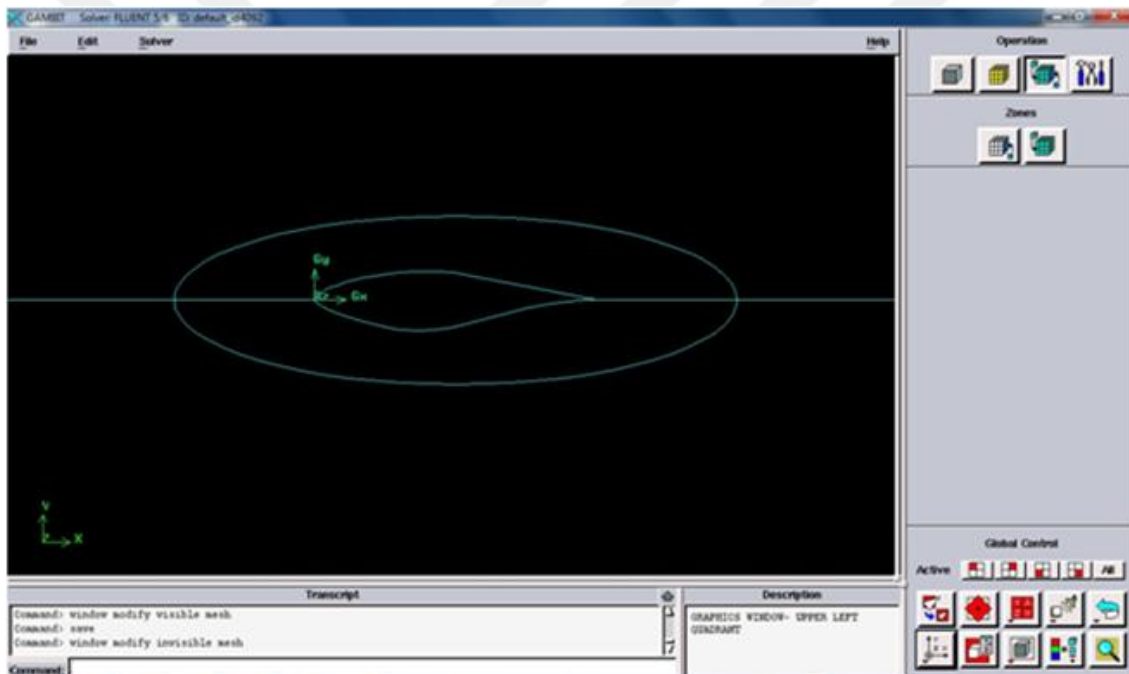


Figure 3.4 NREL S809 Airfoil Profile in GAMBIT Mesh Generator

3.2.1 Domain size

Domain size was 30 chord length in longitudinal axis, 20 chord length in vertical axis. Leading edge of the airfoil was stationed 10 chord lengths far from the inlet and 20 chord lengths far from the outlet. In vertical direction, the airfoil was stationed in the symmetry axis.

3.2.2 Mesh geometry

An elliptic surface was defined around the airfoil. Structured mesh was applied inside the ellipse; mapped mesh was applied at the outer field of the ellipse. Finer mesh was applied around the airfoil as shown in **Figure 3.6**.

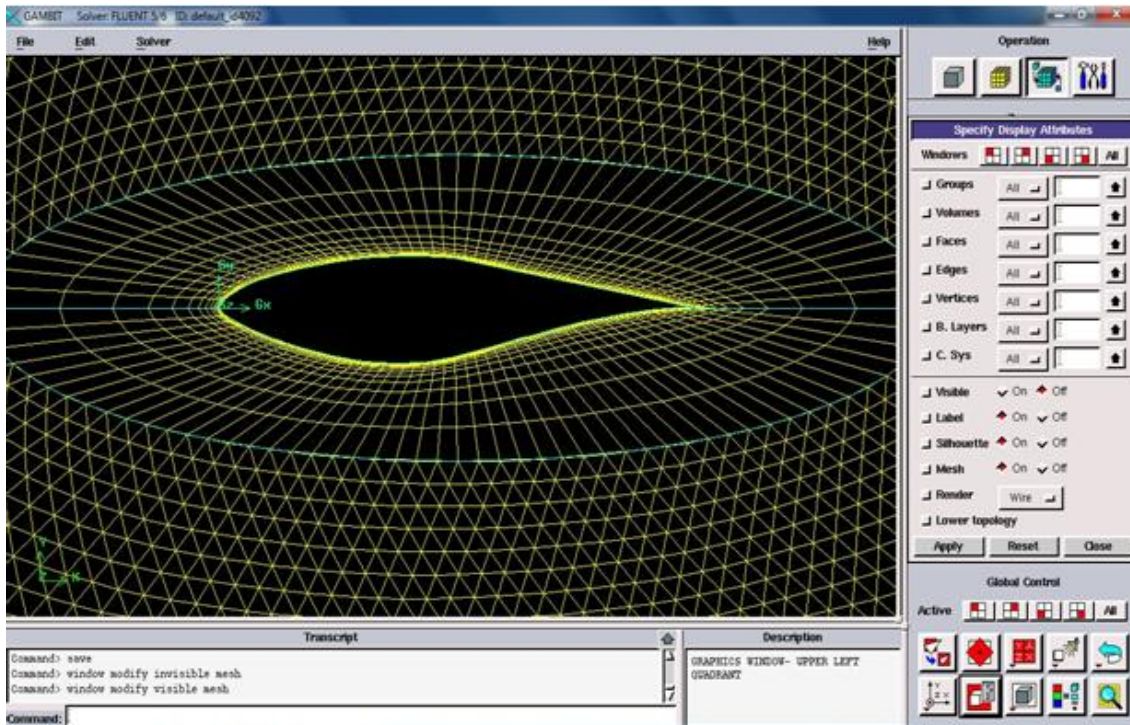


Figure 3.5 Mesh Geometry

3.2.3 Boundary conditions

Boundary conditions of the domain were chosen as follows; velocity inlet at the inlet, pressure outlet at the outlet, periodic boundary condition at the top and at the bottom, wall boundary condition on the airfoil surface. Finer mesh was applied near the airfoil.

3.2.4 Turbulence model

One of the two equation turbulence models based on Reynolds Averaged Navier Stokes (RANS) equations is k-epsilon models. K-epsilon models are standard, RNG (Renormalization Group Method), and realizable k-epsilon model. The meaning of "realizable" is that the model satisfies definite mathematical constraints on the Reynolds stresses. Neither the standard k-epsilon model nor RNG k-epsilon model is realizable [25].

Realizable k-epsilon model has some advantages over standard k-epsilon model. K-epsilon model provides improvements for flows having rotation, recirculation, streamline curvature, and vortices. Moreover, realizable k-epsilon model exhibits better performance for separated flows [25]. For that reason, viscous model with Realizable k-epsilon (2 equation) turbulence model was chosen.

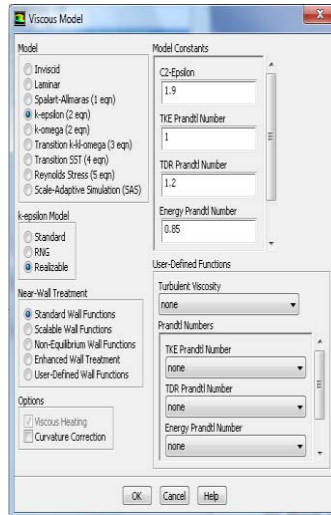


Figure 3.6 Turbulence Model in ANSYS

3.3. Acoustic Model, Assumptions and Corrections

3.3.1 Acoustic model

Ffowcs-Williams & Hawkings equation was applied as acoustic model. Convective effects were included since the analysis was dealing with external flow around a body.

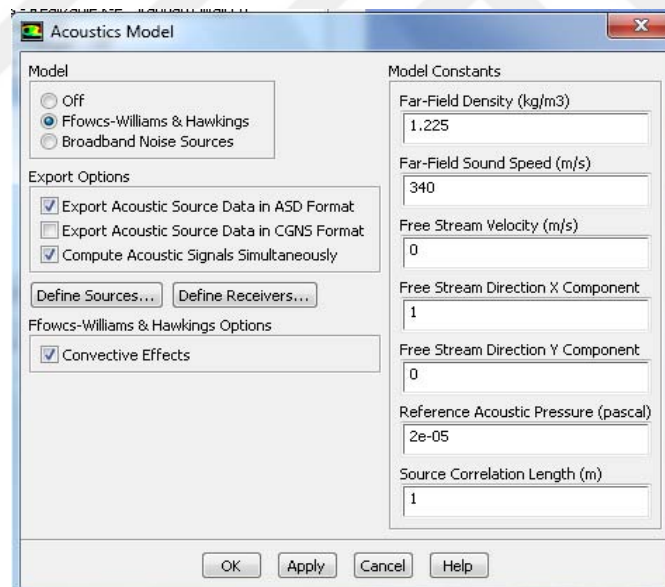


Figure 3.7 Acoustic Model in ANSYS

3.3.2 Assumptions

The explicit formulation which was available only for the density-based solver was utilized mainly to capture the transient behavior of moving waves. While performing transient analysis, acoustic signals were computed simultaneously.

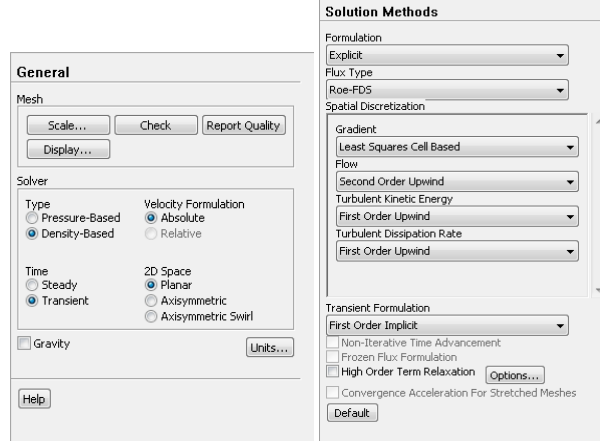


Figure 3.8 Solution Methods in ANSYS

During the calculations, time step size was 0.002 seconds, number of time steps was 1000, Max iterations/time step were selected to be 100 considering stability of the results and convergence.

Frequencies of the results were depended on the time step size. Smaller the time step size, higher the frequency range of the sound pressure level.

One of the distinguished aspects of the analysis was applying dynamic angle of attack velocity to the inlet conditions. By applying dynamic angle of attack calculation, horizontal (X) and vertical (Y) components of residual velocity on each blade section were calculated and integrated to the analysis by using User Defined Functions. Incoming wind speed was a step input, then phi angle was calculated; angle of attack (α) was calculated by subtracting twist angle from the flow angle. Resultant velocity, $W(t)$ was determined. Horizontal component of velocity $W_x(t)$ was obtained by multiplying $W(t)$ by cosine of $\alpha(t)$ and similarly, the vertical component of velocity $W_y(t)$ was found by multiplying $W(t)$ by sine of $\alpha(t)$. This phenomenon was presented in the **Figure 3.9**.

$$\tan \varphi(t) = \frac{\Omega r}{v_{inf}(t)} \quad (3.1)$$

$$\varphi(t) = \text{Arctan} \frac{\Omega r}{v_{inf}(t)} \quad (3.2)$$

$$\alpha(t) = \varphi(t) - \theta_T \quad (3.3)$$

Here, $\varphi(t)$ is the relative wind angle, $v_{inf}(t)$ is the velocity of incoming wind, Ω is the radial velocity, $\alpha(t)$ is the angle of attack, θ_T is the blade twist angle.

Resultant velocity, $W(t)$ was determined as follows.

$$W(t) = \sqrt{V_{inf}(t)^2 + (\Omega r)^2} \quad (3.4)$$

$$W_x(t) = W(t) * \cos(\alpha(t)) \quad (3.5)$$

$$W_y(t) = W(t) * \sin(\alpha(t)) \quad (3.6)$$

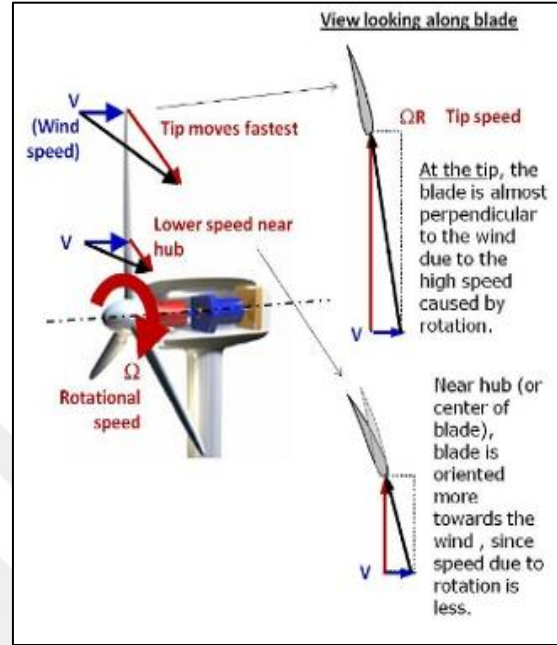


Figure 3.9 Dynamic Angle of Attack Calculation [46]

Unsteady velocity components of x and y directions were calculated and applied as inlet boundary conditions simultaneously through a User Defined Function (UDF).

Selected span wise sections for two-dimensional calculations for comparison were shown in the **Figure 3.10**.

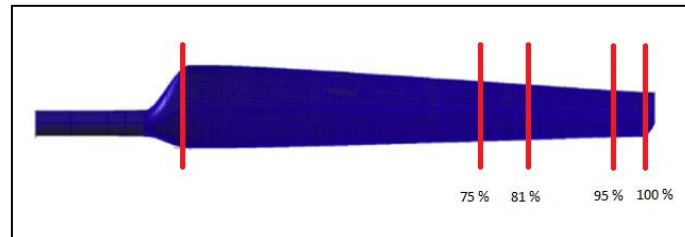


Figure 3.10 Selected Sections For Calculation

Variation of W_x and W_y velocity components with dynamic angle of attack were presented for $r/R = 0.47$ and $r/R = 1.0$ in **Figure 3.11**.

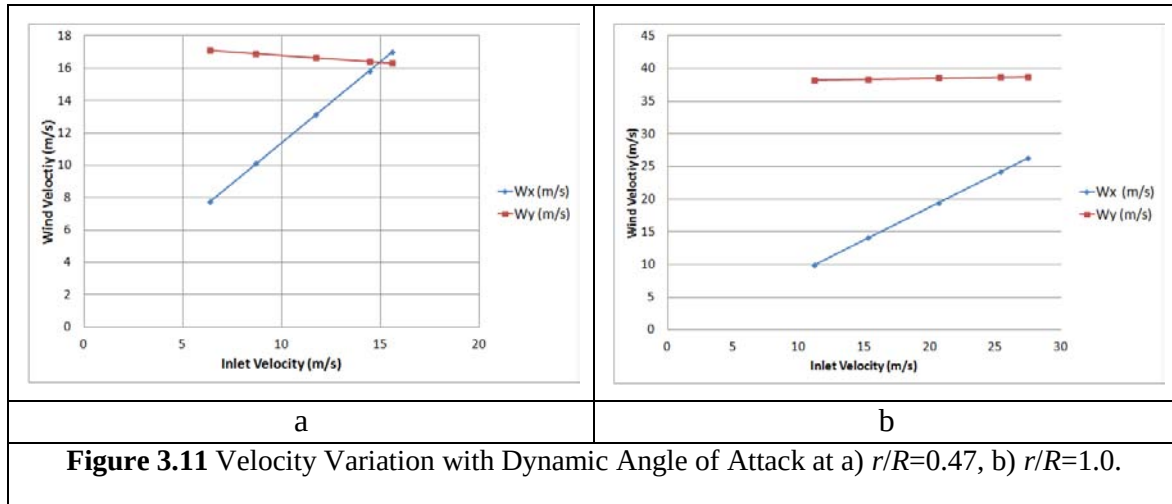


Figure 3.11 Velocity Variation with Dynamic Angle of Attack at a) $r/R=0.47$, b) $r/R=1.0$.

3.3.3 Corrections

Corrections were made to simulate the two dimensional section noise analysis to blade noise. First correction was to adapt the tapered geometry of blade to 2D section. Reynolds similarity was used to simulate the tapered geometry. Inlet speed kept constant at $r/R = 0.25$, for outer sections inlet speed was corrected to keep the same Reynolds number. Graphical representation was shown in **Figure 3.12**.

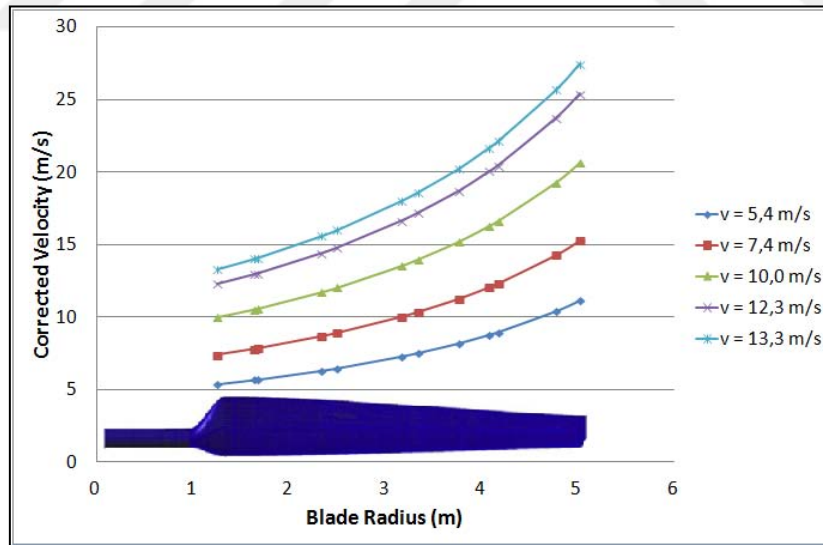


Figure 3.12 Velocity Corrections For Tapered Geometry of the Blade

Second correction was to scale the 2D analysis to 12% scaled model. By using Reynolds similarity, 12% of dynamic viscosity was used to simulate the 12% model test.

$$Re = \frac{vc}{\nu} \quad (3.7)$$

Here, c is the chord length of the airfoil, v is the velocity of the fluid and ν is the kinematic viscosity of the fluid.

Major differences between the three dimensional 12% scaled model test and two dimensional analyses were defined below.

i) In three dimensional (12% scaled) Model Test, actual model noise measurement were performed by using 144 microphones [43].

ii) In two dimensional analysis of the present study;

- Noise of each zone was represented by single two dimensional section noise,
- Single receiver was located 1.88 m away in vertical, 1.49 m away in transversal directions, respectively. These correspond to the coordinates of center of 12% Model Test microphones.
- Interference between sections, tip vortex, and hub vortex effects were not included.

3.4 Sound Power Level vs. Sound Pressure Level

A sound source produces sound power and this generates a sound pressure fluctuation in the air. Where the sound pressure is distance dependent effect, sound power is independent from the distance. Reference values are highly critical for the sound analysis. Reference pressure for sound pressure level (for air) was 2×10^{-5} Pascal. Reference power for sound power level was 1×10^{-12} Watt.

In order to compare the noise measurements of the study [43] and the two dimensional analysis results, predictions in sound pressure levels (dB) were converted to sound power levels.

The conversion was done by the following formula;

$$L_w = L_p + \left| 10 \log \left(\frac{Q}{4\pi r^2} \right) \right| \quad (3.8)$$

Where L_w is the sound power level, L_p is the sound pressure level and Q is the directivity factor, assumed to be unity for spherical propagation.

3.5 Predicting the Total Noise Of The Blade

First, the blades of the wind turbine were nonuniformly divided into two-dimensional airfoil sections. Then, the summation of the contribution from the each blade section was used to predict the total noise emission [47].

According to the study of Zhu et al. [47], the two dimensional noise prediction theory was

applied for each blade section and later on the total noise was determined by summing up all noise sources. In the study Zhu et al., airfoil noise components were calculated based on two dimensional semiempirical formulae [47]. On the other hand, noise generation of airfoil sections were calculated by CFD solution in the current study.

The total noise in terms of Sound Pressure Level for the i^{th} blade element was presented in the following formulation [47]:

$$SPL_{Total}^i = 10 \log_{10} \left(\sum_j 10^{0.1(SPL_j)} \right) \quad (3.9)$$

3.6. Analysis Under Extreme Operating Gust (EOG) Condition

Definition and formulation of Extreme Operating Gust was given in Chapter 2, Theoretical Background. In the IEC 61400-1 EOG formulation is applied for $V_{hub} = 25$ m/s, Class I_A, and $D = 42$ m. input conditions. The graphical representation of the example is shown **Figure 3.13**.

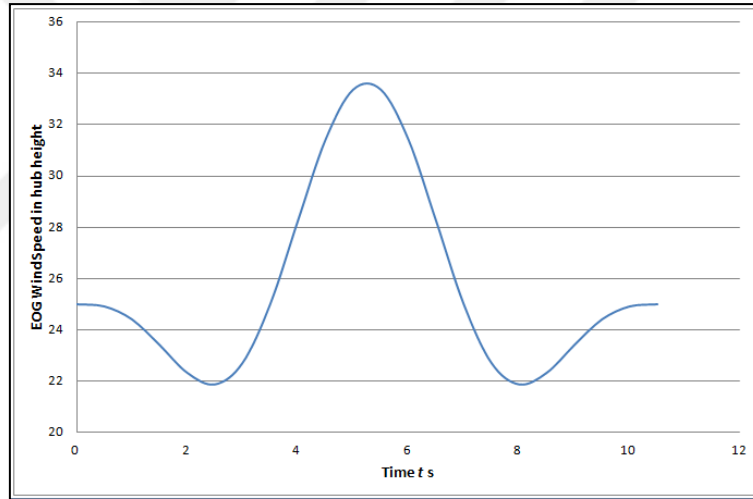


Figure 3.13 IEC61400-1 Example of Extreme Operating Gust [37]

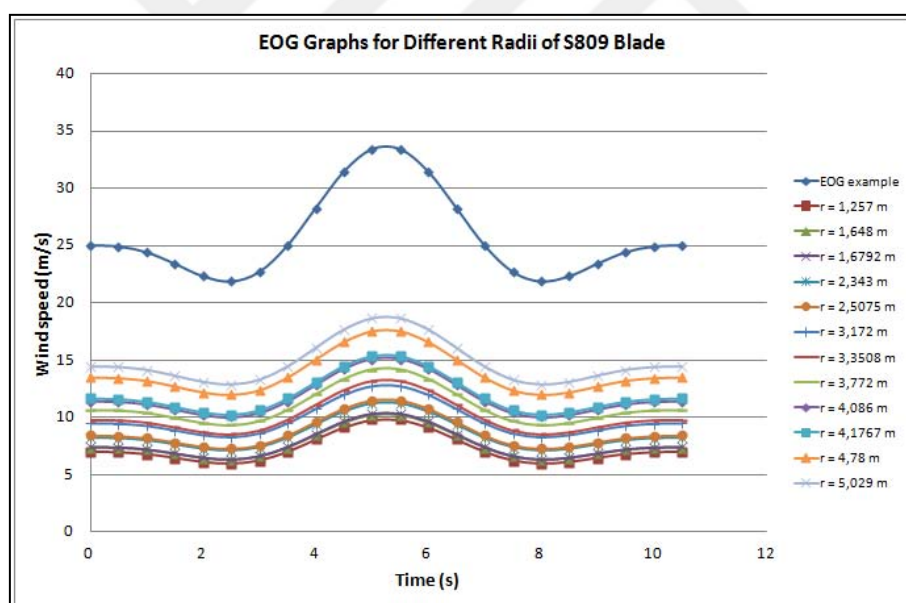
In the current study, calculations were performed for 7.0 m/s inlet wind speed. This inlet wind speed was kept constant for $r/R = 0.25$ ($r = 1.257$ m) section. For other sections, inlet velocities were calculated after applying corrections based on Reynolds similarity.

Corrected inlet velocities for sections and EOG formulations for all sections through the blade were presented in **Table 3.1**.

Table 3.1 Extreme Operating Gust Velocities for Sections

Radius (m)	r/R (%)	Corr.Speed (m/s)	EOG Formulation (m/s)
1.257	25	7.000	$V(t) = 7.000 - 1.44522 \cdot \sin(0.8976 \cdot t) \cdot (1 - \cos(0.5984 \cdot t))$
1.648	33	7.382	$V(t) = 7.382 - 1.48338 \cdot \sin(0.8976 \cdot t) \cdot (1 - \cos(0.5984 \cdot t))$
1.679	33	7.414	$V(t) = 7.414 - 1.48658 \cdot \sin(0.8976 \cdot t) \cdot (1 - \cos(0.5984 \cdot t))$
2.343	47	8.207	$V(t) = 8.207 - 1.5658 \cdot \sin(0.8976 \cdot t) \cdot (1 - \cos(0.5984 \cdot t))$
2.508	50	8.428	$V(t) = 8.428 - 1.5878 \cdot \sin(0.8976 \cdot t) \cdot (1 - \cos(0.5984 \cdot t))$
3.172	63	9.476	$V(t) = 9.476 - 1.6926 \cdot \sin(0.8976 \cdot t) \cdot (1 - \cos(0.5984 \cdot t))$
3.351	67	9.801	$V(t) = 9.801 - 1.7250 \cdot \sin(0.8976 \cdot t) \cdot (1 - \cos(0.5984 \cdot t))$
3.772	75	10.653	$V(t) = 10.653 - 1.8101 \cdot \sin(0.8976 \cdot t) \cdot (1 - \cos(0.5984 \cdot t))$
4.086	81	11.409	$V(t) = 11.409 - 1.8856 \cdot \sin(0.8976 \cdot t) \cdot (1 - \cos(0.5984 \cdot t))$
4.177	83	11.642	$V(t) = 11.642 - 1.9089 \cdot \sin(0.8976 \cdot t) \cdot (1 - \cos(0.5984 \cdot t))$
4.780	95	13.505	$V(t) = 13.505 - 2.0951 \cdot \sin(0.8976 \cdot t) \cdot (1 - \cos(0.5984 \cdot t))$
5.029	100	14.454	$V(t) = 14.454 - 2.1898 \cdot \sin(0.8976 \cdot t) \cdot (1 - \cos(0.5984 \cdot t))$

Graphical presentation of values in preceding table was shown in **Figure 3.14**, including EOG example given in IEC 61400-1.

**Figure 3.14** EOG Values for S809 Airfoil Sections

Before proceeding the EOG analysis, time step size sensitivity analysis was performed since the required computational effort was enormous considering 0 second to 14.0 second analysis duration. EOG formulation was adapted to the User Defined Functions and 0.0001 s/time step, 0.0002 s/ time step, 0.00025 s/ time step, 0.0004 s/ time step, and 0.0005 s/ time step

analysis alternatives were applied for 0 second to 3.5 second computation duration to see the variation of Overall Sound Pressure Level (dB) to the time step size. The results were presented in **Figure 3.15**.

