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PERCEPTION OF AMPLITUDE-MODULATED NOISE FROM WIND TURBINES

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Noise from modern wind turbines is generally lower than that from other environmental noise sources such as road, railway, and aircraft noise. Nonetheless, some residents living more than 1km away from wind turbines have claimed that they suffer sleep disturbance caused by wind turbine noise. Several researchers have maintained that at night residents near a wind farm may perceive large amplitude modulation of wind turbine noise because of noise directivity or atmospheric stability, and this amplitude modulation is the main cause of the noise annoyance. However, to date only few studies exist on the prediction of the amplitude modulation of wind turbine noise. Thus, this study predicts amplitude modulated noise generated from a generic 2.5MW wind turbine. Semi-empirical noise models are employed in order to predict the modulation depth and the overall sound pressure level of the wind turbine noise. The result shows that the amplitude modulation is observed regardless of atmospheric stability, but the modulation depth in a stable atmosphere is 1~3dB higher than that in an unstable atmosphere near the plane of rotation where the blades move downward. Moreover, using the result of the noise prediction, this study estimates perceptible area of the wind turbine noise due to the amplitude modulation. The result indicates that the wind turbine noise can be perceived at a distance of up to 1600m in the range of about 30~60 degree from the on axis in a low background noise environment.

1. Introduction

Noise from modern wind turbines is generally lower than that from other environmental noise sources such as road, railway, and aircraft noise. For a generic 2MW wind turbine, the A-weighted sound pressure level is about 35~45dBA at a distance of 400m from the wind turbine [1]. Since this is similar to the sound level inside a typical living room or the reading room of a library, wind turbine noise seems to cause little effect on residents near a wind farm [2].

Nonetheless, some residents living more than 1km away from wind turbines have claimed that they suffer sleep disturbance caused by wind turbine noise especially at night [3, 4]. The author of Ref. [3] reported that the residents near the Rhede wind farm complain of annoyance due to the wind turbine noise, even though they live at 500m and up to 1900m from the wind farm. The study also claimed that at night sometimes the wind turbines generate periodically fluctuating sound at a blade passing frequency, which is easily perceptible by the residents. This sound is called amplitude modulation or a swishing sound.

Several possible mechanisms of the amplitude modulation have been proposed such as stable atmospheric condition [3], tower shadow effect [5], and noise directivity pattern [6], but only few studies exist on the prediction of the amplitude modulation. In ref. [6], the modulation depth and the directivity of the noise from a 2.3MW turbine is predicted by a semi-empirical formula, and it is compared with experimental data. The result of this study showed that modulation depth of up to 5dB can be expected for cross-wind direction.

From these previous studies it can be concluded that, the perception of wind turbine noise may lead to annoyance even at low sound levels, and the amplitude modulation seems to be the main reason for the perception of wind turbine noise at large distance from the noise source. Thus, it is essential to examine the perception of amplitude modulated noise from wind turbines.

The purpose of this study is to predict the amplitude modulated noise generated from a generic 2.5MW wind turbine and to estimate perceptible area of the amplitude modulated noise. Semi-empirical noise models are employed in order to predict the modulation depth and the overall sound pressure level of the wind turbine noise. Since turbulence ingestion noise and turbulent-boundary-layer trailing edge noise are the main aerodynamic noise mechanism [1], the noise prediction in this study only includes these two noise sources. Turbulent-boundary-layer trailing edge noise is obtained by the semi-empirical formula proposed by Brook, Pope, and Marcolini [7]. The model proposed by Lowson is also used for predicting turbulence ingestion noise [8]. Moreover, this study utilizes the vortex lattice method [9] to calculate the aerodynamic properties such as inflow velocity and effective angle of attack, which are necessary for the broadband noise prediction. The XFOIL code [10] is also used for obtaining boundary layer parameters at the trailing edges, which is also essential for trailing edge noise prediction.

Using the result of the noise prediction, this study estimates maximum perceptible distance of the wind turbine noise due to amplitude modulation. This estimation is based on the assumption that the result of just-noticeable degree of sinusoidally amplitude-modulated white noise can be applied to that of amplitude modulated broadband sound.

2. Method

2.1 Wind turbine

The wind turbine model is a generic 2.5MW upwind 3-blade wind turbine which has typical multi-MW onshore wind turbine characteristics. This turbine is pitch regulated, variable speed wind turbine with a rotor diameter of 93m and a hub height of 82m. It reaches a maximum rotational speed of 15.4rpm at a wind speed of 9m/s, and its rated power is 2.5MW at a wind speed of 11.5m/s.