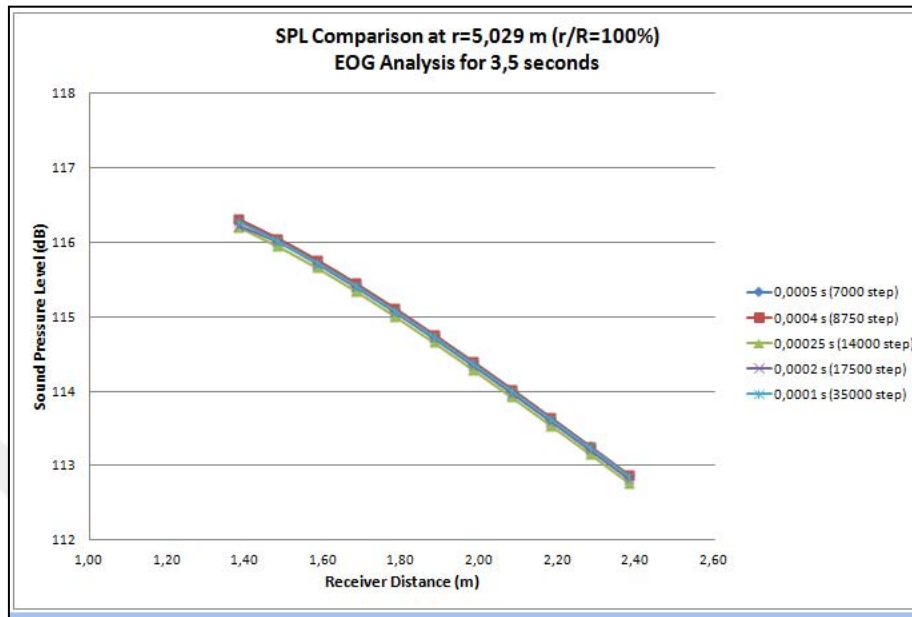


Figure 3.15 Time Step Size Sensitivity Analysis

More number of time steps (meaning less step size) necessitate more computational effort. Since the time step size sensitivity analysis did not result major SPL variation between the 0.0001 s and 0.0005 s, 0.0005 second was defined in ANSYS Fluent for the following EOG predictions.

The EOG formulations were adapted to the User Defined Functions as inlet boundary conditions. The analyses were performed from 0 second to 14.0 second including constant velocity period from 10.5 second to 14.0 second. Modified User Defined Functions were interpreted to the validated prediction model that was defined in Chapter 3.2. and 3.3.

Noise results of EOG at 7.0 m/s from 0 second to 3.5 seconds (0.0001 s * 35000 time step) were compared with the constant flow (7.4 m/s) analysis results including the measurements. Additionally, results of 5.4 m/s EOG inlet velocity and 5.4 m/s constant flow velocity results were compared in frequency domain.

Additionally, after applying EOG formulations as inlet boundary conditions, the results were evaluated and plotted in terms of 1/3 Octave band (Hz) in x axis and Sound Power Level (dB) in y axis in order to see the frequency dependence of EOG effect.

3.7. Alternative Twist Angles for Noise Reduction

In the current part of the thesis research, efforts were done to improve the acoustic behavior of the baseline NREL Phase VI blade. Original NREL Phase VI Blade geometry was presented in **Table 3.2**.

Table 3.2 NREL Phase VI Blade Geometry [42]

Radial Distance r (m)	Span Station ¹ (r/5.532 m)	Span Station ¹ (r/5.029 m)	Chord Length (m)	Twist ² (degrees)	Thickness (m)	Twist Axis (% chord)
0.0	0.0	0.0	Hub - center of rotation	Hub - center of rotation	Hub - center of rotation	Hub - center of rotation
0.508 ³	0.092	0.101	0.218 (root hub adapter)	0.0 (root hub adapter)	0.218	50 (root hub adapter)
0.660 ⁴	0.120	0.131	0.218	0.0	0.218	50
0.883 ³	0.160	0.176	0.183	0.0	0.183	50
1.008 ³	0.183	0.200	0.349	6.7	0.163	35.9
1.067 ³	0.193	0.212	0.441	9.9	0.154	33.5
1.133 ³	0.205	0.225	0.544	13.4	0.154	31.9
1.257 ³	0.227	0.250	0.737	20.040	0.154	30
1.343	0.243	0.267	0.728	18.074	20.95% chord	30
1.510	0.273	0.300	0.711	14.292	20.95% chord	30
1.648	0.298	0.328	0.697	11.909	20.95% chord	30
1.952	0.353	0.388	0.666	7.979	20.95% chord	30
2.257	0.408	0.449	0.636	5.308	20.95% chord	30
2.343	0.424	0.466	0.627	4.715	20.95% chord	30
2.562	0.463	0.509	0.605	3.425	20.95% chord	30
2.867	0.518	0.570	0.574	2.083	20.95% chord	30
3.172	0.573	0.631	0.543	1.150	20.95% chord	30
3.185	0.576	0.633	0.542	1.115	20.95% chord	30
3.476	0.628	0.691	0.512	0.494	20.95% chord	30
3.781	0.683	0.752	0.482	-0.015	20.95% chord	30
4.023	0.727	0.800	0.457	-0.381	20.95% chord	30
4.086	0.739	0.812	0.451	-0.475	20.95% chord	30
4.391	0.794	0.873	0.420	-0.920	20.95% chord	30
4.696	0.849	0.934	0.389	-1.352	20.95% chord	30
4.780	0.864	0.950	0.381	-1.469	20.95% chord	30
5.000	0.904	0.994	0.358	-1.775	20.95% chord	30
5.305	0.959	1.055	0.328	-2.191	20.95% chord	30
5.532	1.000	1.100	0.305	-2.500	20.95% chord	30

Original twist angle was 20.04 degrees at 1.257 m ($r/R = 0.25$) radial distance at the hub and -2.5 degrees at 5.532 m radial distance. Noise characteristic of the blade was investigated by changing the twist distribution of the blade. Five different twist distributions were introduced in the current study. The twist distribution was changed in certain percentages in the first four alternatives, however the twist magnitude was changed while keeping the twist distribution constant in the fifth alternative. Namely;

Alternative-1 : 10% decrease in twist angle

Alternative-2 : 25% decrease in twist angle

Alternative-3 : 10% increase in twist angle

Alternative-4 : 25% increase in twist angle

Alternative-5: 3 degree decrease in twist angle

These twist angle alternatives were defined in the **Table 3.3** for the selected sections in the analysis. The selected sections were presented in **Figure 3.16**. Twist axis location was kept constant as 30% of the chord.

Table 3.3 Alternative Twist Angles For Noise Reductions Studies

Radial Distance (m)	Span Station (r/5.029 m)	Chord Length (m)	Twist (deg)	Alt-1 Twist Angle (10% decrease)	Alt-2 Twist Angle (25% decrease)	Alt-3 Twist Angle (10% increase)	Alt-4 Twist Angle (25% increase)	Alt-5 Twist Angle (-3 deg)	Thickness (m)
1,648	0,328	0,697	11,909	10,718	8,932	13,100	14,886	8,909	0,146
2,343	0,466	0,627	4,715	4,244	3,536	5,187	5,894	1,715	0,131
3,3508	0,666	0,525	0,761	0,685	0,571	0,837	0,951	-2,239	0,110
4,086	0,812	0,451	-0,475	-0,428	-0,356	-0,523	-0,594	-3,475	0,094
5,029	1,000	0,356	-1,815	-1,634	-1,361	-1,997	-2,269	-4,815	0,075

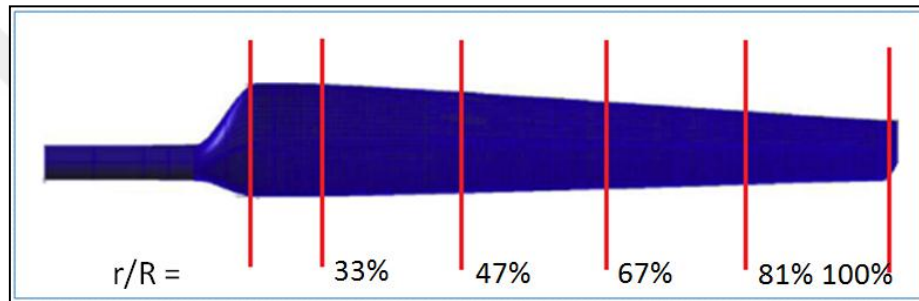


Figure 3.16 Five Selected Sections for Noise Reduction Studies

Original twist angles and alternative twist angles through the blade sections were shown in **Figure 3.17**.

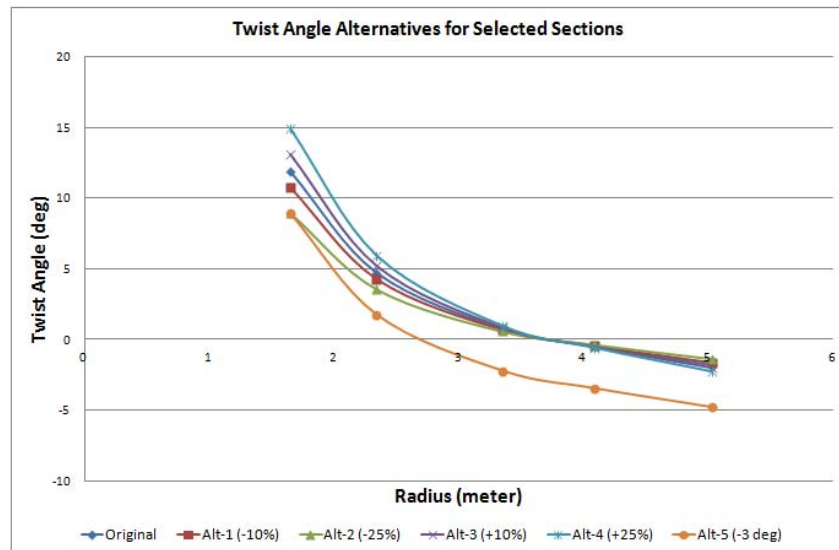


Figure 3.17. Twist Angle Alternatives for Noise Reduction Studies

The predictions were done for four different inlet velocities, namely 5.4 m/s, 7.4 m/s, 12.3 m/s, and 13.3 m/s in order to see the effect of velocity change on twist alternatives. The local velocities of selected sections were shown in **Table 3.4**.

Table 3.4 Local Velocities of Selected Sections

radius (m)	r/R	v = 5.4 m/s	v = 7.4 m/s	v = 12.3 m/s	v = 13.3 m/s
1.648	0.328	5.695	7.804	12.972	14.027
2.343	0.466	6.331	8.676	14.420	15.593
3.3508	0.666	7.561	10.361	17.222	18.622
4.086	0.812	8.801	12.061	20.048	21.678
5.029	1.000	11.150	15.280	25.398	27.462

Based on the alternative twist angles, the User Defined Functions were updated based on angle, inlet wind velocity and radius of the section. The updated UDFs were interpreted to the ANSYS FLUENT.

Additionally, blade noise calculation was performed by applying formulae presented in Chapter 3.5. Noise of five selected sections contributed for the blade noise calculation.

Forces of sections were calculated in order to see the variation of lift forces of sections depending on the alternative twist angles. Force calculations were done based on lift and drag coefficients of the test measurements of S809 [48] and local dynamic angles of attack at the selected sections. The lift and drag forces were summed up based on the relative inflow angle and torque of sections per unit length were calculated. The torques per unit length produced by the sections were integrated over the span to calculate the total blade torque. Torque per unit length of sections plotted in the graph and second order polynomials were fitted to the tangential force data by regression analysis. In the analysis, the coefficient of determination (R^2) was above 0.99 in all cases. Torque per unit length was calculated by integrating the second order polynomials over the defined boundaries (limiting sections) as definite integral solution via online integral solver. An example of regression analysis of blade torque was presented in **Figure 3.18**.

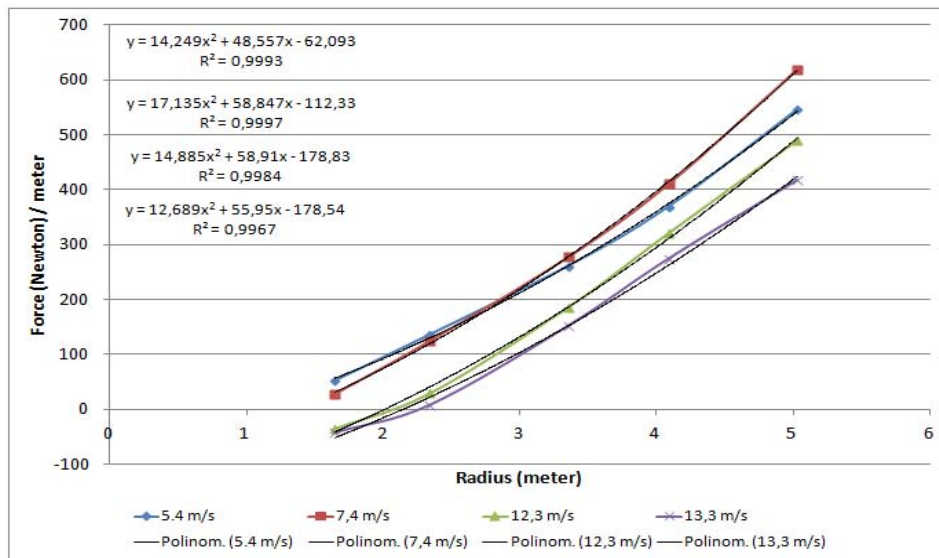
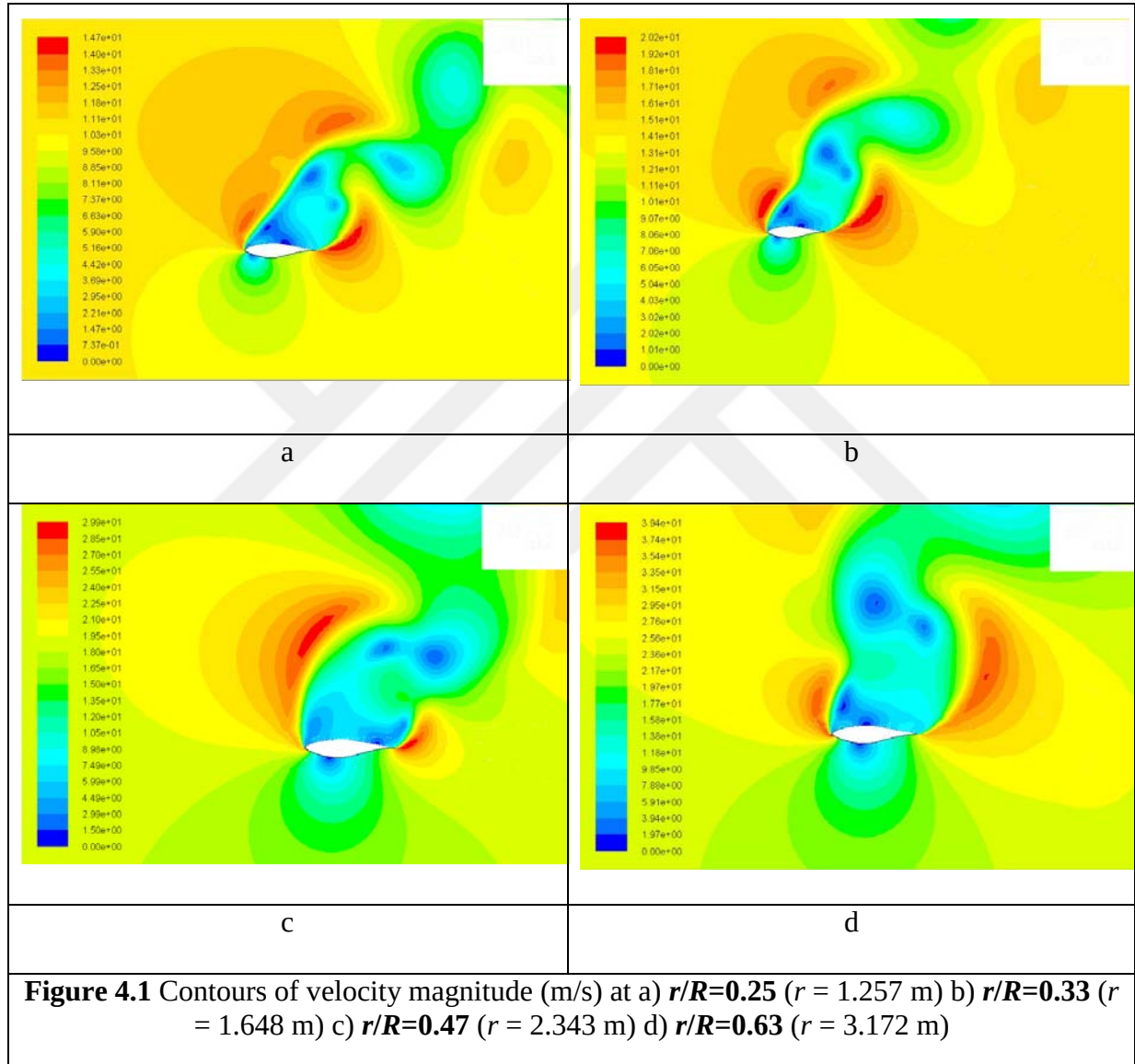


Figure 3.18 Regression Analysis of Blade Torque (Nm) Calculation for Alternative 1.

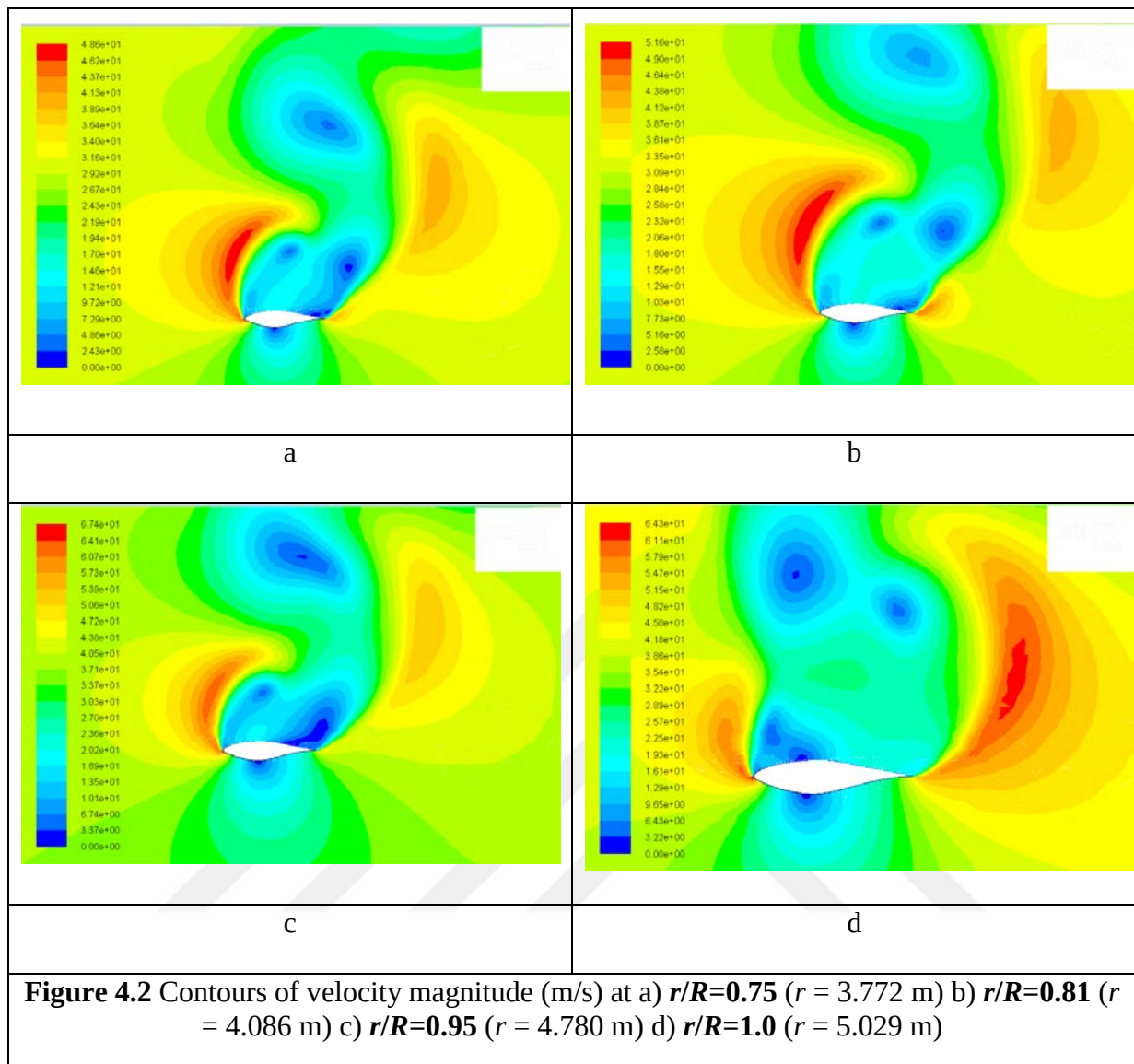
4. RESULTS AND DISCUSSION

4.1. Flow Field Analysis

Contours of velocity magnitude in meter per second at sections from closest to the hub to the tip section are presented in **Figure 4.1 and 4.2** for the inlet speed of 5.4 m/s and corrected speed accordingly.

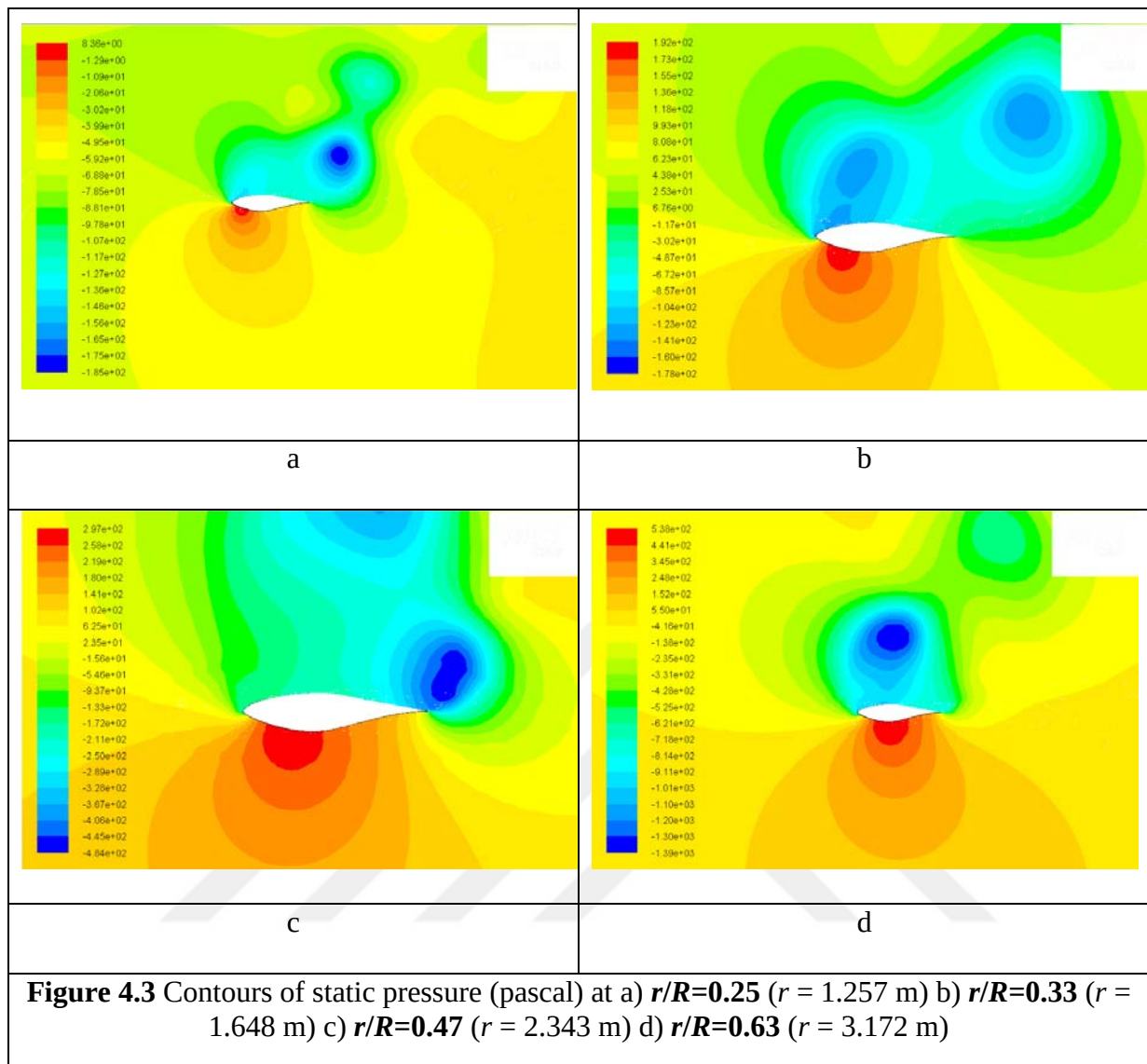


Sections from $r/R = 0.75$ to $r/R = 1.0$ were presented in **Figure 4.2**.

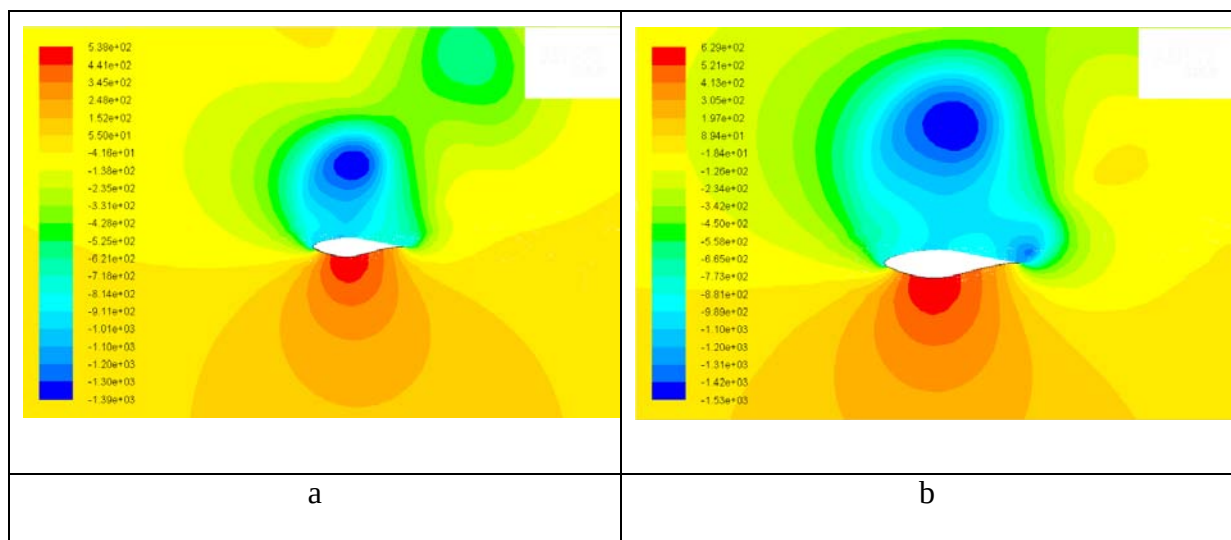


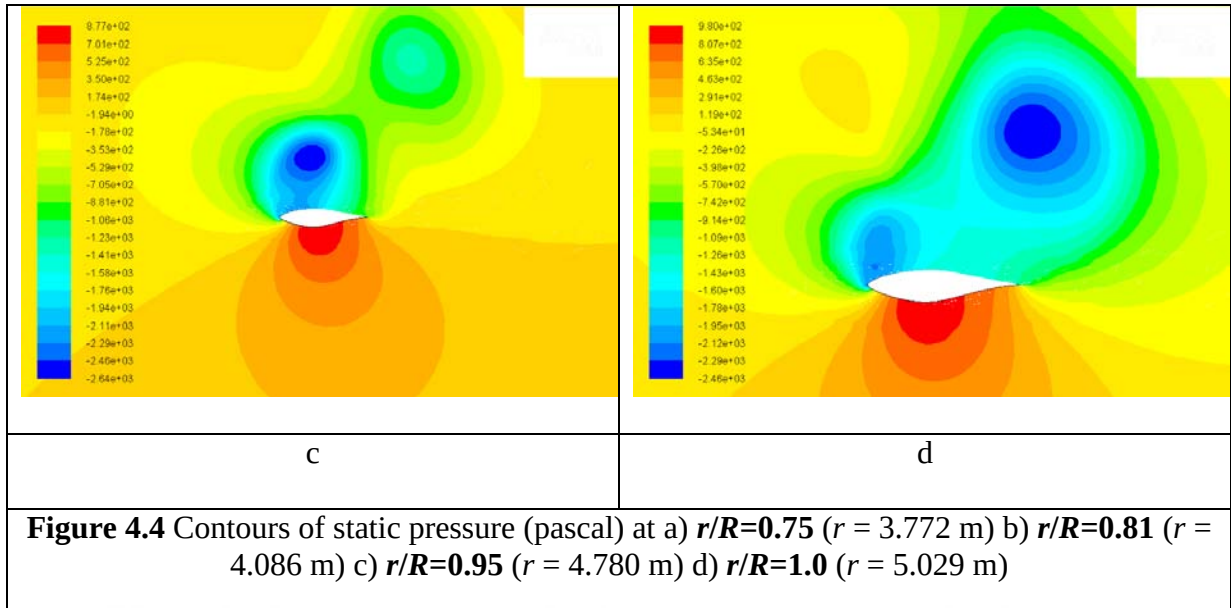
While getting closer to the tip, angle of attacks and the velocity magnitudes increased based on the applied corrections. The relative velocities and angle of attacks differed considerably close to the tip. Even though the same geometry and mesh was utilized, the difference between the sections through the blade was demonstrated by applying User Defined Functions.

Furthermore, contours of static pressure in Pascal were shown in **Figure 4.3** and **4.4**.



Contours of static pressure for sections from $r/R=0.75$ to $r/R=1.0$ were shown in following figure.





As a summary, by utilizing UDFs for different inlet conditions, the same airfoil section and mesh model provided variety of flow fields based on the circular distance. The identical mesh grid was utilized for the analysis of all sections through the blade. For that reason, three dimensional analysis was aimed to obtain by way of simple two dimensional mesh grid by the methodology defined within the scope of this study.

4.2. Experimental Results for Comparison and Validation

In the study of T.Cho et al., two bladed turbine was rotated at constant rotating speed for wind speeds increasing from 0 to 13 m/s. Array of 144 microphones were installed in circular pattern on the bottom wall of the wind tunnel. The center of the microphones was located 1.88 m away from the turbine center in the downwind direction and 1.49 m in vertical direction toward to the floor [43]. Test arrangement of the 12% scaled model was shown in **Figure 4.5**.

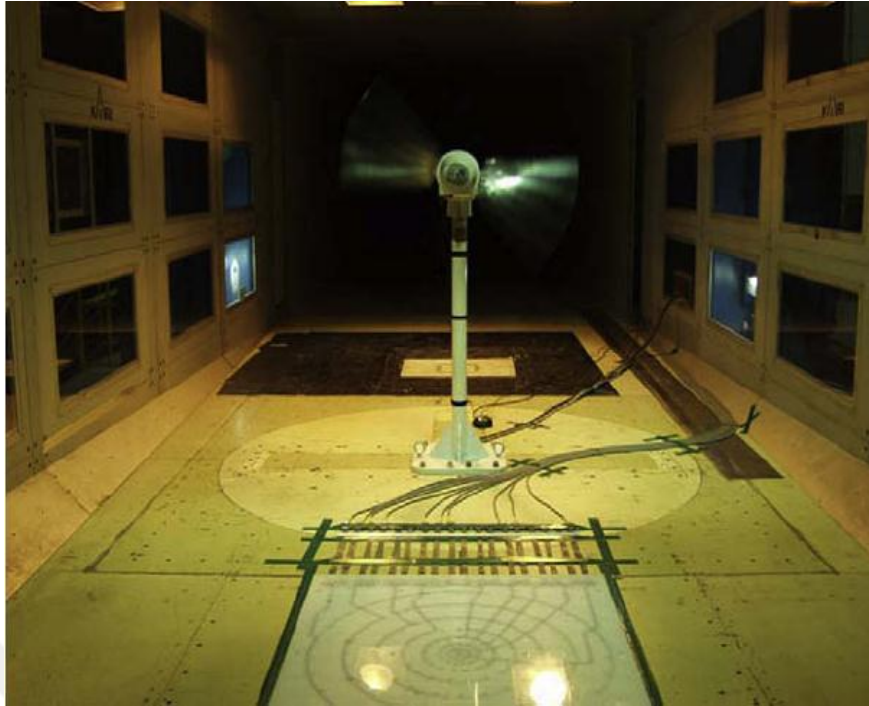


Figure 4.5 Test arrangement of the 12% scaled model [43]

According to the study of T Cho et al., the dimensions of %12 scaled model of NREL Phase VI Blade were presented in following Figure.

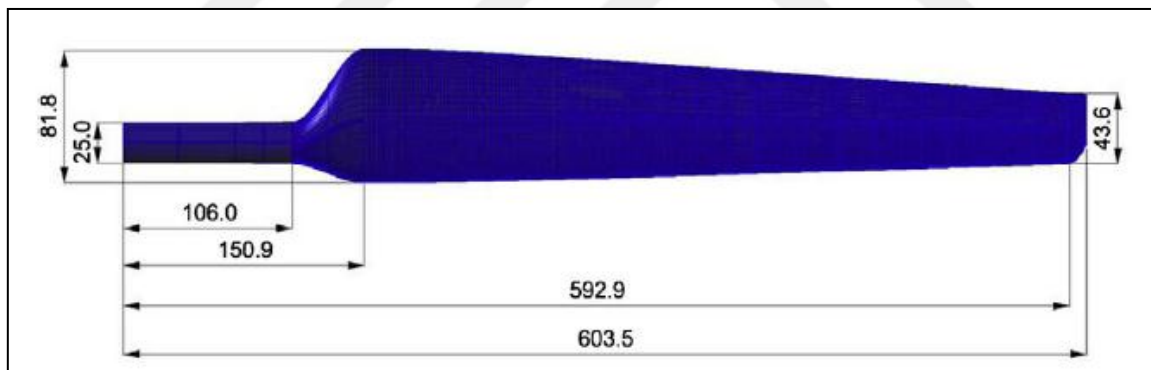


Figure 4.6 %12 scaled model of NREL Phase VI Blade [43]

The area around the blade was divided to sequential five zones at different radii as shown in **Table 4.1**.

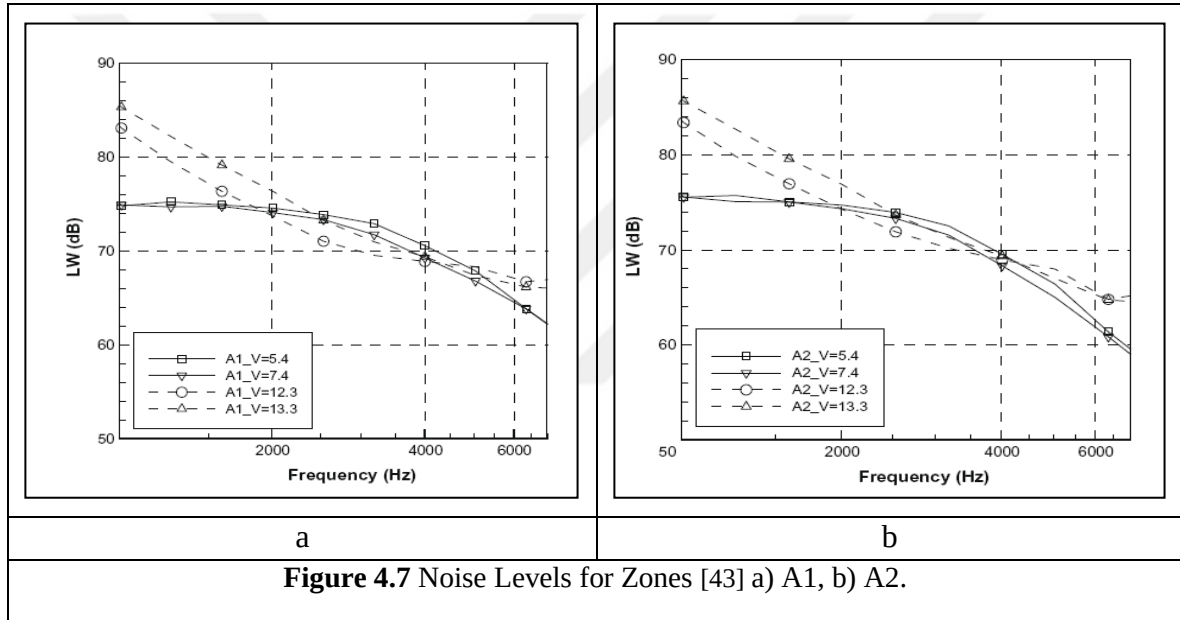
Table 4.1 Zones of the Blade for Noise Measurement [43]

Zone Description	Boundaries (r/R)
A1	0.83 - 1.0
A2	0.67 - 0.83
A3	0.50 - 0.67
A4	0.36 - 0.50
A5	0.25 - 0.36

In the study of T. Cho et al., the corresponding noise levels were obtained by using time base beamforming methodology for rotating source. The average source strength for each zone was calculated for specified octave bands. The noise levels were presented as source power level with 1×10^{-12} Watt reference power in the study [43].

Average source strengths were presented in the study of T. Cho et al. for wind speeds of 5.4 m/s, 7.4 m/s, 12.3 m/s, and 13.3 m/s at Zones A1 and A2. Graphs were shown as frequency between 1 kHz – 6.3 kHz in X-coordinate and noise power level at dB scale in Y-coordinate [43].

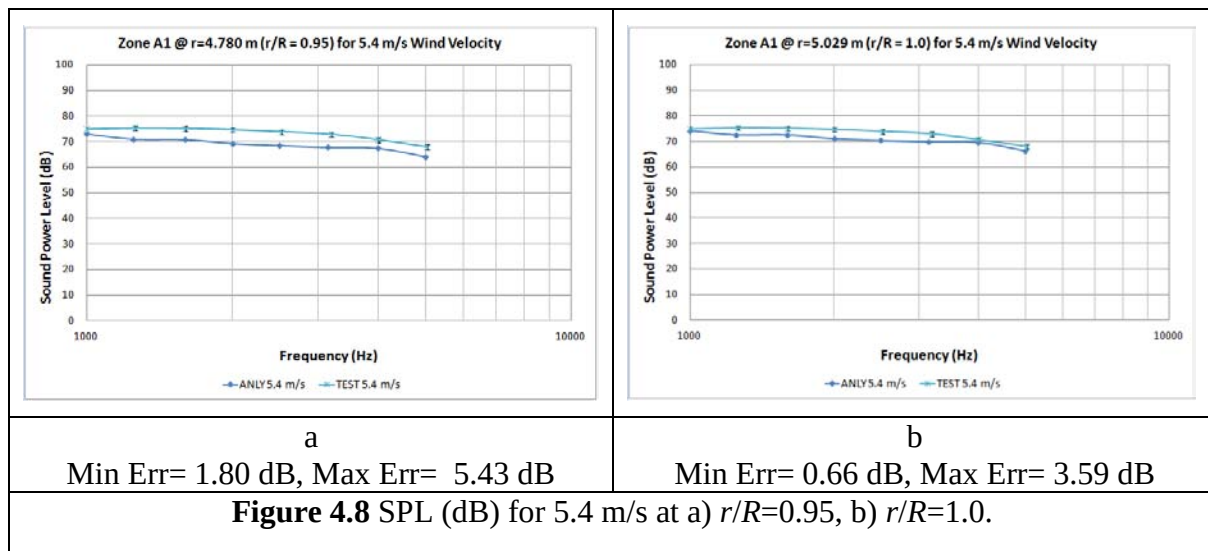
The results were presented in the study of T. Cho et al. for wind speeds of 5.4 m/s, 7.4 m/s, 12.3 m/s, and 13.3 m/s as presented in **Figure 4.7**.



In the current work, analyses were performed for Zone A1 and A2 in order to validate the predictions by comparing them with the measurements.

4.3. Analysis Results for Zone A1

Zone A1 was defined as the area between $r/R = 0.83$ and $r/R = 1.0$ [43]. Comparison of noise predictions at $r/R=0.95$ and 1.0 with Zone A1 measurements at 5.4 m/s wind velocity were presented in following **Figure 4.8**.



General trend of the predictions has agreed well with the measurements. Difference increased about 1 dB for inner section. 1 dB change in sound level typically cannot be distinguished other than laboratory conditions. By combining previous results, following noise graph at 5.4 m/s for Zone A1 was calculated and displayed in **Figure 4.9**. The combination of these two different sections' noise was calculated by using the equation (3.9) to obtain the noise of the defined Zone.

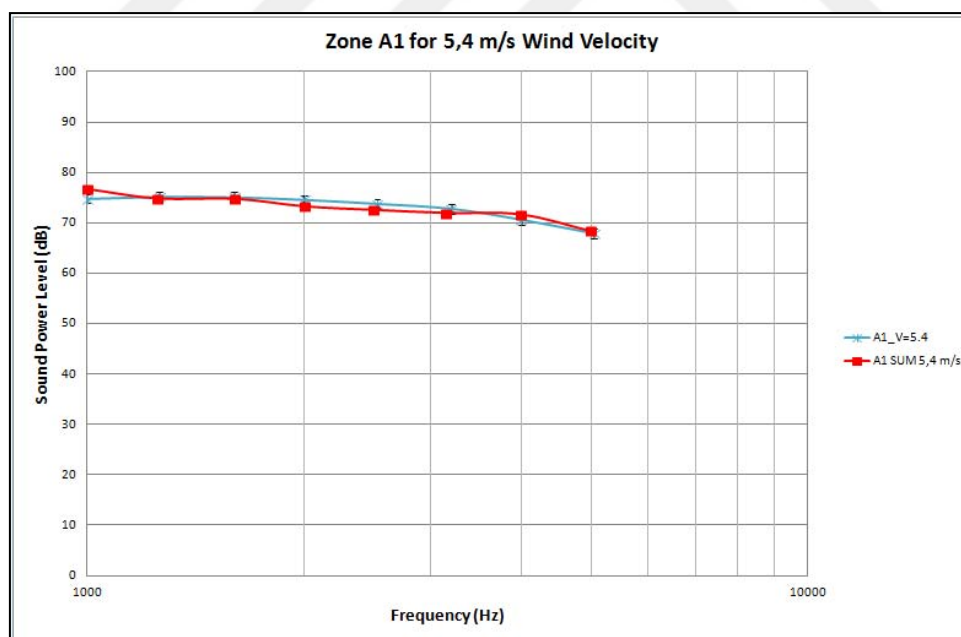


Figure 4.9 Comparison of Section Noise for Zone A1 at 5.4 m/s

Noise of the airfoil in the tip region was predicted fairly well at 5.4 m/s. The analysis results were in very good agreement with the experimental results for lower wind speeds.

Comparison of noise predictions $r/R=0.95$ and $r/R=1.0$ for Zone A1 measurements at 7.4 m/s wind velocity were presented in **Figure 4.10**. Predictions agreed reasonably with the

measurements except at 1.25 kHz and 2.0 kHz frequencies. Predictions underestimated the measurements about 6 – 11 dB at $r/R=0.95$ section, 8 - 13 dB at $r/R=1.0$ section. After combining previous results, following noise graph at 7.4 m/s for Zone A1 was calculated and displayed in **Figure 4.11**.

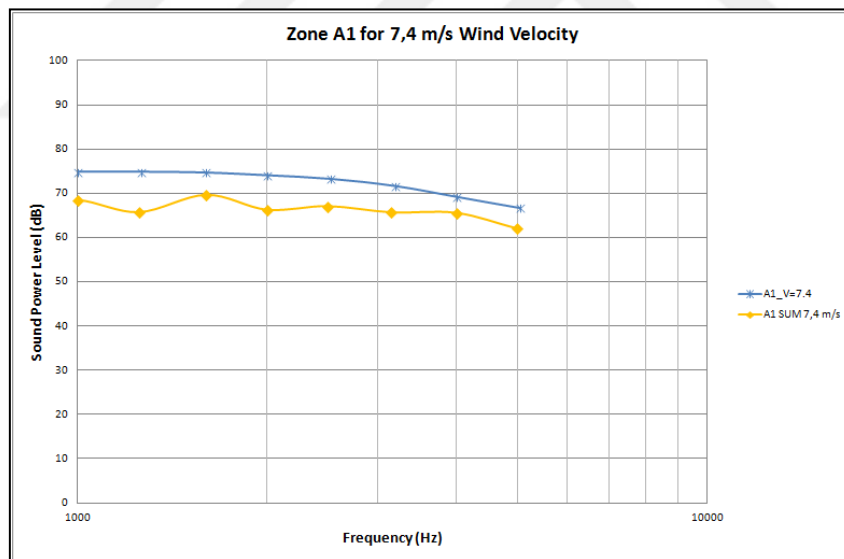
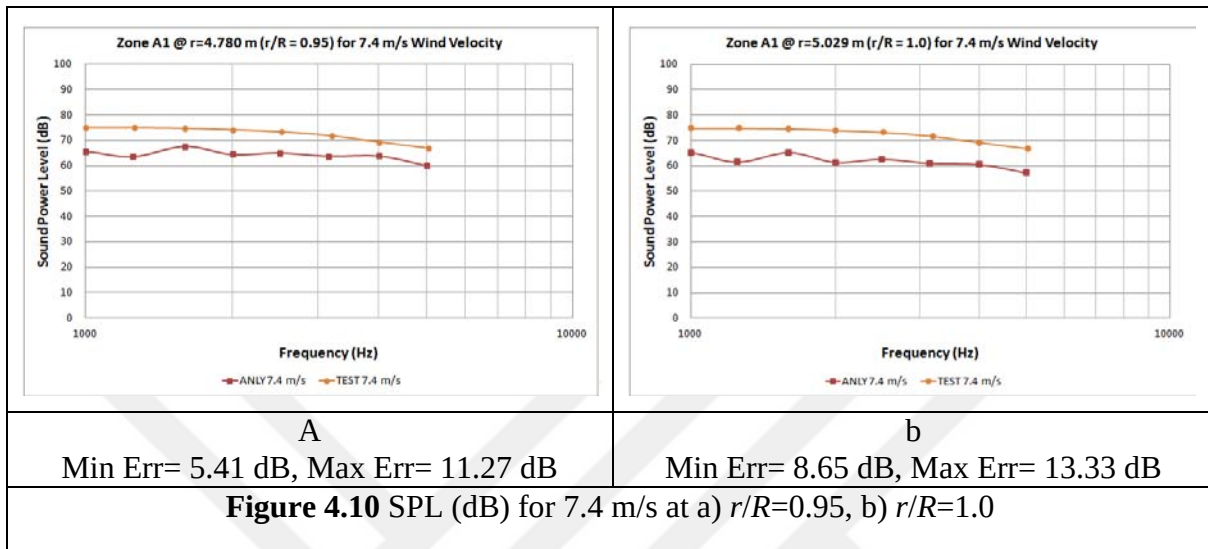
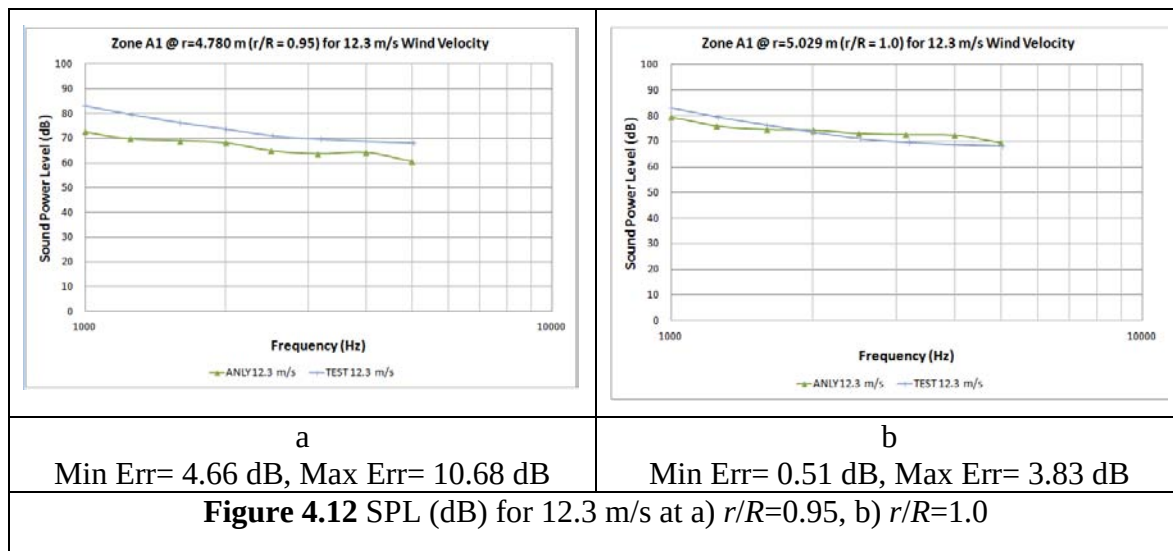


Figure 4.11 Comparison of Section Noise for Zone A1 at 7.4 m/s

Predictions obtained at 7.4 m/s of wind speed underestimated the measurements about 5 – 7 dB through the Zone A1. It was believed that this might be due to laminar-turbulent transition which occurs in actual flow but neglected in the computations.

SPL predictions and comparisons with experimental data at 12.3 m/s wind velocity were presented in **Figure 4.12**.



For $r/R=1.0$ section, computations underestimated the SPL until 2.0 kHz and overestimated it between 2.0 - 4.0 kHz. But less than 4 dB difference for all frequency band was observed.

Similarly, the combined noise graph at 12.3 m/s for Zone A1 was shown in **Figure 4.13**.

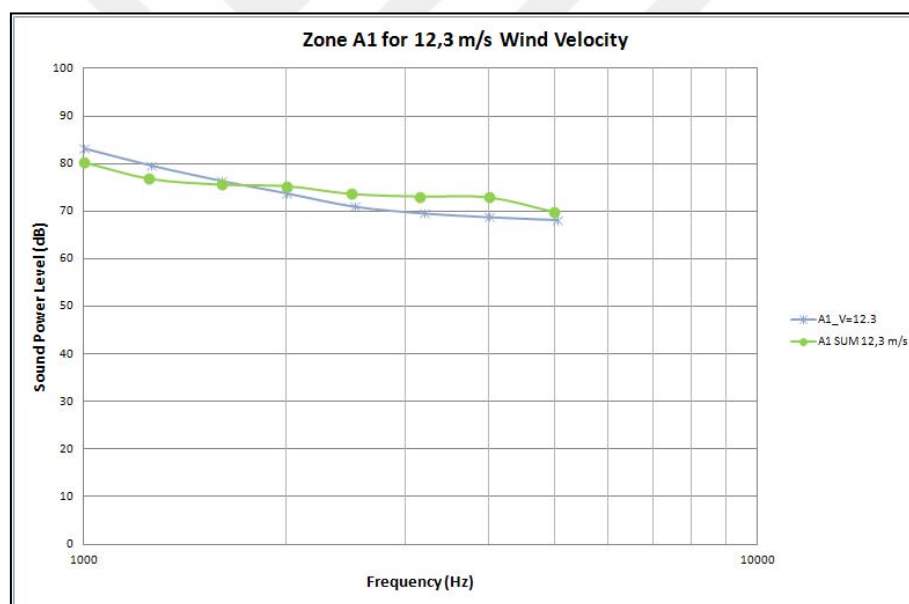
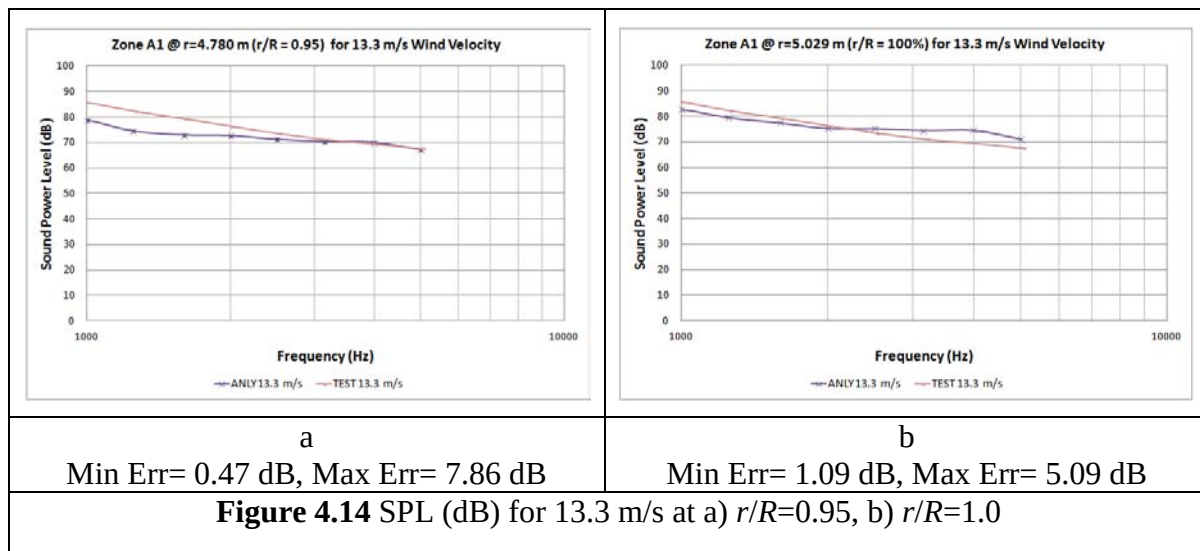


Figure 4.13 Comparison of Section Noise for Zone A1 at 12.3 m/s

For Zone A1, noise of the airfoil in the tip region was predicted fairly well at 12.3 m/s. Maximum deviation was around 3 dB in all frequency band.

Finally for Zone A1 predictions at 13.3 m/s wind velocity were presented and compared with measurements in **Figure 4.14**.



For $r/R=1.0$ section, predictions were agreed well until 2.0 kHz frequency, above this frequency the predictions were overestimated the measurements. But less than 5 dB difference for all frequency band was observed. For $r/R=0.95$ section, predictions were in very good agreement with measurements at high frequencies but they underestimated SPL at lower ones.

The combined noise graph at 13.3 m/s for Zone A1 was calculated and presented in **Figure 4.15**. At 13.3 m/s, predictions were fitted well to the measurements until 2.0 kHz frequency. Above this frequency the analysis results were overestimated the measurements. However, above 2.0 kHz frequency, maximum difference between the computations and measurements was about 5 dB and average difference between them was about 3 dB.

Overall, for Zone A1, the agreement between predictions and measurements was best at 5.4 m/s and worst for 7.4 m/s wind speed. At higher wind speeds, computations predicted SPL with reasonable accuracy at lower frequencies. However, for all wind speeds, SPL difference between computations and measurements remained less than approximately 7 dB.

In general, even though the wind velocity was increased, the noise level change was insignificant considering the test measurements especially for 2000 - 4000 Hz range. It was evaluated that thickness noise component was dominant in aforementioned frequency range of blade noise, since thickness noise was generated by the displacement of the fluid in the flow field by the rotor blade.

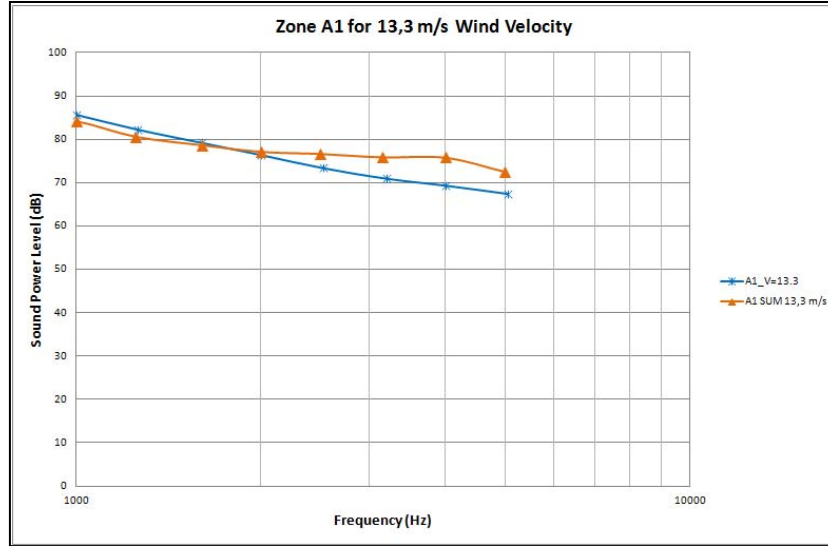


Figure 4.15 Comparison of Section Noise for Zone A1 at 13.3 m/s

4.4. Analysis Results for Zone A2

Zone A2 was defined as the area between $r/R= 0.67$ and $r/R= 0.83$ [43]. Again, SPL predictions were obtained at wind speeds of 5.4, 7.4, 12.3 and 13.3 m/s and compared with the corresponding wind tunnel measurements [43]. Similar to the analyses performed for Zone A1, SPL predictions were first obtained at two radial stations in the zone and then they were combined to obtain an SPL prediction for the whole zone.

SPL predictions at $r/R=0.75$ and $r/R=0.81$ at 5.4 m/s wind velocity were presented and compared with measurements **Figure 4.16**. For both stations, computations underestimated the SPL. However, numerical results obtained for these two stations turned out to be almost same unlike predictions represented in the previous section. This behavior emphasizes the redundancy of analysis for this zone.

Combined SPL predictions and corresponding wind tunnel measurements for 5.4 m/s wind speed were displayed in **Figure 4.17**. Predictions and measurements were agreed well within the 1.0 - 1.25 kHz band. However, at higher frequencies the computations were underestimated SPL values. The maximum and average difference between predictions and measurements was about 6 dB and 4 dB within the 1.25 - 4.0 kHz band, respectively.

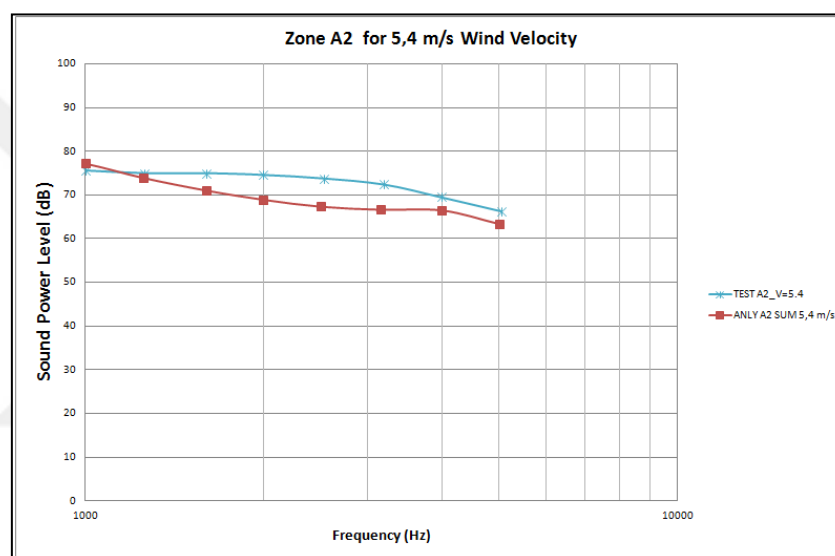
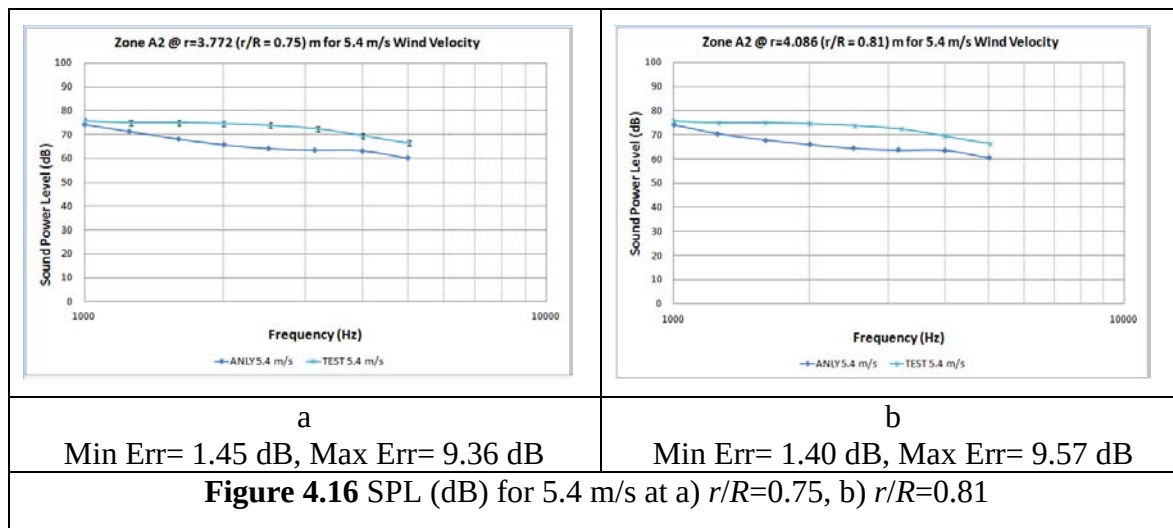


Figure 4.17 Comparison of Section Noise for Zone A2 at 5.4 m/s

Local and combined SPL predictions obtained at 7.4 m/s were displayed in **Figure 4.18** and **Figure 4.19**, respectively. Similar the 5.4 m/s case, numerical predictions obtained for both radial stations were almost same. However, unlike the results obtained for Zone A1, the predictions for this zone were relatively in better agreement with the experiment at this wind speed.

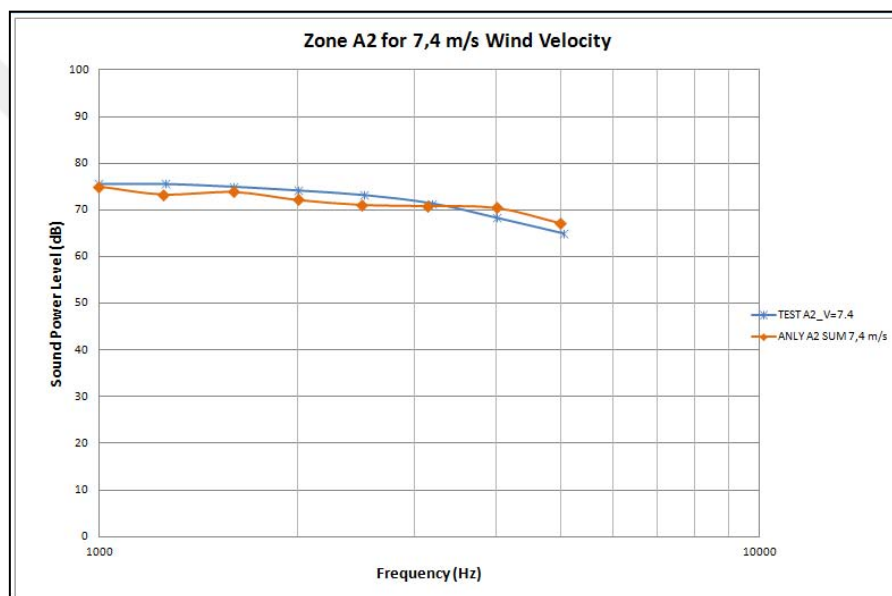
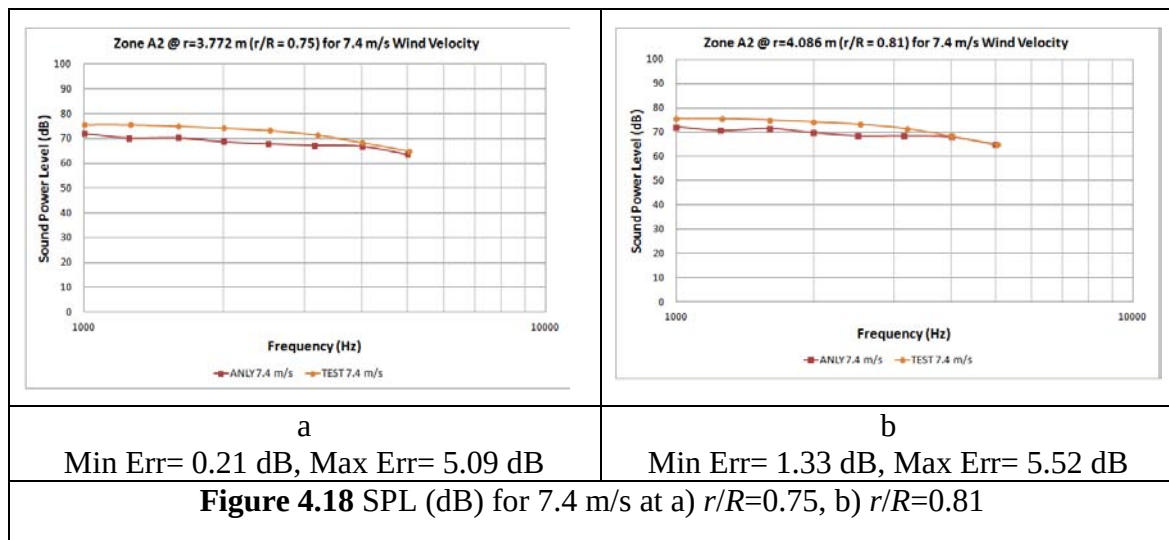


Figure 4.19 Comparison of Section Noise for Zone A2 at 7.4 m/s

Figure 4.20 and **Figure 4.21** display the local and combined SPL predictions obtained at 12.3 m/s wind speed, respectively. It was clear from **Figure 4.20** that, as the wind speed increased the effect of the location of the radial station on the predictions became more distinct. The overall predictions underestimated the SPL values about 10 – 12 dB at all frequencies. However, computations were able to predict the slope of the curve fairly accurately.

Finally, local and combined SPL predictions obtained at 13.3 m/s were displayed in **Figure 4.22** and **Figure 4.23**, respectively. Predictions obtained in this wind speed were similar to those obtained for 12.3 m/s. Here, computations were underestimated the measurements about 14 – 18 dB for the frequency band but again they were able to compute the general trend of the curve fairly accurately. It was evaluated that methodology could provide reasonable results even in higher wind speeds based on the accurate prediction of the slope of the curve.

It was anticipated that the reasonable prediction of the general trend of noise was important and valuable. Because, the trend of noise predictions could provide information about the comparisons of alternative blade/section geometries.

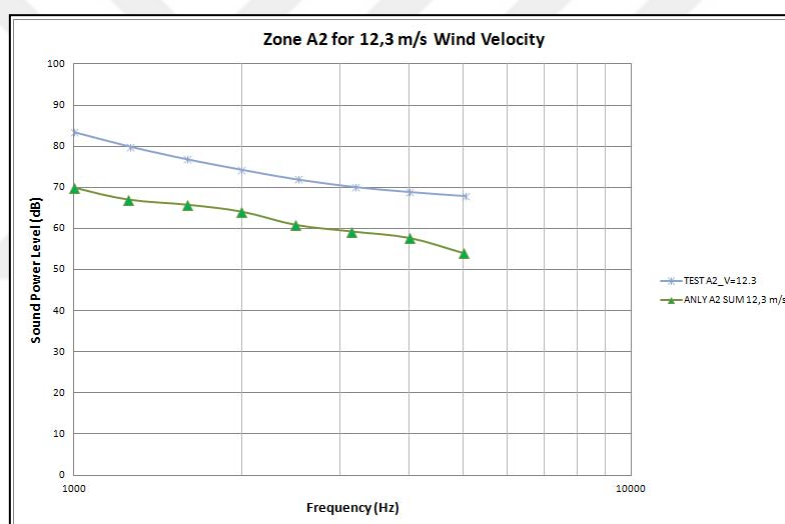
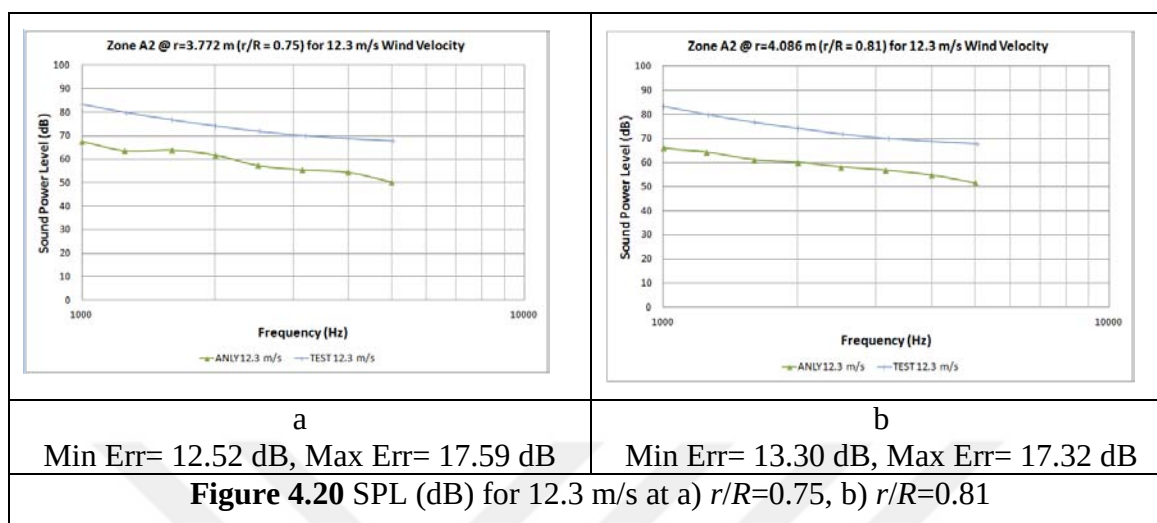
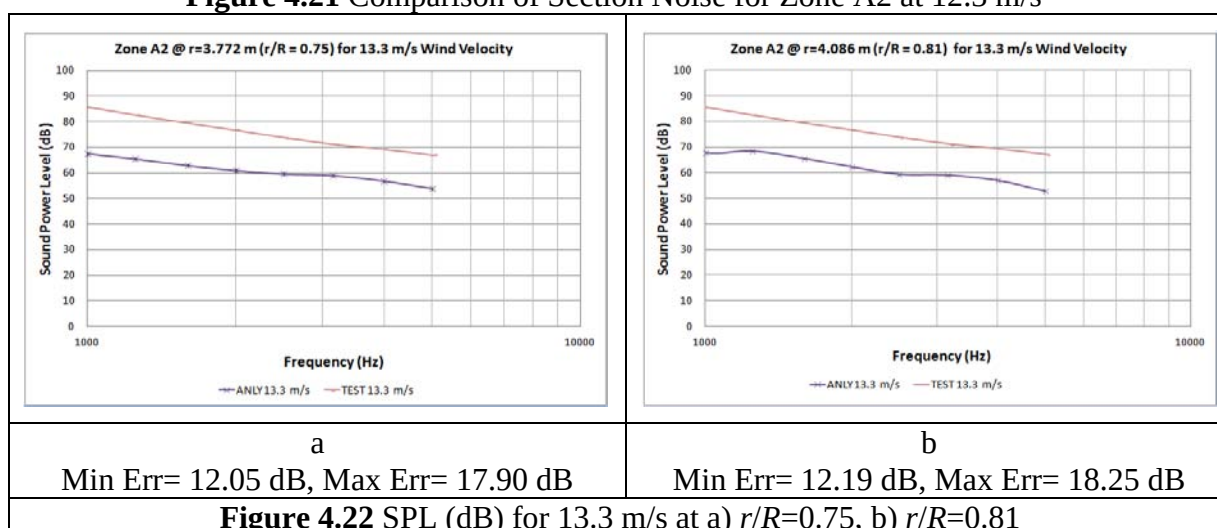


Figure 4.21 Comparison of Section Noise for Zone A2 at 12.3 m/s



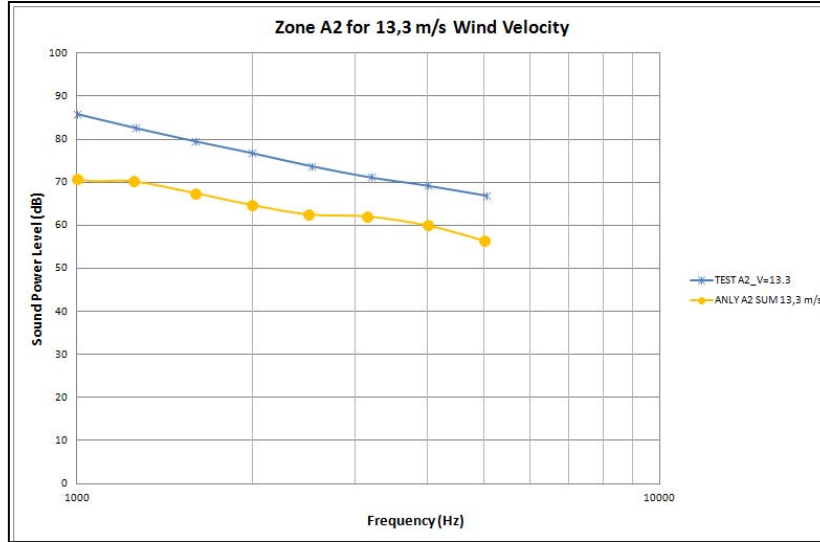


Figure 4.23 Comparison of Section Noise for Zone A2 at 13.3 m/s

Considering the comparisons between predictions and measurements presented above, it can be concluded that the two dimensional model employed in this study could predict the noise generated by the turbine blade with reasonable accuracy at low wind speeds like 5.4 m/s although it does not take into account the interactions between the sections two-dimensional sections. As the wind speed increased however, the quality of the predictions were affected by the zone in consideration. Therefore, this two-dimensional model tested in this study can be used with reasonable confidence to predict noise generated by wind turbines at low wind speeds where the flow is mainly attached to the blades. Considering the fact that the wind turbines that would be placed in urban areas would have to operate at low wind speeds [49,50], the model can be considered as a valuable tool to design and optimize wind turbines for lower noise generation.

4.5. Prediction of the Total Blade Noise

The summation of the contribution from the each blade section was used to predict the total noise emission by using following formulation [47].

$$SPL_{Total}^i = 10 \log_{10} \left(\sum_j 10^{0.1(SPL_j)} \right) \quad (4.1)$$

The total noise generated by the blade (comprised of S809 airfoil sections) at different wind speeds was presented in **Figure 4.24**. According to the figure the hub and the tip regions of the blade generated more noise compared to the intermediate spanwise locations. Therefore, the design of these sections can be said to be more critical to obtain quieter blades.

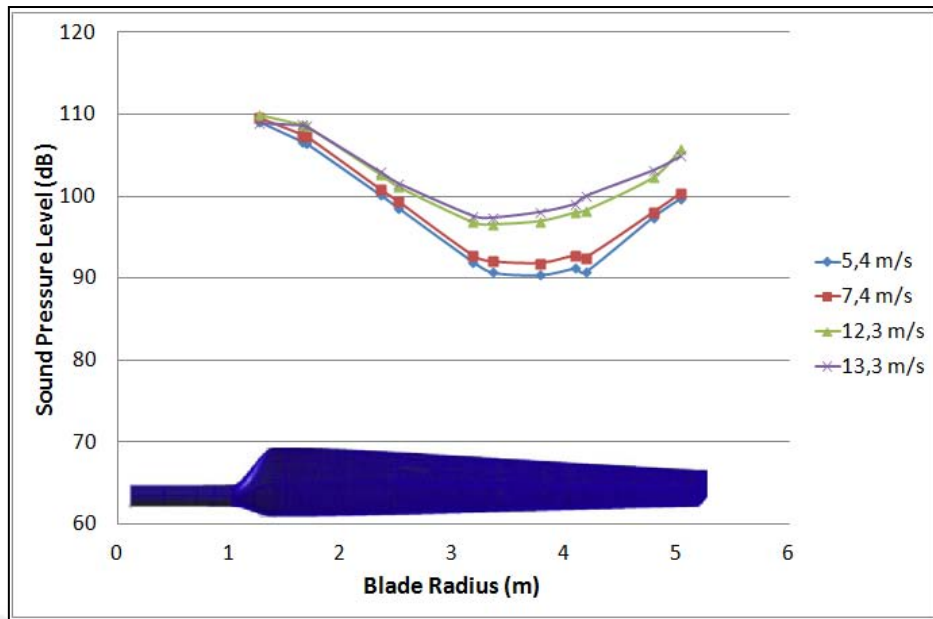
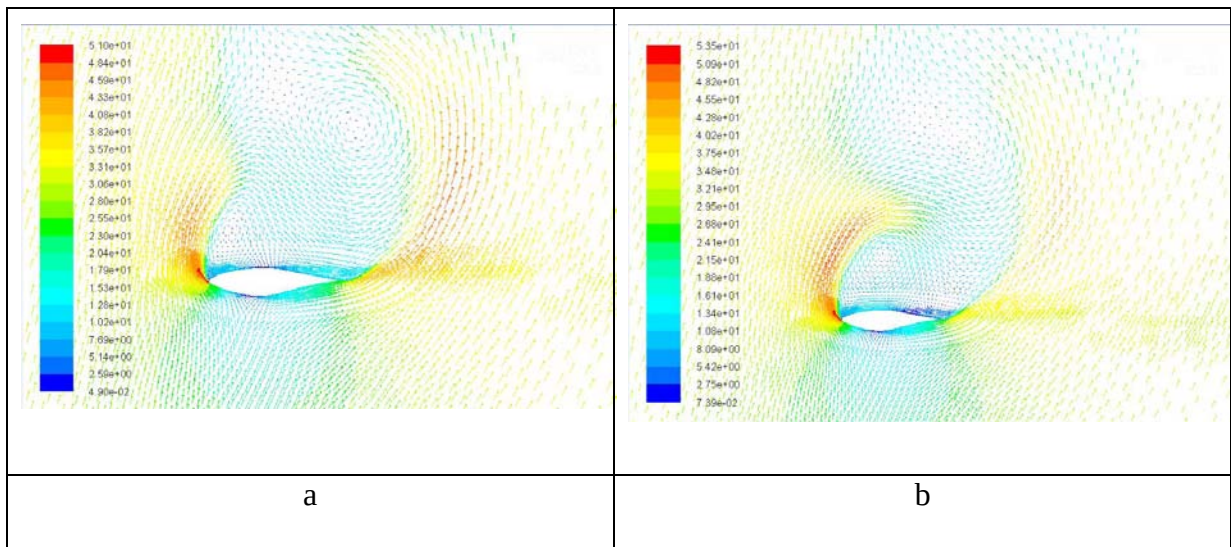


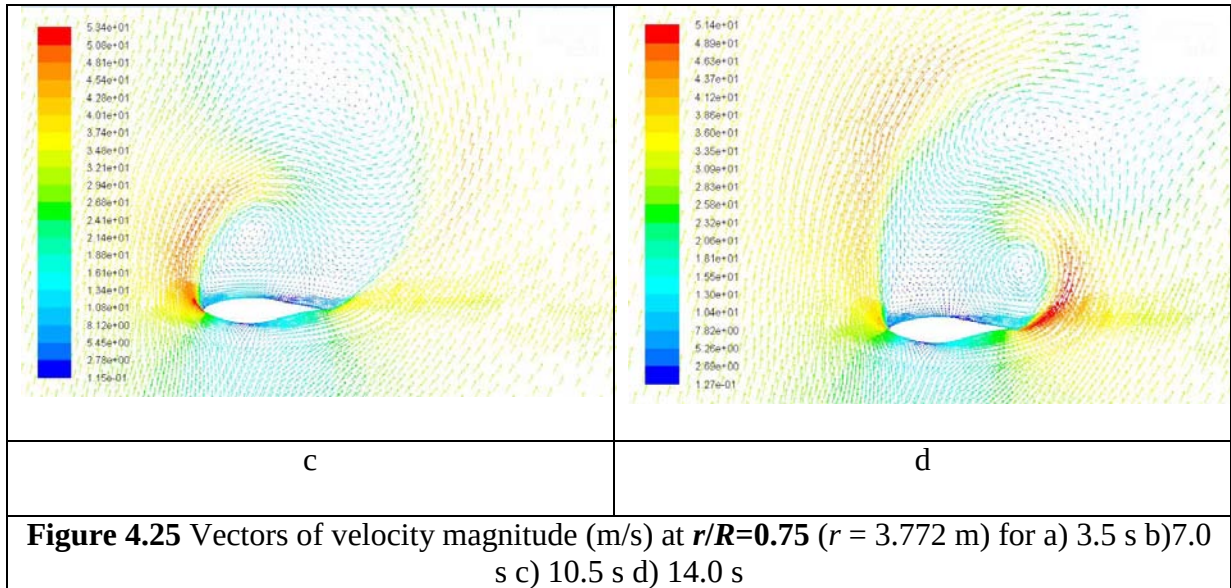
Figure 4.24 Prediction of the Blade Noise

4.6. Extreme Operating Gust Analysis Results and Comparison

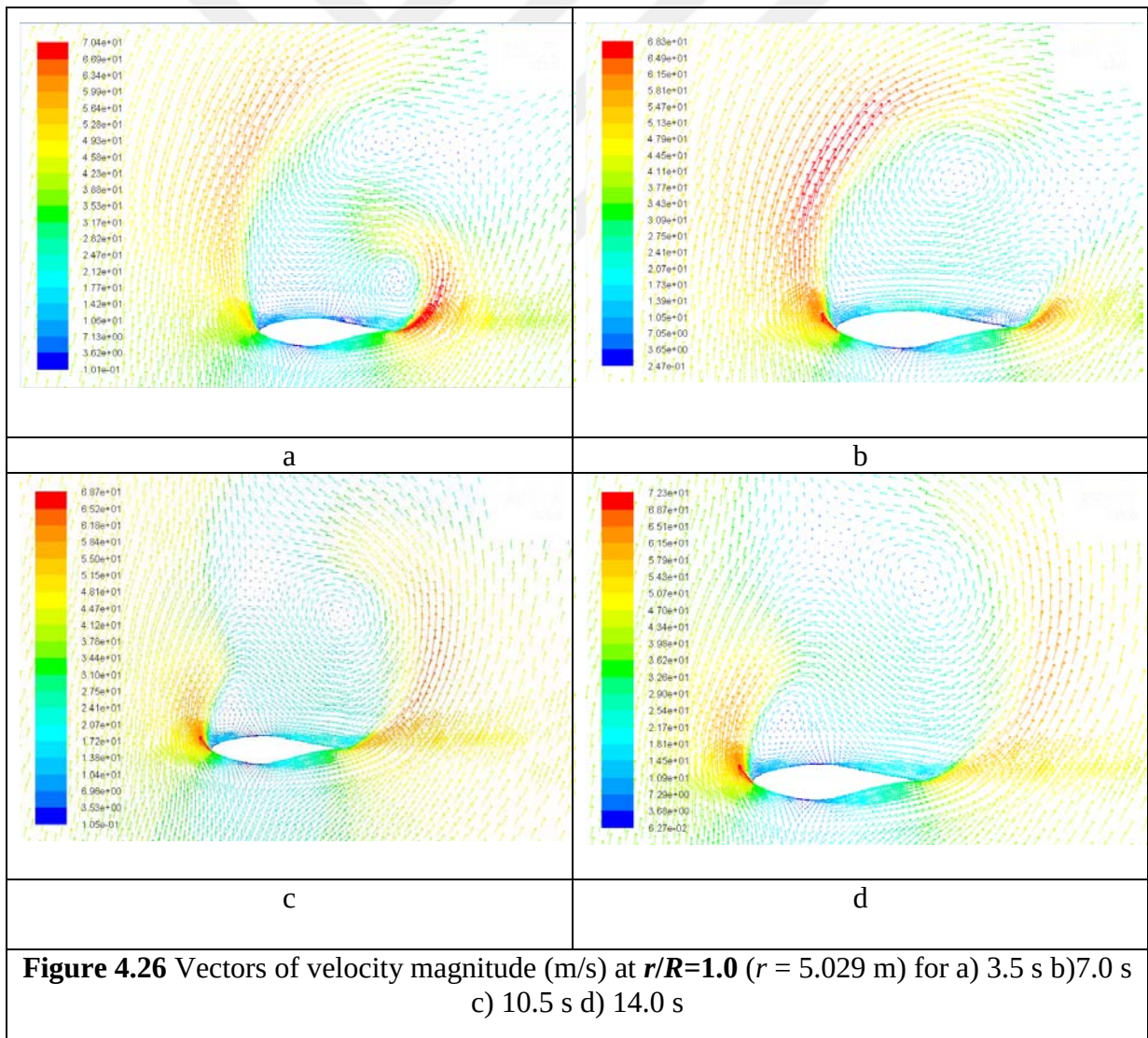
4.6.1. Flow fields of predictions under EOG effect

Velocity vectors colored by velocity magnitude in meter per second at $r/R = 0.75$ were presented for 3.5 s, 7.0 s, 10.5 s, and 14.0 s in **Figure 4.25** at the inlet speed of 7.0 m/s which is corrected for stations accordingly.

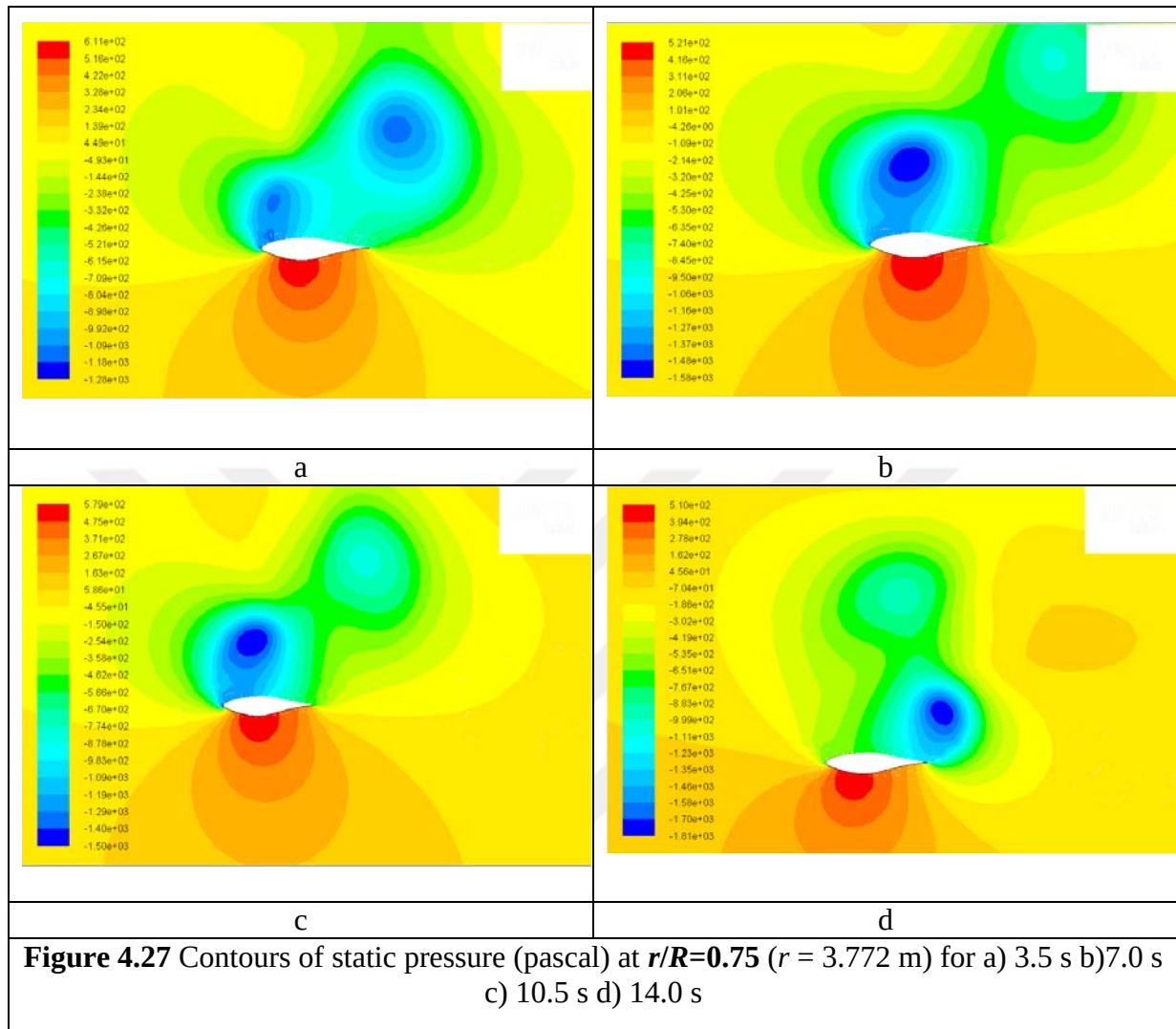




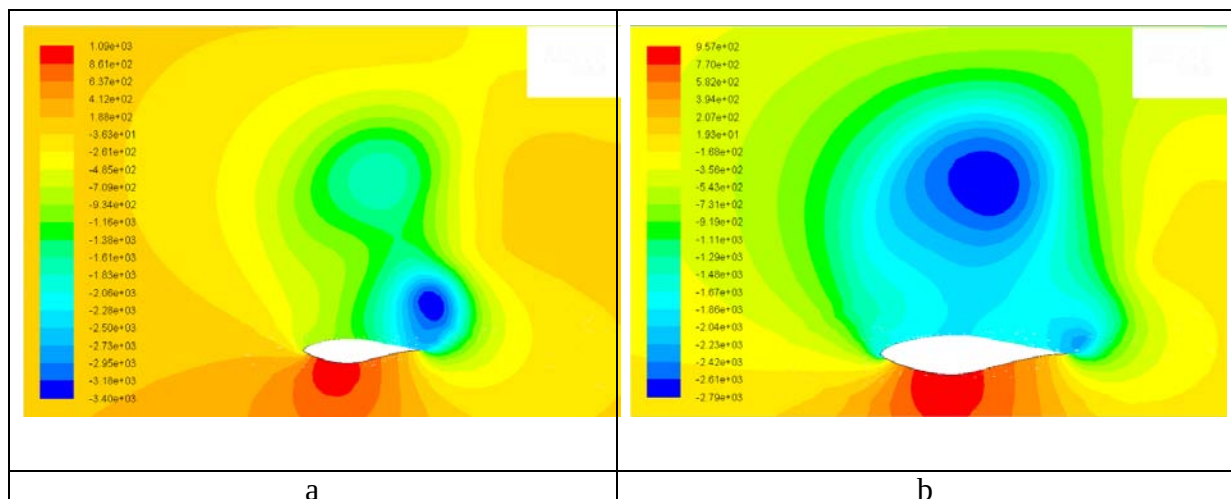
Vectors of velocity magnitude in meter per second at $r/R = 1.0$ were presented for 3.5 s, 7.0 s, 10.5 s, and 14.0 s in **Figure 4.26**.

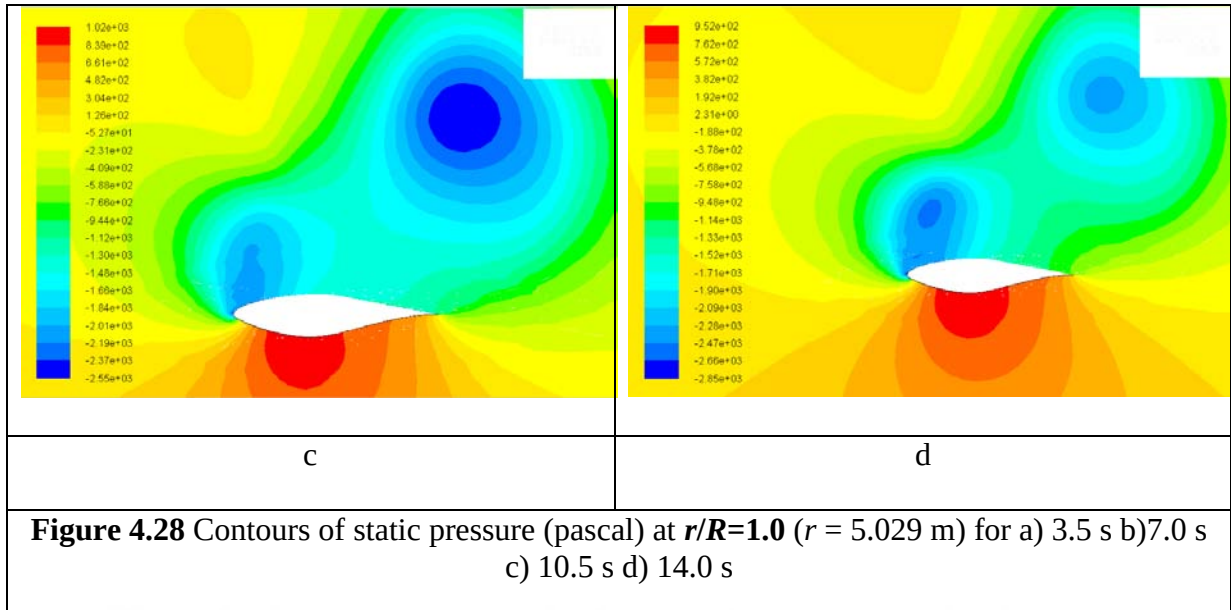


Furthermore, contours of static pressure in unit of pascal presented at $r/R = 0.75$ and $r/R = 1.0$ for 3.5 s, 7.0 s, 10.5 s, and 14.0 s in **Figure 4.27** and **4.28**.



Contours of static pressure in Pascal at $r/R = 1.0$ were presented for 3.5 s, 7.0 s, 10.5 s, and 14.0 s in **Figure 4.28**.



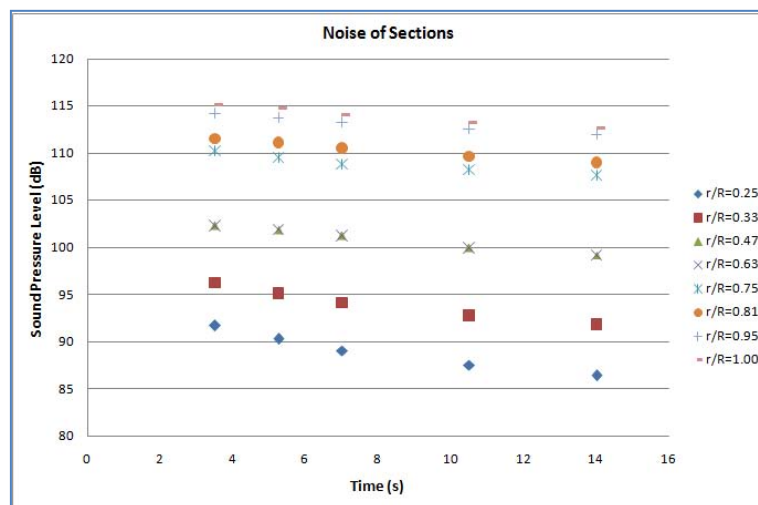


Flow fields around the section in terms of velocity and static pressure provided information and separation behavior of the flow. It is clear that flow is massively separated at the stations presented and vortex shedding can also be observed from the pressure contours.

4.6.2. Total noise of the blade under EOG effect

Noise predictions were made considering Extreme Operating Gust formulation as inlet wind speed. The details of methodology were explained in Chapter 3.6.

Noise predictions under Extreme Operating Gust were done for 3.5, 5.25, 7.0, 10.5, and 14.0 seconds to observe the effect of time on noise for each section through the blade. Noise variations of sections in time were presented in **Figure 4.29**.

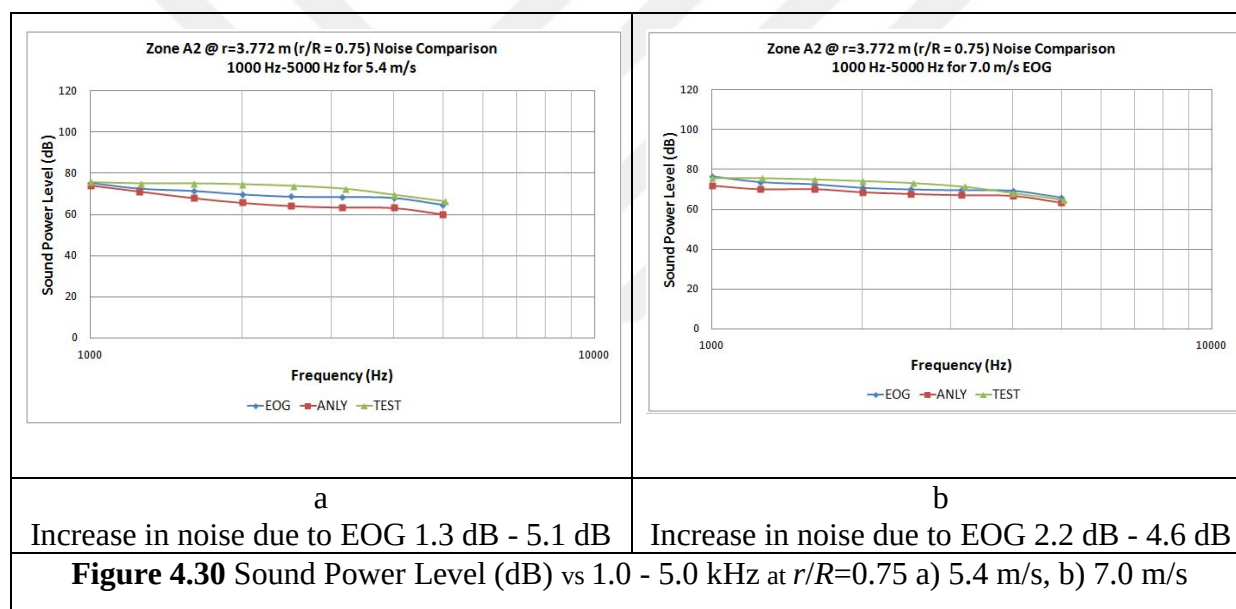


Even though EOG formulation defines trigonometric speed vs time curve, noise predictions provided decaying SPL (dB) in time. Noise at 3.5 seconds was the highest and decreased in time until the end of the analysis, 14.0 seconds.

4.6.3. Comparison of frequency based predictions under EOG effect

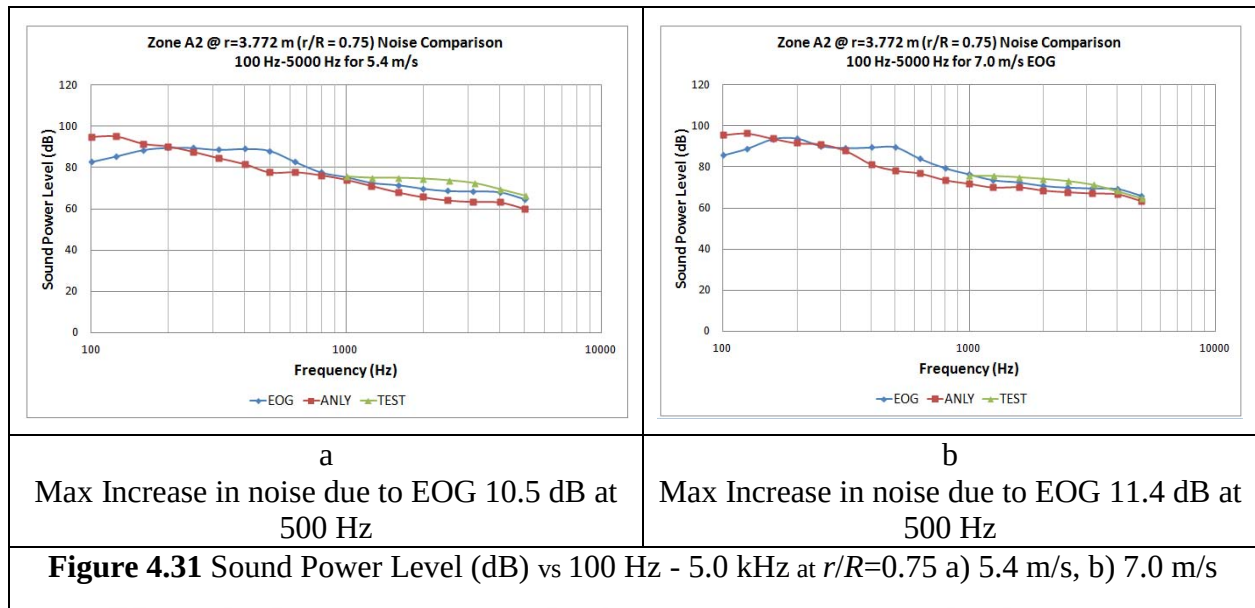
In addition to the SPL comparison, the results of the frequency based predictions were compared with the original predictions and measurements at the 3.5 second of EOG formulation [43].

Sound Power Level (dB) vs frequency between 1.0 - 5.0 kHz for $r/R=0.75$ was shown in **Figure 4.30**. In the Figure, measurement [43] values, initial noise predictions with 7.4. m/s inlet velocity and noise predictions under EOG were compared with each other for 3.5 second.



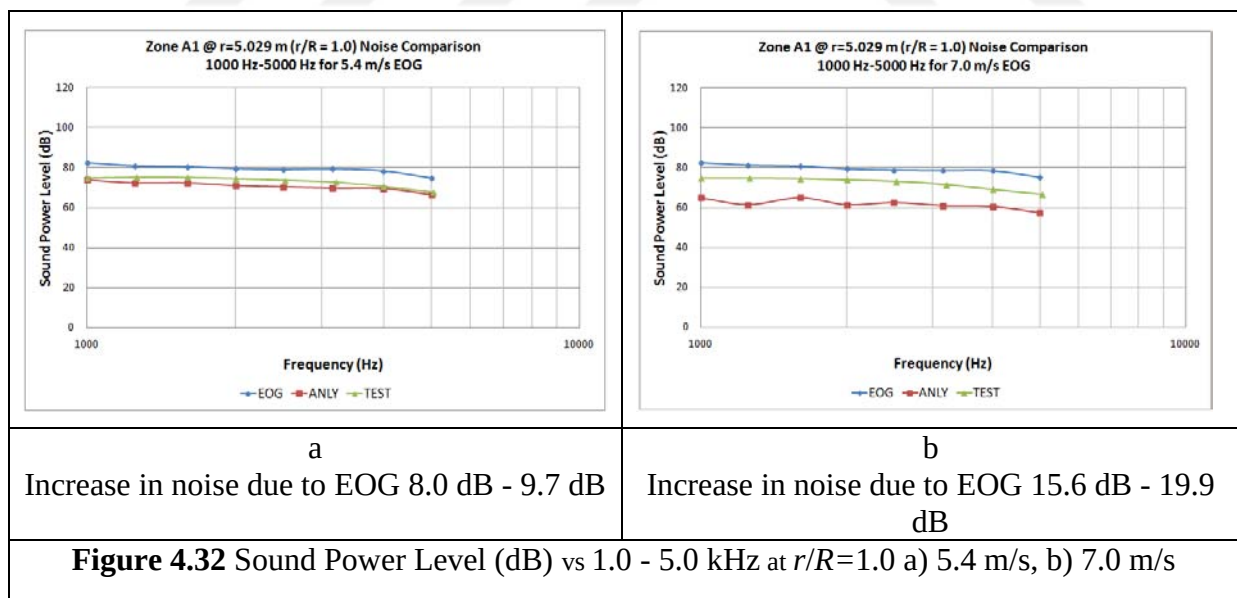
Noise predictions under EOG for 5.4 m/s and 7.0 m/s inlet velocities resulted moderate increase between 1.0 kHz and 5.0 kHz frequency. The magnitude of the increase was changing between 1.3 dB and 5.1 dB for EOG with 5.4 m/s inlet velocity. On the other hand, the increase was between 2.2 dB and 4.6 dB for EOG with 7.0 m/s inlet velocity. The increases due to EOG at both inlet velocities were nearly parallel to the initial noise predictions at 5.4 m/s and 7.4 m/s.

The same comparisons were made for wider frequency range, between 100 Hz - 5 kHz and results were presented in **Figure 4.31**.



The major increase due to EOG was predicted 10.5 dB for 5.4 m/s, 11.4 dB for 7.0 m/s at 500 Hz frequency. Between 400 Hz - 1.0 kHz frequency higher increase was predicted compare to 1.0 - 5.0 kHz frequency range at $r/R=0.75$.

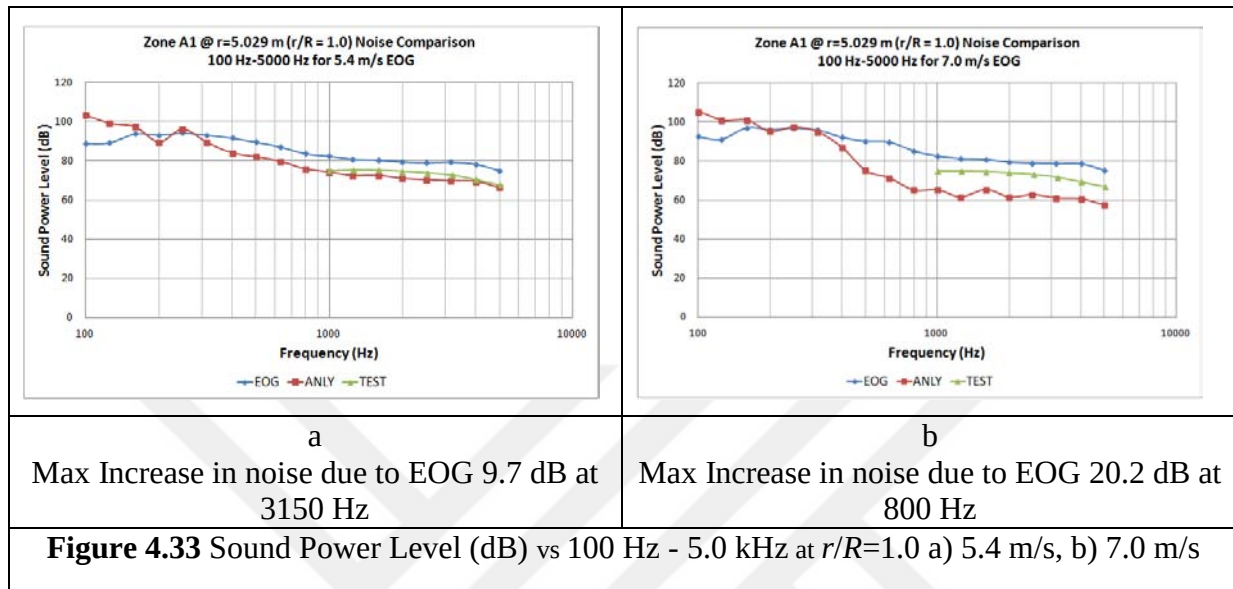
Another comparison were made for the tip section at $r/R = 1.0$. Sound Power Levels (dB) vs 100 Hz - 5.0 kHz frequencies were plotted for 5.4 m/s and 7.0 m/s inlet velocities and shown in **Figure 4.32**.



For the tip section at $r/R = 1.0$, moderate increase 8.0 - 9.7 dB was predicted at 5.4 m/s due to Extreme Operating Gust. Almost parallel Sound Power Levels and constant increase were predicted at this speed. On the other hand, noise predictions gave almost double Sound Power

Level at 7.0 m/s inlet velocity under Extreme Operating Gust effect. As shown in **Figure 4.32 b**, EOG effect provided between 15.6 dB - 19.9 dB increases for 1.0 kHz - 5.0 kHz frequency range.

The same analysis between 100 Hz - 5.0 kHz was presented in **Figure 4.33** for the tip section.



The frequencies above 400 Hz, Extreme Operating Gust effect increased the noise values similar to 1.0 kHz - 5.0 kHz range. At this tip section, moderate increase in inlet speed (5.4 m/s vs 7.0 m/s) resulted big shifts in noise predictions under EOG effect. Even though higher frequency sound decays faster than lower frequency sound, human ear perceives higher frequency sound more disturbing. Increase in higher frequency noise due to EOG effect, it was evaluated that noise became more disturbing in terms of perception of noise especially 2000 - 5000 Hz range as illustrated in **Figure 2.13**.

4.7. Noise Reduction Efforts By Changing The Twist Angle

Before proceeding to change the twist angle of the blade, sound pressure levels of the sections for four different inlet speeds, 5.4 m/s, 7.4 m/s, 12.3 m/s, and 13.3 m/s were shown in **Figure 4.34**.

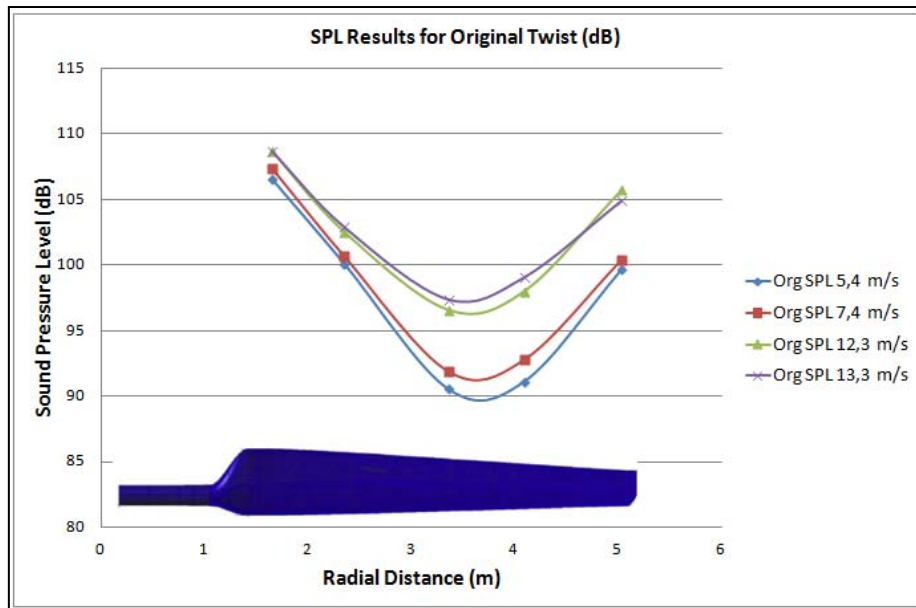


Figure 4.34 SPL Predictions for Original Twist Angles

At 5.4 m/s inlet wind velocity, noise was decreased around 16 dB from $r/R=0.33$ to mid section and increased about 9 dB from mid section to tip section at $r/R = 1.0$. For other inlet wind velocities similar trend was predicted. When the effect of inlet wind velocity was considered, noise increased in different amount depending on the section. At $r/R = 0.33$ section close to the hub, the noise prediction was increased only 2.2 dB, at mid sections the increase was about 7 - 8 dB, and at $r/R = 1.0$ section the noise prediction was increased about 5 dB.

4.7.1. Sound Pressure level comparison for alternatives

Initially, SPL comparison of four twist angle alternatives and original twist angle was done for 5.4 m/s inlet velocity. The predictions were shown in **Figure 4.35**. Noise predicted 3.6 dB lower at $r/R = 0.33$ section, 3 dB lower at $r/R = 0.47$ and 2.5 dB less at $r/R = 1.0$ section for twist angle alternative - 2.

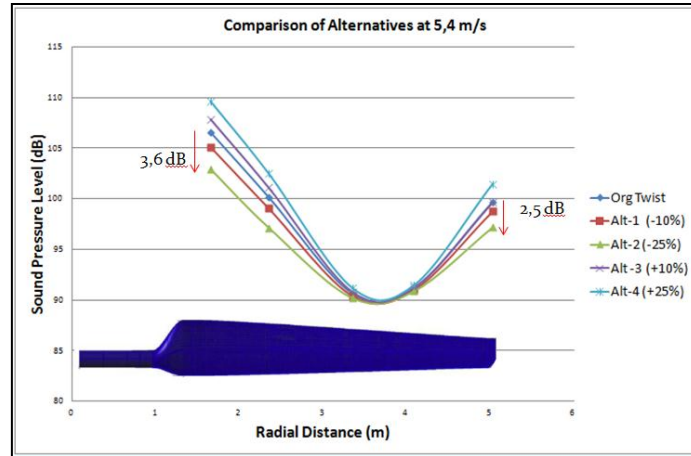


Figure 4.35 SPL Comparisons of Four Twist Angle Alternatives for 5.4 m/s

Similar noise reduction pattern was predicted for 7.4 m/s and 13.3 m/s inlet speeds. The major noise reduction was revealed at $r/R = 0.33$ about 3.5 dB - 4.1 dB, at $r/R = 0.47$ about 2.5 - 3.0 dB, and 1.0 dB at tip section $r/R = 1.0$ for twist angle alternative-2 (-25% reduced). The associated results were presented in **Figure 4.36** and **Figure 4.37**, respectively.

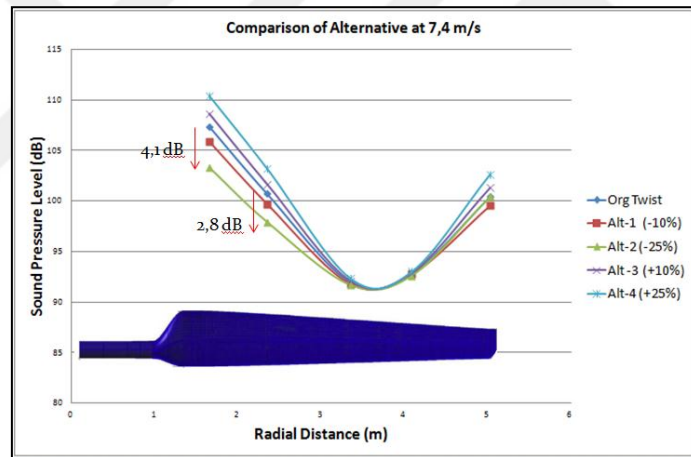


Figure 4.36 SPL Comparisons of Four Twist Angle Alternatives for 7.4 m/s

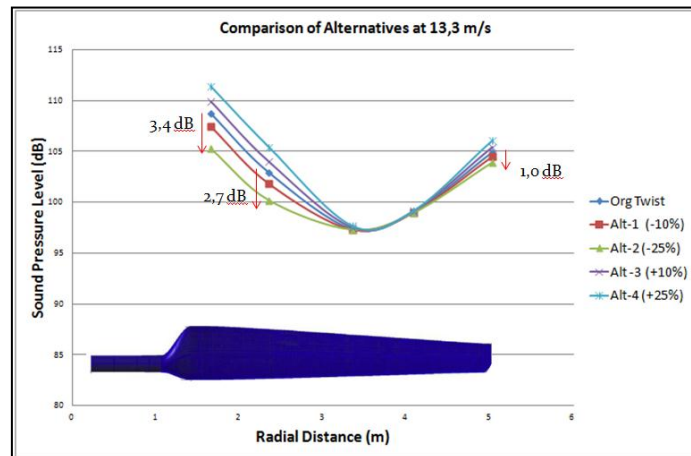
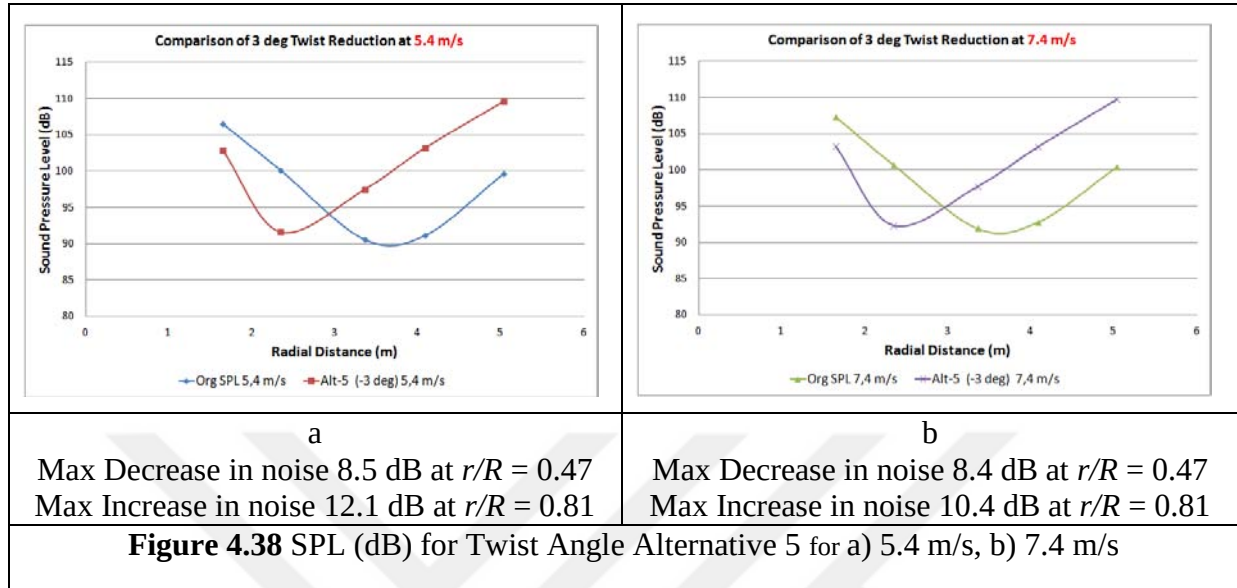
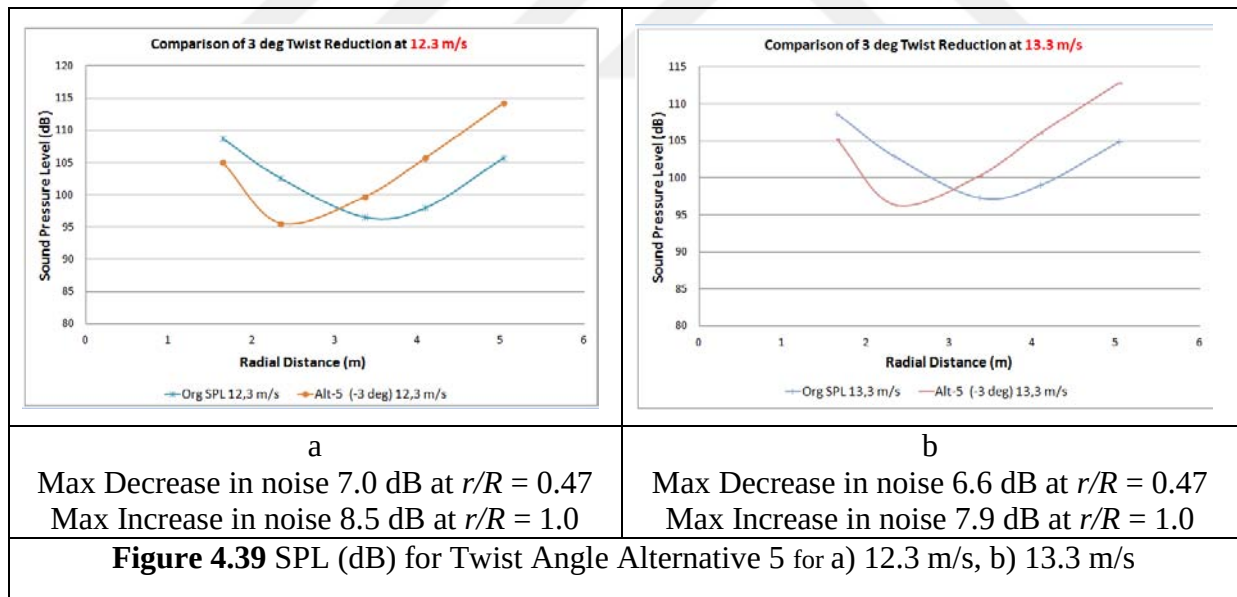


Figure 4.37 SPL Comparisons of Four Twist Angle Alternatives for 13.3 m/s

Besides the SPL results of four alternative twist angles, the fifth twist angle alternative was analyzed by reducing the twist angle 3 degrees of all sections. **Figure 4.38** exhibited the predictions for 5.4 m/s and 7.4 m/s inlet wind velocities.



The noise predictions of twist angle alternative - 5 were presented in **Figure 4.39** for 12.3 m/s and 13.3 m/s inlet wind velocities.

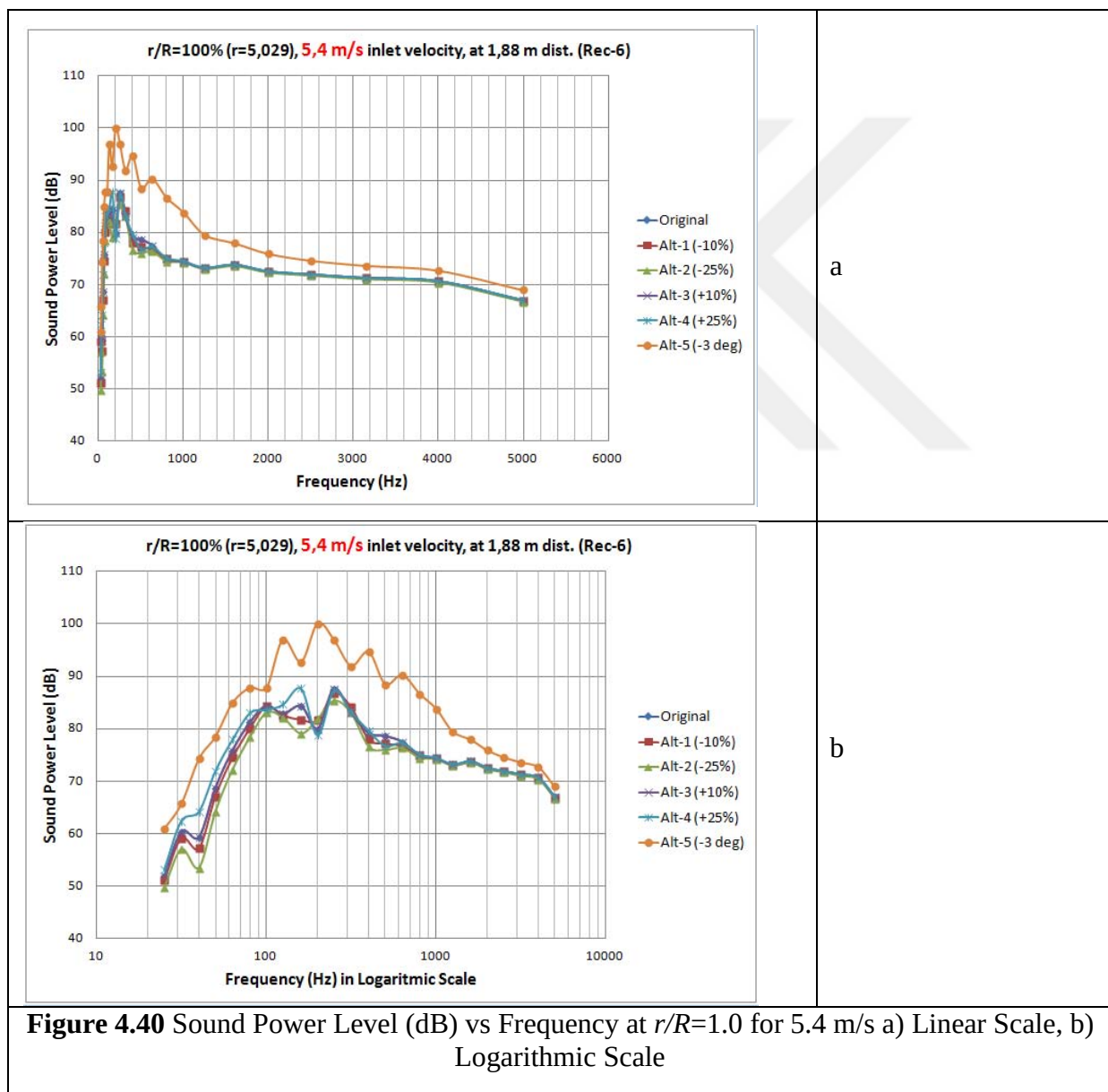


The defined twist angle alternative 5 did not provide noise reduction considering any section of the blade. The location of noise contributions of sections to the blade was shifted towards the hub in the scope of SPL comparison for alternative 5.

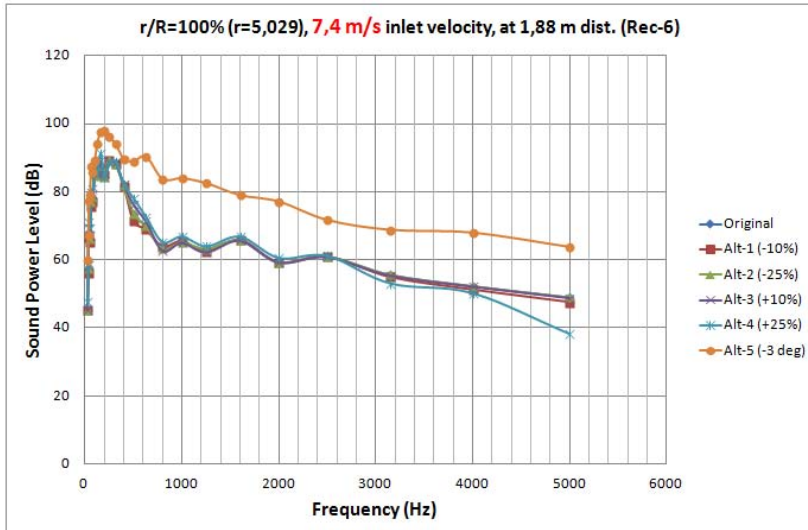
4.7.2. Frequency based noise comparison for alternatives

Frequency based noise predictions were done for $r/R = 1.0$ tip section and for $r/R = 0.33$ section close to the hub. Comparisons for each section were done at 5.4 m/s, 7.4 m/s, 12.3 m/s, and 13.3 m/s inlet wind velocities.

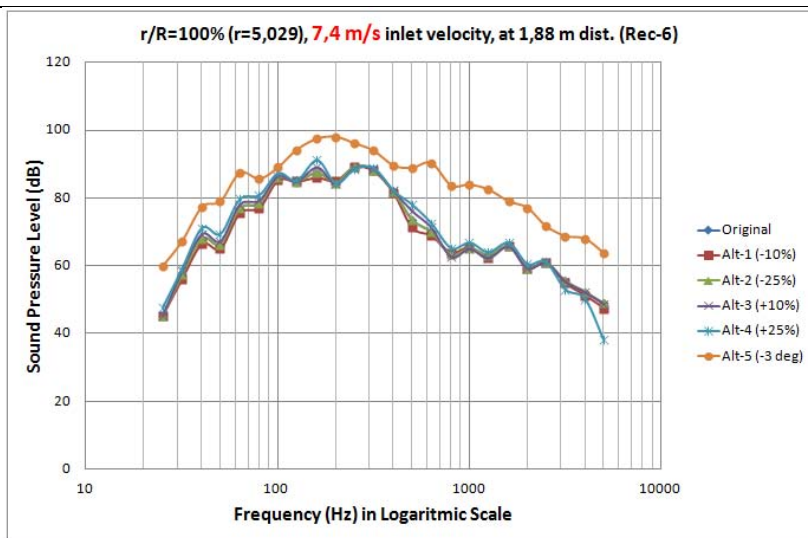
Sound Power Levels (dB) versus were presented for tip section $r/R = 1.0$ in **Figure 4.40**, **Figure 4.41**, **Figure 4.42**, and **Figure 4.43**. X axis of following figures were shown in linear scale on the left hand side, in logarithmic scale on the right hand side in order to interpret the deviation of noise in lower frequencies.



For the 5.4 m/s inlet velocity, alternative 5 yielded the highest SPL values through the all frequency spectrum. Noise predictions of alternative 2 showed some noise reduction between 100 and 200 Hz.



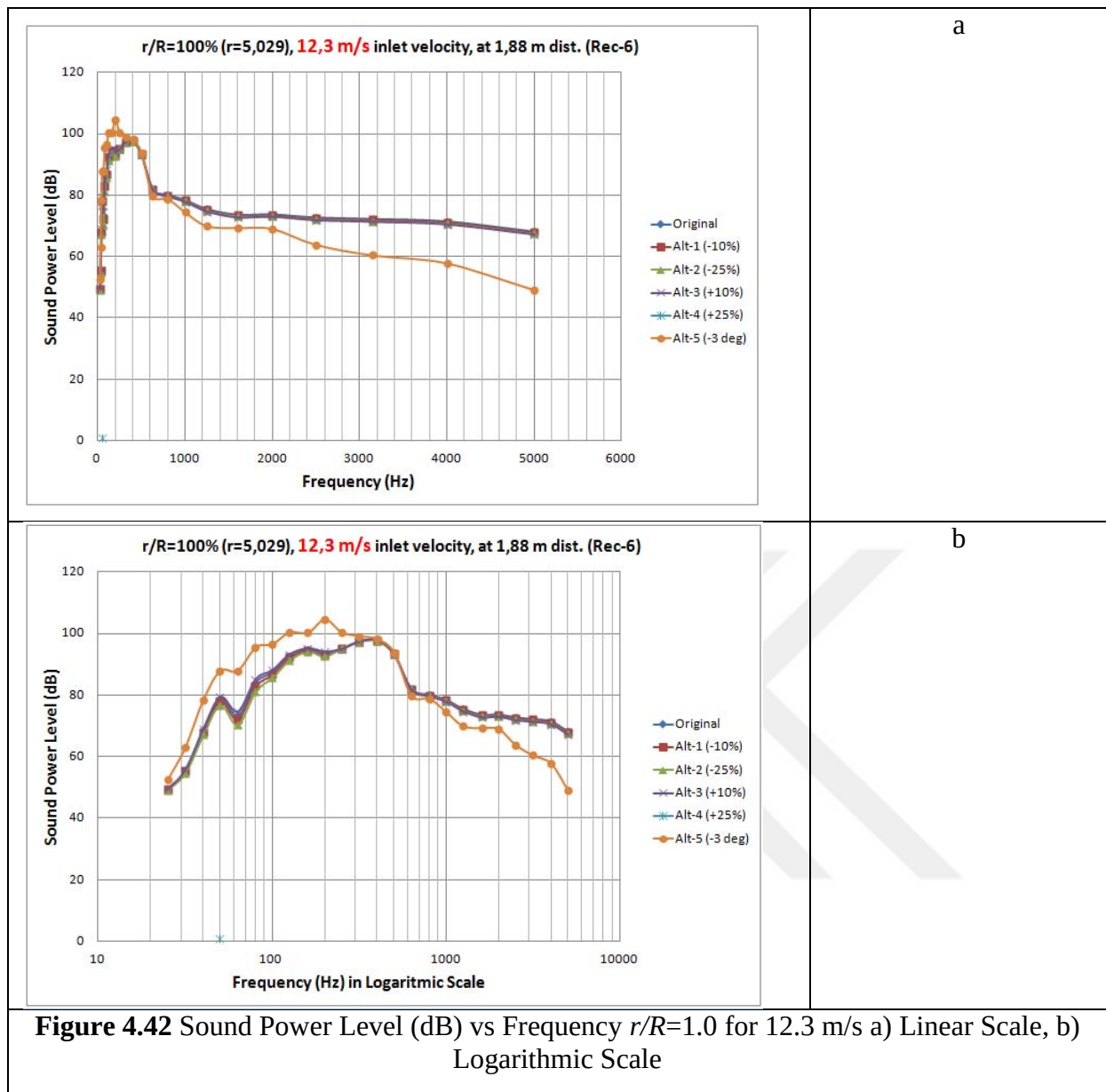
a



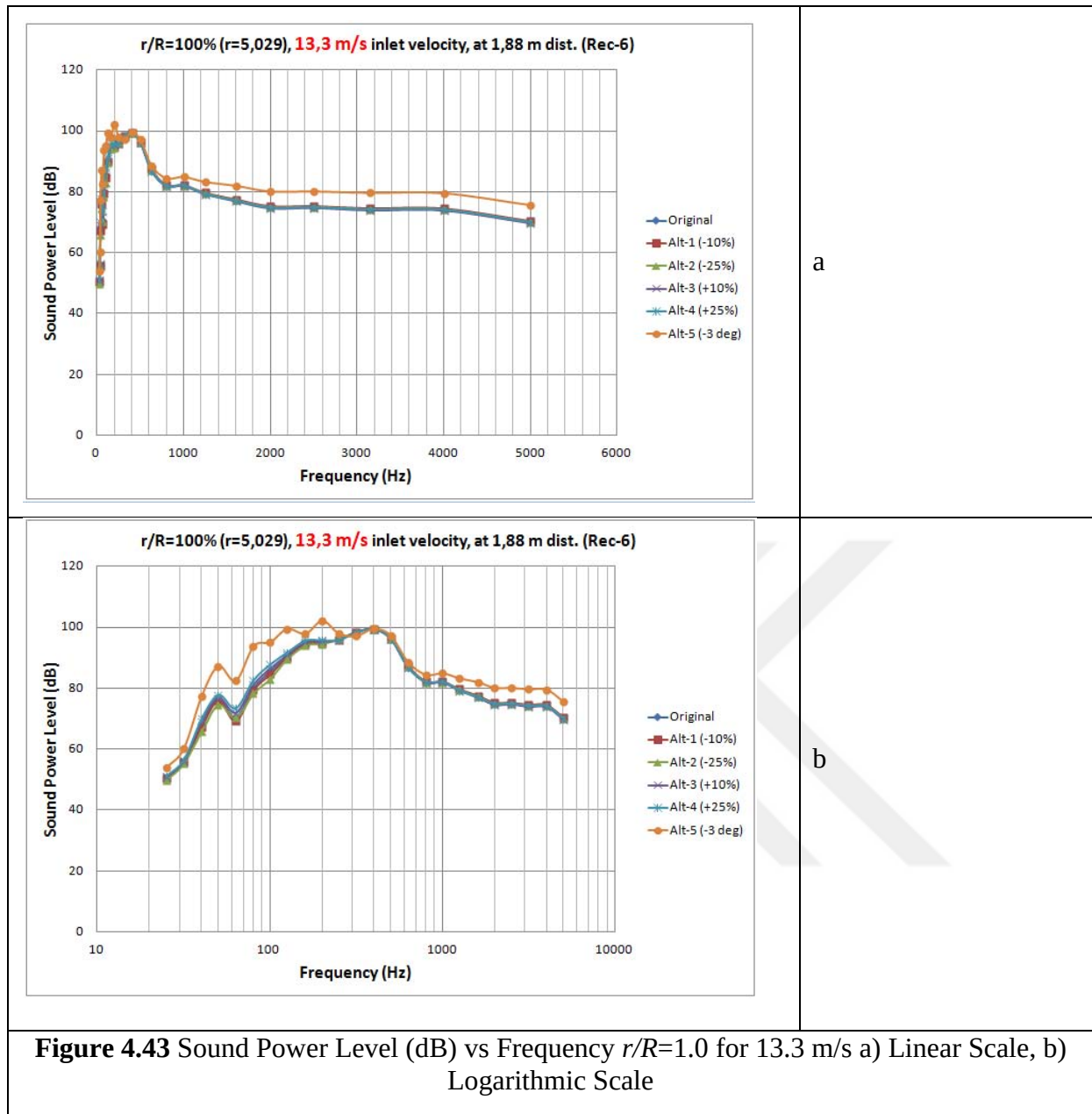
b

Figure 4.41 Sound Power Level (dB) vs Frequency $r/R=1.0$ for 7.4 m/s a) Linear Scale, b) Logarithmic Scale

At 7.4 m/s and at 13.3 m/s inlet speeds, all alternatives gave similar results other than alternative 5. Results of alternative 5 remained highest in all frequencies.



At 12.3 m/s inlet speed, alternative 1 - 4 gave similar predictions. Alternative 5 predictions were seemed lower between 700 Hz and 5.0 kHz, but these results were not consistent with other inlet velocities.

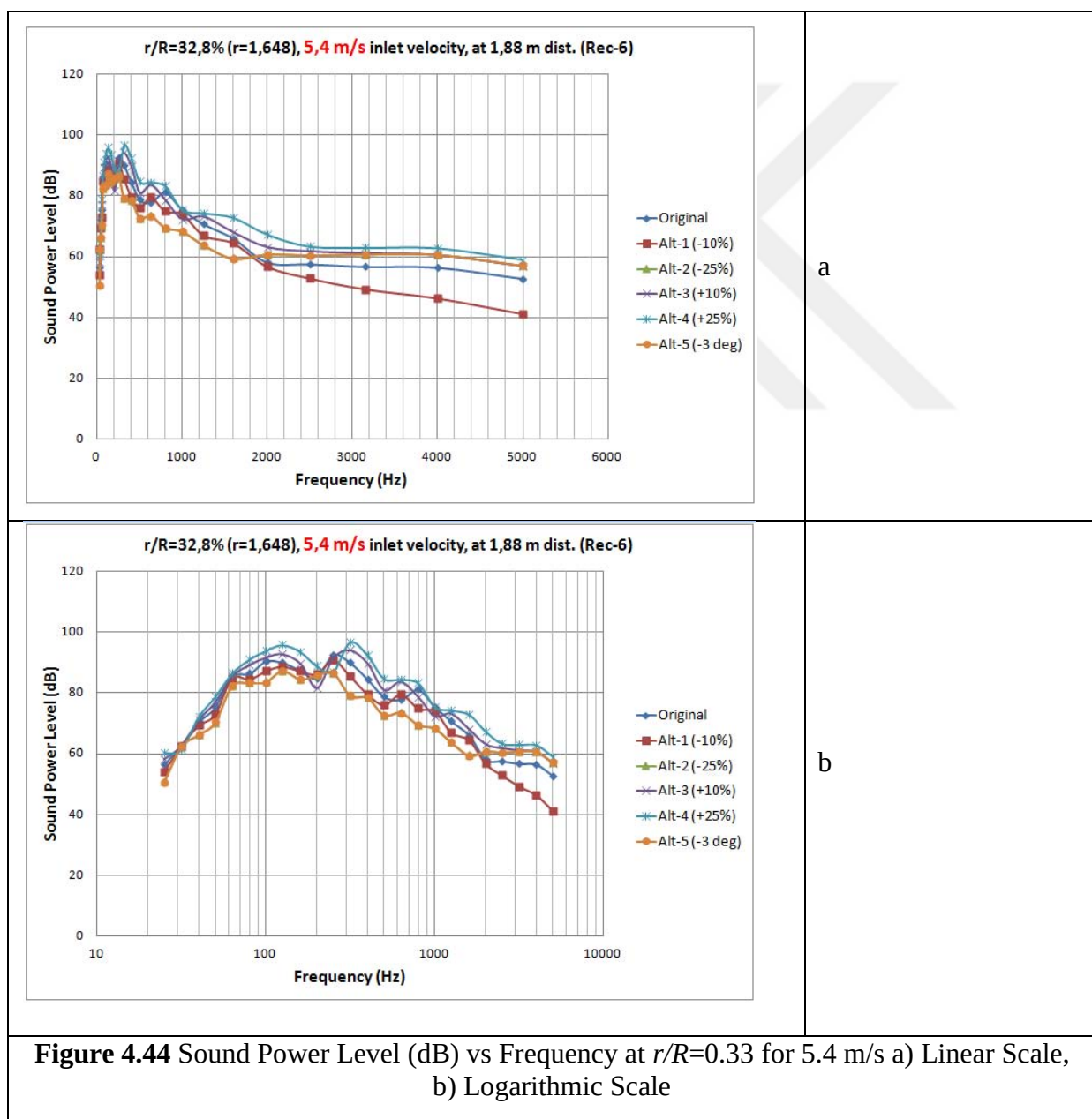


Frequency Analysis for $r/R=1.0$ section; Sound Power Level (dB) vs Frequency (Hz) graphics did not reveal specific improvement in linear scale and logarithmic scale. Alternative 5 (-3 degree twist reduction) prediction gave higher noises compared to the other twist angle alternatives.

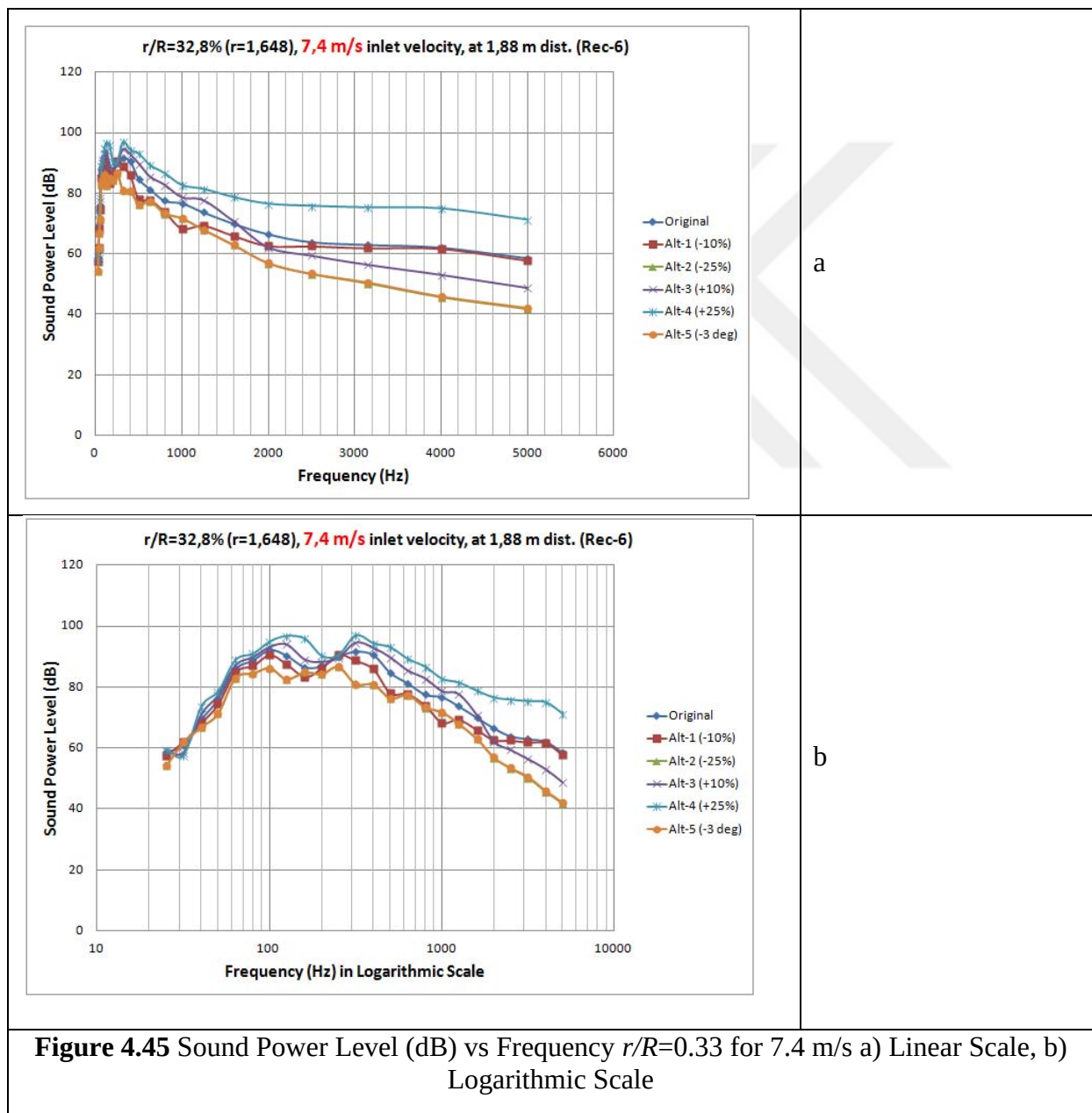
Alternative 2 (-25% twist reduction) for 5.4 m/s, predictions provided noise improvement above 5 dB (5.24 dB at 160 Hz specifically) between 100 and 200 Hz for tip section. This noise improvement in low frequency band was important considering the fact that lower frequencies have low atmospheric absorption rate meaning longer dissipation range, even though human threshold was higher in this frequency band. In other words, longer dissipation range was meant this low frequency noise component could travel further distance and by

way of this improvement, audible range of this noise component was diminished significantly. In general, 5 dB reductions in noise is discernible change and a 5 dB sound level change usually causes an obvious public response [30].

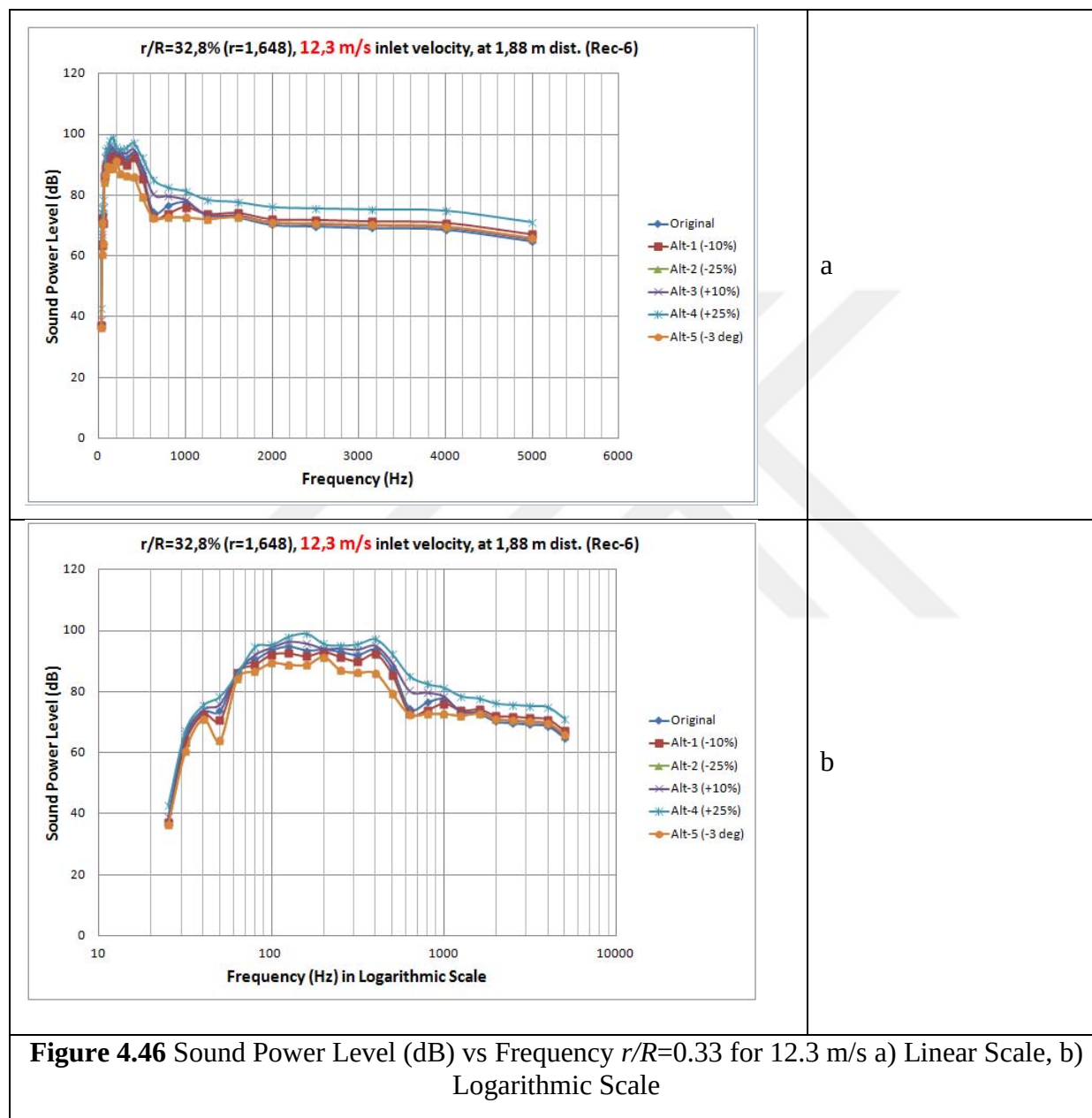
In addition to the tip section at $r/R = 1.0$, $r/R = 0.33$ section was analyzed in frequency domain to see the variation of noise. Sound Power Levels (dB) versus frequency (Hz) were presented for hub section $r/R = 0.33$ in **Figure 4.44**, **Figure 4.45**, **Figure 4.46**, and **Figure 4.47**. Twist angles of alternative 2 (8.932 degree) and alternative 5 (8.909 degree) pretty close to each other at this section, the predictions of these two alternatives gave almost identical results.



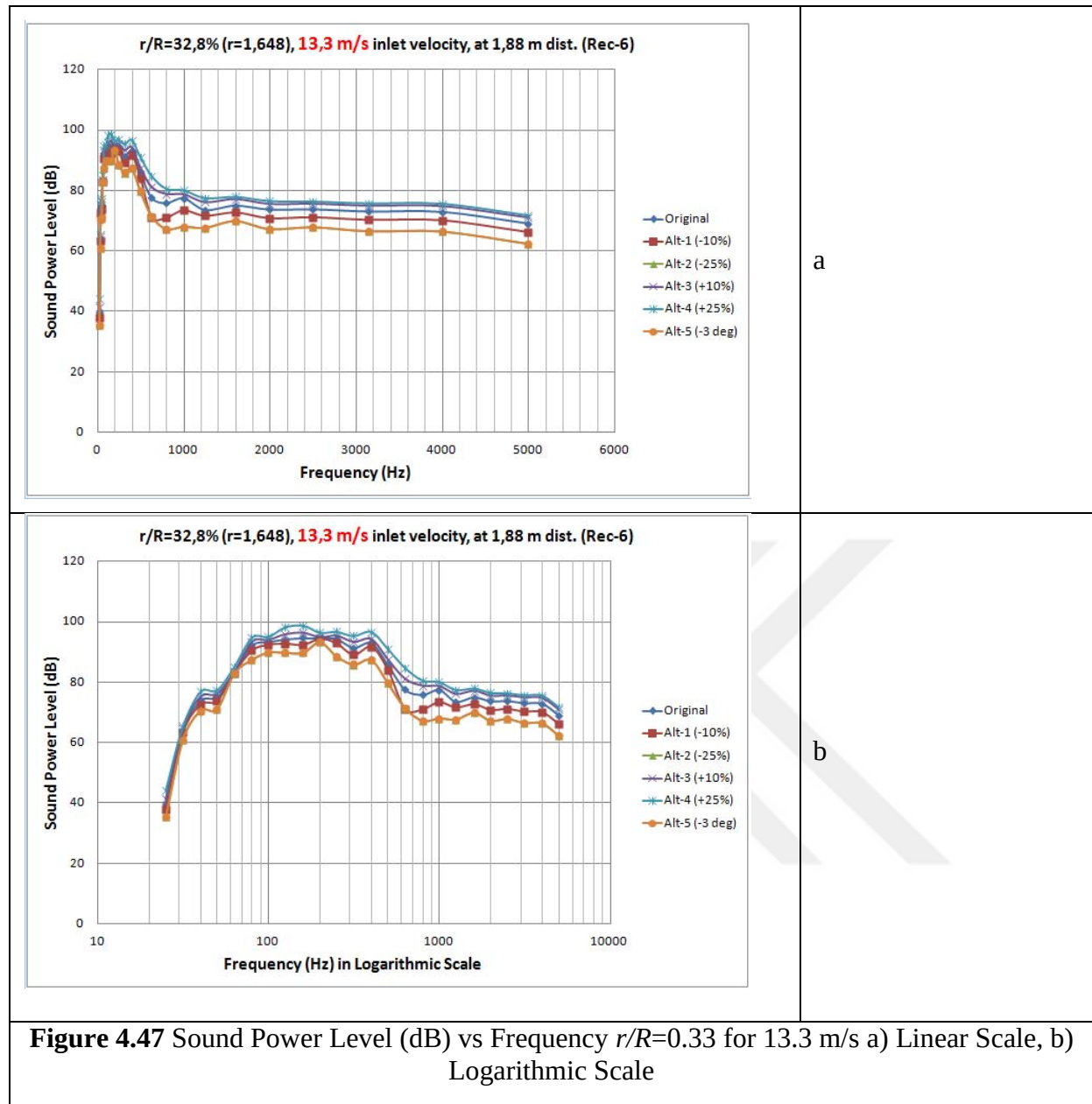
For the mid section at $r/R = 0.33$ different results were obtained compared to the $r/R = 1.0$ section. Even though alternative 2 provided maximum reduction up to 2.0 kHz, after 2.0 kHz up to 5.0 kHz the predictions showed maximum noise reduction for alternative 1 at 5.4 m/s inlet velocity. Alternative -2 provided noise reduction about 6 dB at 100 Hz and maximum decrease 11.5 dB at 800 Hz and finally 6.5 dB reduction at 1.6 kHz, these values meant significant noise reduction. Alternative -1 showed reduction 1.4 dB at 2.0 kHz, gradually increase was observed until 5.0 kHz that was 11.5 dB reduction at 5.4 m/s inlet speed for section $r/R = 0.33$.



Alternative 2 gave the minimum noise at 7.4 m/s inlet velocity above 250 Hz in general. Substantial reduction was predicted at mid frequencies, 3 – 10.6 dB between 100 Hz and 500 Hz. Especially above 1.25 kHz up to 5.0 kHz, significant reduction was calculated compared to original twist, 5.8 dB to 16.7 dB respectively. It was already mentioned that high frequency noise became more disturbing due to the sensitivity of human ear for high frequency noise.



Alternative 2 provided minimum noise between 100 Hz and 700 Hz. Above this frequency all alternatives gave similar predictions at 12.3 m/s inlet velocity. Similarly, alternative 2 predictions showed lower noise level above 100 Hz frequency at 13.3 m/s.



Frequency Analysis for $r/R=0.33$ section; Sound Power Level (dB) vs Frequency (Hz) graphics provided specific improvements in linear scale and in logarithmic scale.

Alternative 1 (-10% twist reduction) for 5.4 m/s, predictions revealed considerable noise reduction about 4.5 dB to 11.5 dB between 2.0 kHz and 5.0 kHz. Even though higher frequencies of sound decay in shorter distances due to higher atmospheric absorption rate, this noise reduction was considered highly valuable in case of close wind turbine installation to residences [31]. Moreover, alternative 2 also showed reduction up to 11.5 dB at mid frequencies that could travel further distances for 5.4 m/s inlet speed.

Alternative 2 (-25% twist reduction) predictions provided lower noise meaning better noise reduction characteristics for other inlet velocities.

4.7.3. Total blade noise comparison based on twist angle alternatives

Blade noise calculation was performed by applying formulae presented in Chapter 3.5 by contributing the noise of five selected sections. Total blade noise predictions were presented in **Figure 4.48**, **Figure 4.49**, **Figure 4.50**, and **Figure 4.51** for all five twist angle alternatives and at all inlet wind velocities.

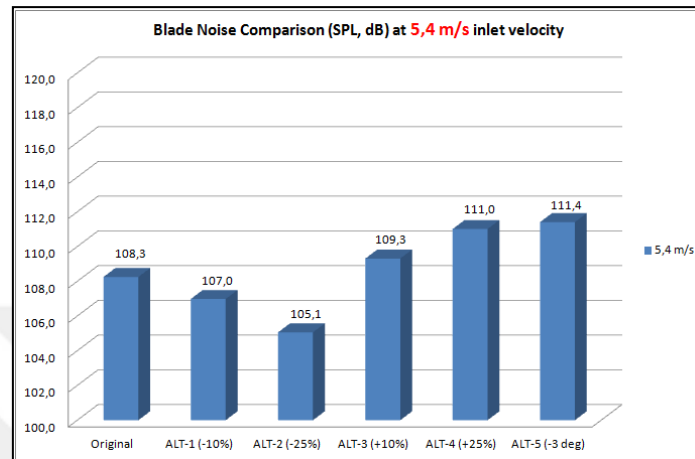


Figure 4.48 Total Blade Noise Comparisons at 5.4 m/s for Twist Angle Alternatives

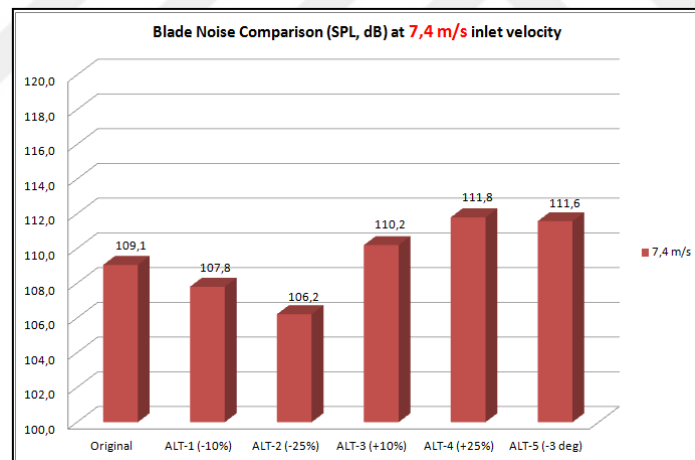


Figure 4.49 Total Blade Noise Comparisons at 7.4 m/s for Twist Angle Alternatives

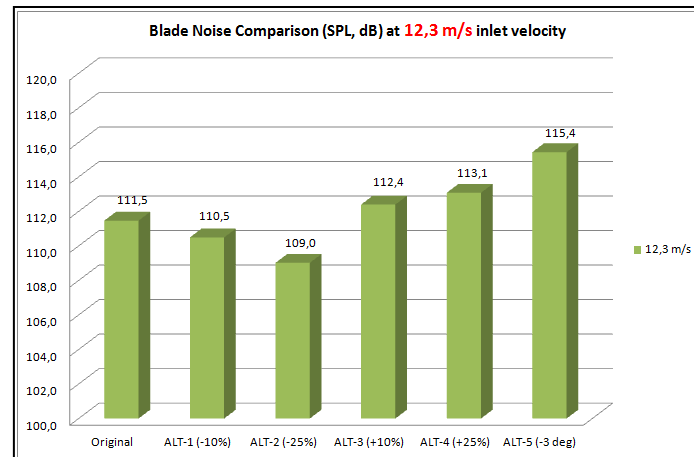


Figure 4.50 Total Blade Noise Comparisons at 12.3 m/s for Twist Angle Alternatives

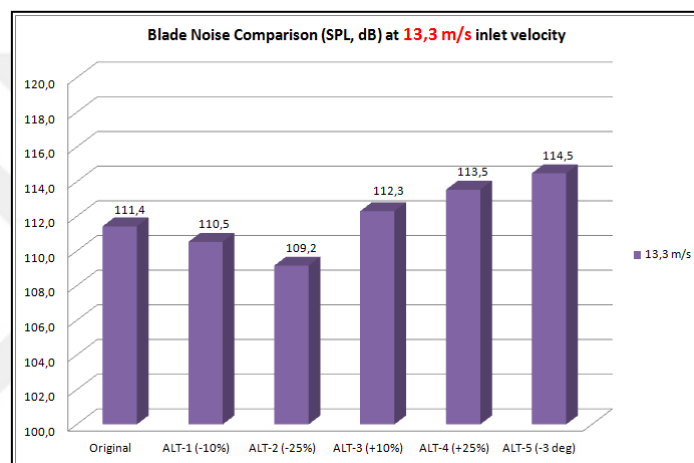
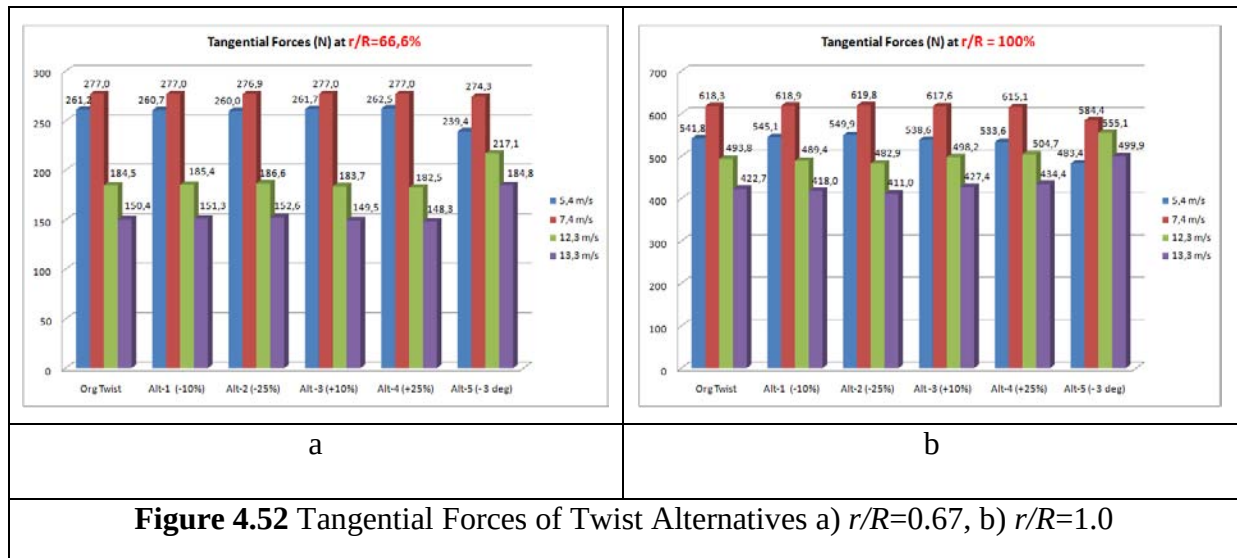


Figure 4.51 Total Blade Noise Comparisons at 13.3 m/s for Twist Angle Alternatives

Alternative 2 (25% reduced twist angle) provided the best noise reduction about 2.2 dB - 3.2 dB considering the all twist angle alternatives and all inlet wind velocities in scope of total blade noise. On the other hand, the effect of changing the twist angle on generated torque by the blade was investigated.

4.7.4. Generated torque of the blade based on twist angle alternatives

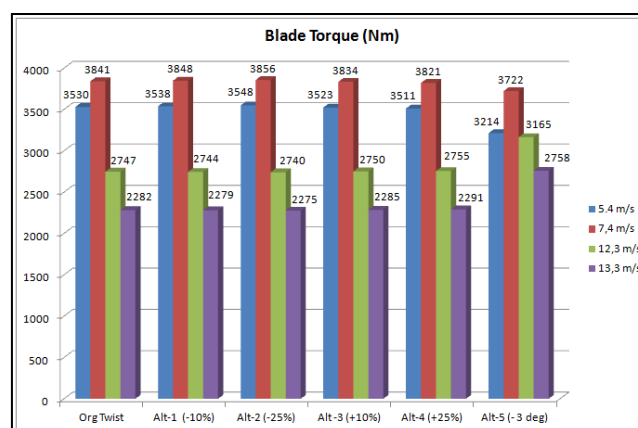
For the force calculation of sections, reduced twist angles and resulting angles of attack were considered in force calculation. Tangential forces of twist alternatives including original twist angle at $r/R=0.67$ and $r/R=1.0$ for four different inlet velocities (5.4 m/s, 7.4 m/s, 12.3 m/s and 13.3 m/s) were presented in the following **Figure 4.52**.



Twist alternatives 1 - 4 revealed similar force predictions compare to the original twist angle considering tangential forces. Alternative 5 (-3 deg decrease) provided 8% less force at $r/R=0.67$, 11% less force at $r/R=1.0$ for 5.4 m/s inlet speed and 1% less force at $r/R=0.67$, 5% less force at $r/R=1.0$ for 7.4 m/s inlet speed.

$r/R = 1.0$ section, gained force of alternative 2 was higher about 1.5% and 0.2% for 5.4 m/s and 7.4 m/s inlet velocities compare to the original gained force. On the other hand, gained force of alternative 2 was lower about 2% and 3% for 12.3 m/s and 13.3 m/s inlet velocities at this section. Alternative 1 presented similar gained force characteristics like alternative 2.

Considering these numbers, calculated blade torques were presented in **Figure 4.53** at different inlet speeds for twist angle alternatives.



Alternative 1 and 2 generated more torque around 0.2% for lower inlet speeds 5.4 m/s, 7.4 m/s. On the other hand, these two twist angle alternatives provided less torque 0.1% and 0.3% for higher inlet speeds 12.3 m/s and 13.3 m/s, respectively. The biggest change in blade

torque was calculated for twist alternative 5. For lower speeds torque results were around 9% lower, in the meanwhile calculations presented 15% increase in blade torque for higher speeds.

Alternative 1 and 2 did not only provide noise reduction but also they generated more blade torque (0.2%) at lower wind speeds and sacrificed some generated torque (less than 0.3%) at higher wind speeds compare to the original twist angle of the blade.

Another important finding was about the frequency dependence of the noise reduction of alternative 2 and 1. At $r/R = 0.33$ section for 5.4 m/s inlet wind velocity, alternative 1 noise prediction provided better noise reduction between 2.0 kHz and 5.0 kHz even though alternative 2 prediction had better noise reduction below 2.0 kHz. As shown in **Figure 2.11**, lower frequencies decays in longer distances due to low atmospheric absorption rate and higher frequencies decays in shorter distances because of high atmospheric absorption rate. By considering this reality, these two alternative twist angles might be utilized based on the distance between turbine installation site and residential areas. If close installation of wind turbine is mandatory, noise reduction in higher frequencies shall be more emphasized.

5. CONCLUSIONS

In order to compare the generated noise of the 12% scaled model of the NREL Phase VI wind turbine with the analysis results, certain steps were applied.

First, relative velocity components ($W_x(t)$ and $W_y(t)$) were calculated simultaneously for each section by using UDFs. Secondly, tapered geometry of actual blade was simulated by keeping the Reynolds number constant to be able to utilize the current mesh. Third, 12% dynamic viscosity was used to simulate the 12% scaled model. And finally, calculated Sound Pressure Levels (dB) were converted to Sound Power Levels (dB) to compare the measurements and analysis results.

The summary of the results;

For tip area (Zone A1), noise analysis at 5.4 m/s wind speed showed good agreement with the model measurements in terms of trend and magnitude. At higher wind speeds the quality of the predictions was degraded however the difference between predictions and measurement did not exceed 7 dB in the frequency range considered.

For inboard area (Zone A2), noise predictions were also in good agreement with measurements at low wind speeds, especially at 7.4 m/s. However, at higher wind speeds the computations underestimated the SPL considerably while predicting the general trend of the SPL vs. frequency curve reasonably accurately.

Considering the comparisons made at different zones and wind speeds, it was concluded that the two-dimensional model used in this study can be used to predict the noise level of wind turbine blades with reasonable accuracy at low wind speeds.

Additionally, overall SPLs of the whole blade were calculated at 1.88 m away along the blade sections. Higher SPLs were observed around tip and hub regions compare with the mid sections of the blade. These sections may be critical while optimizing the blade geometry for low noise emission.

The effect of **extreme wind conditions** on wind turbine noise was investigated in the current study by applying Extreme Operating Gust according to the International Standard on "Wind Turbines Design Requirements". Even though EOG formulation defines trigonometric speed vs time curve, noise predictions provided decaying SPL (dB) in time. Noise at 3.5 seconds was the highest and decreased in time until the end of the analysis, 14.0 seconds for all

sections.

In the frequency based predictions provided two different results for two different sections, $r/R = 0.75$, and $r/R = 1.0$.

For mid section ($r/R = 0.75$); between 1.0 kHz and 5.0 kHz, the measurements were already available, moderate increase were predicted between 1.5 dB and 5.1 dB due to EOG effect.

In the all frequency range between 100 Hz and 5.0 kHz, maximum increase was predicted at 500 Hz and around 11.0 dB.

On the other hand for tip section ($r/R = 1.0$), the predictions provided higher increase in Sound Power Level (dB) between 1.0 kHz and 5.0 kHz. Around 8.0 - 9.7 dB increase for 5.4 m/s inlet velocity and 15.0 - 20.0 for 7.0 m/s inlet velocity. Higher inlet speed under EOG effect almost doubled the increase in noise.

In the all frequency range between, the maximum increments were predicted at different frequencies. As a result, the effect of Extreme Operating Gust was predicted stronger at the tip section and dissimilar behavior of EOG effect on noise was predicted for tip section and for mid section of the turbine blade.

Noise reduction efforts were performed by changing the twist angle of the NREL Phase VI blade through the five selected sections. Five alternatives were applied to the validated noise model verified in the previous chapters.

First, **sound pressure levels** of alternative twist angles were compared with the noise of the original twist angles for five selected sections. Five different twist angle alternatives were analyzed for 5 selected sections throughout the blade at 4 different inlet speeds, namely 5.4 m/s, 7.4 m/s, 12.3 m/s, and 13.3 m/s.

Improvements in SPLs (dB) for all inlet speeds were bigger for sections closer to the hub. Moderate improvements were observed for tip section. Too little or no improvement revealed at mid sections for the given analysis conditions. The noise reduction was predicted about 3.4 dB to 4.1 dB at the $r/R = 0.33$ section for 25% reduced twist angle alternative. For the same 25% reduced twist angle alternative, the predicted noise reduction was about 1.0 to 2.5 dB at the tip section ($r/R = 1.0$).

Later, in order to have wider analysis and to draw some conclusions, **frequency based** noise comparisons were done. The main improvements were confirmed after frequency based analysis. Tip section improvements observed at lower frequencies that have longer dissipation range even though human hearing threshold is higher in this frequency band. The section

closer to the hub provided the main improvement in noise both in SPL comparison and in frequency based analysis. Alternative 1 (-10% twist reduction) for 5.4 m/s, predictions revealed considerable noise reduction about 4.5 dB to 11.5 dB between 2.0 kHz and 5.0 kHz. Even though higher frequencies of sound decay in shorter distances due to higher atmospheric absorption rate, this noise reduction was considered highly valuable in case of close wind turbine installation to residences. Moreover, alternative 2 also showed reduction up to 11.5 dB at mid frequencies that could travel further distances for 5.4 m/s inlet speed.

Alternative 2 (-25% twist reduction) predictions provided lower noise meaning better noise reduction characteristics for other inlet velocities

Additionally, **total blade noise comparisons** were completed for all inlet wind velocities. When the all twist angle alternatives at all inlet wind velocities, alternative 2 (25% reduced twist angle) provided the best noise reduction about 2.2 dB - 3.2 dB.

The generated **torques of twist angle alternatives** were compared with each other for all inlet wind velocities. Alternative 1 and 2 did not only provide noise reduction but also they generated more blade torque (0.2%) at lower wind speeds and sacrificed some generated torque (less than 0.3%) at higher wind speeds compare to the original twist angle of the blade.

Another important finding was about the frequency dependence of the noise reduction of alternative 2 and 1. At $r/R = 0.33$ section for 5.4 m/s inlet wind velocity, alternative 1 noise prediction provided better noise reduction between 2.0 kHz and 5.0 kHz even though alternative 2 prediction had better noise reduction below 2.0 kHz. In the meanwhile, lower frequencies decays in longer distances due to low atmospheric absorption rate and higher frequencies decays in shorter distances because of high atmospheric absorption rate. By considering this reality, these two alternative twist angles might be utilized based on the distance between turbine installation site and residential areas. If close installation of wind turbine is mandatory under the consideration of moderate average wind speed (i.e. 5.4 m/s), noise reduction in higher frequencies shall be more emphasized and might be more useful.

Calculation and evaluation of contribution by each noise term defined in FW-H equation can be performed as future work. This calculation can be beneficial for future noise reduction studies. Another suggestion as future work can be the research of effects by wind turbine noise on wild life as interdisciplinary study.

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APPENDICES

APPENDIX 1: USER DEFINED FUNCTIONS FOR MODEL VALIDATION

APPENDIX 2: USER DEFINED FUNCTIONS FOR EOG ANALYSIS

APPENDIX 3: USER DEFINED FUNCTIONS FOR NOISE REDUCTION
STUDIES



APPENDIX 1

USER DEFINED FUNCTIONS FOR MODEL VALIDATION

```
/******  
  
transient_12perc_54ms_dyn_x_y_vel_section5.c  
  
UDF utilized to specify unsteady velocity profile inlet boundary condition  
  
*****/  
  
#include "udf.h"  
  
/*constants*/  
  
#define OMEGA 7.5398          /*angular velocity in radian per second */  
#define R 3.772              /*radius in meter for SECTION 5*/  
#define BETA 0.0             /*twist angle in radians for SECTION 5*/  
DEFINE_PROFILE(transient_x_velocity, thread, position) /* used for boundary profiles*/  
{  
    real vinf,phi,alpha,wresult; /*variable declarations*/  
    face_t f;                  /*declares an integer data type used to identify faces; f is a face thread  
variable*/  
    real t = CURRENT_TIME;     /*assigns real flow time to variable t*/  
  
    begin_f_loop(f, thread)  
    {  
        vinf = 8.218;          /*constant inlet velocity */  
        phi = atan((OMEGA*R)/vinf);          /*phi angle in radians*/  
        alpha = phi - BETA;     /*angle of attack in radians*/  
        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/  
        F_PROFILE(f, thread, position) = wresult*cos(alpha); /* F_PROFILE macro applies the velocity  
component to face f.*/  
    }  
    end_f_loop(f, thread)  
}  
  
DEFINE_PROFILE(transient_y_velocity, thread, position) /* used for boundary profiles*/  
{  
    real vinf,phi,alpha,wresult; /*variable declarations*/  
    face_t f;                  /*declares an integer data type used to identify faces; f is a face thread  
variable*/  
    real t = CURRENT_TIME;     /* assigns real flow time to variable t */
```

```

begin_f_loop(f, thread)
{
    vinf = 8.218;                      /*constant inlet velocity*/
    phi = atan((OMEGA*R)/vinf);        /*phi angle in radians*/
    alpha = phi - BETA;                /*angle of attack in radians*/
    wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/
    F_PROFILE(f, thread, position) = wresult*sin(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/
}
end_f_loop(f, thread)
}

```



```

/*****

transient_12perc_74ms_dyn_x_y_vel_section6.c

UDF utilized to specify unsteady velocity profile inlet boundary condition
*****/

#include "udf.h"

/*constants*/

#define OMEGA 7.5398          /*angular velocity in radian per second */
#define R 4.086              /*radius in meter for SECTION 6*/
#define BETA -0.00829        /*twist angle in radians for SECTION 6*/
DEFINE_PROFILE(transient_x_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/
    face_t f;                  /*declares an integer data type used to identify faces; f is a face thread
variable*/
    real t = CURRENT_TIME;     /* assigns real flow time to variable t */
    begin_f_loop(f, thread)
    {
        vinf = 12.061;          /*constant inlet velocity */
        phi = atan((OMEGA*R)/vinf); /*phi angle in radians*/
        alpha = phi - BETA;      /*angle of attack in radians*/
        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/
        F_PROFILE(f, thread, position) = wresult*cos(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/
    }
    end_f_loop(f, thread)
}
DEFINE_PROFILE(transient_y_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/
    face_t f;                  /*declares an integer data type used to identify faces; f is a face thread
variable*/
    real t = CURRENT_TIME;     /* assigns real flow time to variable t */

    begin_f_loop(f, thread)
    {
        vinf = 12.061;          /*constant inlet velocity*/
        phi = atan((OMEGA*R)/vinf); /*phi angle in radians*/
        alpha = phi - BETA;      /*angle of attack in radians*/
        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/

```

```
    F_PROFILE(f, thread, position) = wresult*sin(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/
}
end_f_loop(f, thread)
}
```



```

/*****

transient_12perc_123ms_dyn_x_y_vel_section7.c

UDF utilized to specify unsteady velocity profile inlet boundary condition
*****/

#include "udf.h"

/*constants*/

#define OMEGA 7.5398          /*angular velocity in radian per second */

#define R 4.780              /*radius in meter for SECTION 7*/

#define BETA -0.02564        /*twist angle in radians for SECTION 7*/

DEFINE_PROFILE(transient_x_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/

    face_t f;                  /*declares an integer data type used to identify faces; f is a face thread
variable*/

    real t = CURRENT_TIME;     /* assigns real flow time to variable t */

    begin_f_loop(f, thread)
    {
        vinf = 23.731;          /*constant inlet velocity */

        phi = atan((OMEGA*R)/vinf);          /*phi angle in radians*/

        alpha = phi - BETA;      /*angle of attack in radians*/

        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R));    /*resultant wind velocity in m/s*/

        F_PROFILE(f, thread, position) = wresult*cos(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/

    }

    end_f_loop(f, thread)
}

DEFINE_PROFILE(transient_y_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/

```

```

face_t f;                /*declares an integer data type used to identify faces; f is a face thread
variable*/

real t = CURRENT_TIME;   /* assigns real flow time to variable t */

begin_f_loop(f, thread)

{

    vinf = 23.731;        /*constant inlet velocity*/

    phi = atan((OMEGA*R)/vinf);    /*phi angle in radians*/

    alpha = phi - BETA;    /*angle of attack in radians*/

    wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R));    /*resultant wind velocity in m/s*/

    F_PROFILE(f, thread, position) = wresult*sin(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/

}

end_f_loop(f, thread)

}

```

```

/*****

transient_12perc_133ms_dyn_x_y_vel_section8.c

UDF utilized to specify unsteady velocity profile inlet boundary condition
*****/

#include "udf.h"

/*constants*/

#define OMEGA 7.5398          /*angular velocity in radian per second */
#define R 5.029              /*radius in meter for SECTION 8*/
#define BETA -0.03167        /*twist angle in radians for SECTION 8*/

DEFINE_PROFILE(transient_x_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/

    face_t f;                  /*declares an integer data type used to identify faces; f is a face thread
variable*/

    real t = CURRENT_TIME;      /* assigns real flow time to variable t */

    begin_f_loop(f, thread)
    {
        vinf = 27.462;          /*constant inlet velocity */

        phi = atan((OMEGA*R)/vinf);          /*phi angle in radians*/

        alpha = phi - BETA;      /*angle of attack in radians*/

        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/

        F_PROFILE(f, thread, position) = wresult*cos(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/

    }

    end_f_loop(f, thread)
}

DEFINE_PROFILE(transient_y_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/

```

```

face_t f;                /*declares an integer data type used to identify faces; f is a face thread
variable*/

real t = CURRENT_TIME;   /* assigns real flow time to variable t */

begin_f_loop(f, thread)

{

    vinf = 27.462;         /*constant inlet velocity*/

    phi = atan((OMEGA*R)/vinf);    /*phi angle in radians*/

    alpha = phi - BETA;      /*angle of attack in radians*/

    wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R));    /*resultant wind velocity in m/s*/

    F_PROFILE(f, thread, position) = wresult*sin(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/

}

end_f_loop(f, thread)

}

```

APPENDIX 2

USER DEFINED FUNCTIONS FOR EOG ANALYSIS

```

/*****

transient_12perc_EOG_54ms_dyn_x_y_vel_section5.c

UDF utilized to specify unsteady velocity profile inlet boundary condition
*****/

#include "udf.h"

/*constants*/

#define OMEGA 7.5398          /*angular velocity in radian per second */
#define R 3.772              /*radius in meter for SECTION 5*/
#define BETA 0.0             /*twist angle in radians for SECTION 5*/

DEFINE_PROFILE(transient_x_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/

    face_t f;                  /*declares an integer data type used to identify faces; f is a face thread
variable*/

    real t = CURRENT_TIME;     /* assigns real flow time to variable t */

    begin_f_loop(f, thread)
    {

        vinf = 8.218 - 1.567*sin(0.8976*t)*(1. - cos(0.5894*t)); /*inlet velocity by Extreme Operating Gust
formulation*/

        phi = atan((OMEGA*R)/vinf);          /*phi angle in radians*/
        alpha = phi - BETA;                  /*angle of attack in radians*/

        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/

        F_PROFILE(f, thread, position) = wresult*cos(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/

    }

    end_f_loop(f, thread)
}

```

```

DEFINE_PROFILE(transient_y_velocity, thread, position) /* used for boundary profiles*/

{

    real vinf,phi,alpha,wresult; /*variable declarations*/

    face_t f; /*declares an integer data type used to identify faces; f is a face thread
variable*/

    real t = CURRENT_TIME; /* assigns real flow time to variable t */

    begin_f_loop(f, thread)

    {

        vinf = 8.218 - 1.567*sin(0.8976*t)*(1. - cos(0.5894*t)); /*inlet velocity by Extreme Operating Gust
formulation*/

        phi = atan((OMEGA*R)/vinf); /*phi angle in radians*/

        alpha = phi - BETA; /*angle of attack in radians*/

        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/

        F_PROFILE(f, thread, position) = wresult*sin(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/

    }

    end_f_loop(f, thread)

}

```

APPENDIX 3

USER DEFINED FUNCTIONS FOR NOISE REDUCTION STUDIES

```
/******  
transient_twist_Alt_1_54ms_dyn_x_y_vel_section2.c  
UDF utilized to specify unsteady velocity profile inlet boundary condition  
*****/  
  
#include "udf.h"  
  
/*constants*/  
  
#define OMEGA 7.5398          /*angular velocity in radian per second */  
#define R 1.648              /*radius in meter for SECTION 2*/  
#define BETA 0.187064        /*twist angle in radians for SECTION 2 for Alt-1*/  
DEFINE_PROFILE(transient_x_velocity, thread, position) /* used for boundary profiles*/  
{  
    real vinf,phi,alpha,wresult; /*variable declarations*/  
    face_t f;                  /*declares an integer data type used to identify faces; f is a face thread  
variable*/  
    real t = CURRENT_TIME;     /* assigns real flow time to variable t */  
  
    begin_f_loop(f, thread)  
    {  
        vinf = 5.695;          /*constant inlet velocity */  
        phi = atan((OMEGA*R)/vinf); /*phi angle in radians*/  
        alpha = phi - BETA;     /*angle of attack in radians*/  
        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/  
        F_PROFILE(f, thread, position) = wresult*cos(alpha); /* F_PROFILE macro applies the velocity  
component to face f.*/  
    }  
    end_f_loop(f, thread)  
}  
  
DEFINE_PROFILE(transient_y_velocity, thread, position) /* used for boundary profiles*/  
{  
    real vinf,phi,alpha,wresult; /*variable declarations*/  
    face_t f;                  /*declares an integer data type used to identify faces; f is a face thread  
variable*/  
    real t = CURRENT_TIME;     /* assigns real flow time to variable t */  
    begin_f_loop(f, thread)  
    {  
        vinf = 5.695;          /*constant inlet velocity*/
```

```

    phi = atan((OMEGA*R)/vinf);          /*phi angle in radians*/
    alpha = phi - BETA;                  /*angle of attack in radians*/
    wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/
    F_PROFILE(f, thread, position) = wresult*sin(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/
}
end_f_loop(f, thread)
}

```



```

/*****
transient_twist_Alt_2_74ms_dyn_x_y_vel_section2.c
UDF utilized to specify unsteady velocity profile inlet boundary condition
*****/

#include "udf.h"

/*constants*/

#define OMEGA 7.5398          /*angular velocity in radian per second */
#define R 1.648              /*radius in meter for SECTION 2*/
#define BETA 0.15589         /*twist angle in radians for SECTION 2 for Alt-2*/
DEFINE_PROFILE(transient_x_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/
    face_t f;                   /*declares an integer data type used to identify faces; f is a face thread
variable*/
    real t = CURRENT_TIME;      /* assigns real flow time to variable t */
    begin_f_loop(f, thread)
    {
        vinf = 7.804;           /*constant inlet velocity */
        phi = atan((OMEGA*R)/vinf); /*phi angle in radians*/
        alpha = phi - BETA;      /*angle of attack in radians*/
        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/
        F_PROFILE(f, thread, position) = wresult*cos(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/
    }
    end_f_loop(f, thread)
}

DEFINE_PROFILE(transient_y_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/
    face_t f;                   /*declares an integer data type used to identify faces; f is a face thread
variable*/
    real t = CURRENT_TIME;      /* assigns real flow time to variable t */
    begin_f_loop(f, thread)
    {
        vinf = 7.804;           /*constant inlet velocity*/
        phi = atan((OMEGA*R)/vinf); /*phi angle in radians*/
        alpha = phi - BETA;      /*angle of attack in radians*/
        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/

```

```
    F_PROFILE(f, thread, position) = wresult*sin(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/
}
end_f_loop(f, thread)
}
```



```

/*****

transient_twist_Alt_3_123ms_dyn_x_y_vel_section2.c

UDF utilized to specify unsteady velocity profile inlet boundary condition
*****/

#include "udf.h"

/*constants*/

#define OMEGA 7.5398          /*angular velocity in radian per second */
#define R 1.648              /*radius in meter for SECTION 2*/
#define BETA 0.228638        /*twist angle in radians for SECTION 2 for Alt-3*/
DEFINE_PROFILE(transient_x_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/
    face_t f;                   /*declares an integer data type used to identify faces; f is a face thread
variable*/
    real t = CURRENT_TIME;      /* assigns real flow time to variable t */
    begin_f_loop(f, thread)
    {
        vinf = 12.972;          /*constant inlet velocity */
        phi = atan((OMEGA*R)/vinf); /*phi angle in radians*/
        alpha = phi - BETA;      /*angle of attack in radians*/
        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/
        F_PROFILE(f, thread, position) = wresult*cos(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/
    }
    end_f_loop(f, thread)
}

DEFINE_PROFILE(transient_y_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/
    face_t f;                   /*declares an integer data type used to identify faces; f is a face thread
variable*/
    real t = CURRENT_TIME;      /* assigns real flow time to variable t */
    begin_f_loop(f, thread)
    {
        vinf = 12.972;          /*constant inlet velocity*/
        phi = atan((OMEGA*R)/vinf); /*phi angle in radians*/
        alpha = phi - BETA;      /*angle of attack in radians*/
        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/

```

```
    F_PROFILE(f, thread, position) = wresult*sin(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/
}
end_f_loop(f, thread)
}
```



```

/*****
transient_twist_Alt_4_133ms_dyn_x_y_vel_section2.c
UDF utilized to specify unsteady velocity profile inlet boundary condition
*****/

#include "udf.h"

/*constants*/

#define OMEGA 7.5398          /*angular velocity in radian per second */
#define R 1.648              /*radius in meter for SECTION 2*/
#define BETA 0.259809        /*twist angle in radians for SECTION 2 for Alt-4*/
DEFINE_PROFILE(transient_x_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/
    face_t f;                  /*declares an integer data type used to identify faces; f is a face thread
variable*/
    real t = CURRENT_TIME;     /* assigns real flow time to variable t */
    begin_f_loop(f, thread)
    {
        vinf = 14.027;          /*constant inlet velocity */
        phi = atan((OMEGA*R)/vinf); /*phi angle in radians*/
        alpha = phi - BETA;      /*angle of attack in radians*/
        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/
        F_PROFILE(f, thread, position) = wresult*cos(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/
    }
    end_f_loop(f, thread)
}

DEFINE_PROFILE(transient_y_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/
    face_t f;                  /*declares an integer data type used to identify faces; f is a face thread
variable*/
    real t = CURRENT_TIME;     /* assigns real flow time to variable t */
    begin_f_loop(f, thread)
    {
        vinf = 14.027;          /*constant inlet velocity*/
        phi = atan((OMEGA*R)/vinf); /*phi angle in radians*/
        alpha = phi - BETA;      /*angle of attack in radians*/
        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/

```

```
    F_PROFILE(f, thread, position) = wresult*sin(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/
}
end_f_loop(f, thread)
}
```



```

/*****
transient_twist_Alt_5_133ms_dyn_x_y_vel_section2.c
UDF utilized to specify unsteady velocity profile inlet boundary condition
*****/

#include "udf.h"

/*constants*/

#define OMEGA 7.5398          /*angular velocity in radian per second */
#define R 1.648              /*radius in meter for SECTION 2*/
#define BETA 0.15549         /*twist angle in radians for SECTION 2 for Alt-5*/
DEFINE_PROFILE(transient_x_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/
    face_t f;                   /*declares an integer data type used to identify faces; f is a face thread
variable*/
    real t = CURRENT_TIME;      /* assigns real flow time to variable t */
    begin_f_loop(f, thread)
    {
        vinf = 14.027;          /*constant inlet velocity */
        phi = atan((OMEGA*R)/vinf); /*phi angle in radians*/
        alpha = phi - BETA;      /*angle of attack in radians*/
        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/
        F_PROFILE(f, thread, position) = wresult*cos(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/
    }
    end_f_loop(f, thread)
}

DEFINE_PROFILE(transient_y_velocity, thread, position) /* used for boundary profiles*/
{
    real vinf,phi,alpha,wresult; /*variable declarations*/
    face_t f;                   /*declares an integer data type used to identify faces; f is a face thread
variable*/
    real t = CURRENT_TIME;      /* assigns real flow time to variable t */
    begin_f_loop(f, thread)
    {
        vinf = 14.027;          /*constant inlet velocity*/
        phi = atan((OMEGA*R)/vinf); /*phi angle in radians*/
        alpha = phi - BETA;      /*angle of attack in radians*/
        wresult = sqrt(vinf*vinf + (OMEGA*R)*(OMEGA*R)); /*resultant wind velocity in m/s*/

```

```
    F_PROFILE(f, thread, position) = wresult*sin(alpha); /* F_PROFILE macro applies the velocity
component to face f.*/
}
end_f_loop(f, thread)
}
```



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