2.2 Atmospheric condition

2.2.1 Atmospheric absorption

Since the distance from the turbine to an observer point in this study is up to 2km, air absorption should be considered in the noise prediction. It is assumed that the air temperature is $15°C$, the relative humidity is 60%, and the air pressure is one standard atmosphere. Fig. 1 presents the attenuation coefficient due to air absorption in this atmospheric condition [11].

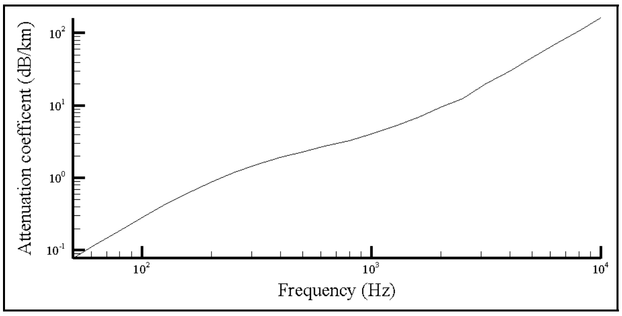

Figure 1. Atmospheric-absorption attenuation coefficient

2.2.2 Atmospheric stability condition

The author of ref. [12] maintained that for a stable atmosphere, the amplitude modulation of wind turbine noise may increase due to a high wind velocity gradient. Thus, in order to examine the effect of atmospheric stability on the amplitude modulation, the noise is calculated in two atmospheric conditions, which are a stable ($\alpha = 0.4$) and an unstable ($\alpha = 0.07$) conditions. The wind profiles are obtained using the atmospheric power law, as shown in Eq. (1).

$$V_2 = V_1 \left(\frac{z_2}{z_1} \right)^{\alpha} \tag{1}$$

As the atmospheric stability increases, not only the velocity profile but also the turbulence intensity changes. Turbulence intensity can be modelled according to a simple power law of the form in Eq. (2) [13, 14]

$$I = cz^{-\alpha} \tag{2}$$

Fig. 2 presents the velocity profiles and the turbulence intensities in two atmospheric conditions, which are the input for the noise calculation. In both stability conditions, the wind velocity at hub height is set to 10m/s. c values in Eq. (2) are selected as 0.2 and 0.4 for a stable and an unstable conditions, respectively.

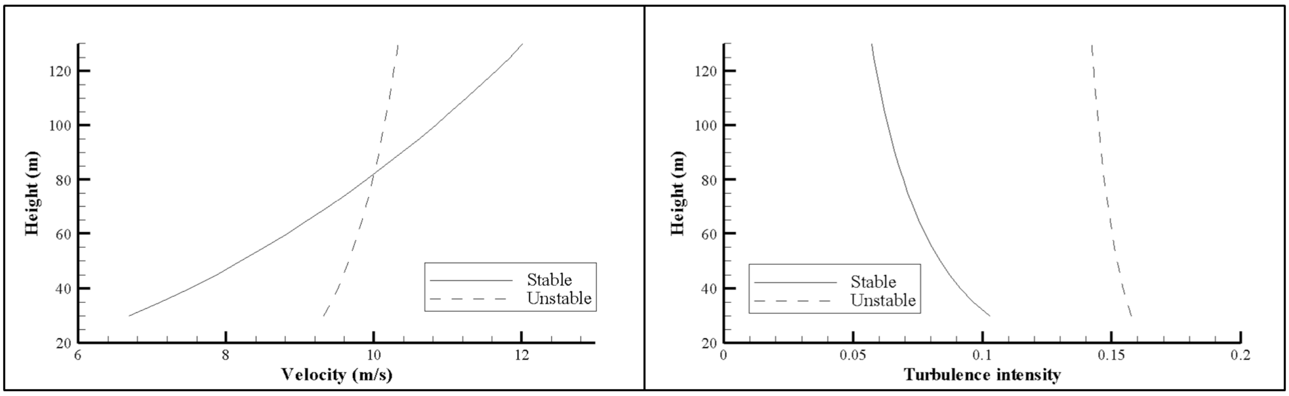

Figure 2. Velocity profile (left) and turbulence intensity (right)

2.3 Aerodynamic analysis

An aerodynamic analysis is carried out for the noise prediction. Each blade is divided into 20 sections, and at each section the inflow velocity and the effective angle of attack are calculated from a vortex lattice method (VLM) code [9]. The XFOIL code [10] is also used in order to obtain boundary-layer thickness and displacement thickness at the pressure and the suction side of airfoil sections. Fig. 3 and Fig. 4 present a sample of results by the VLM and the XFOIL code. Fig. 3 shows that the difference between the maximum and minimum effective angle of attack in a stable atmosphere is about 3° higher than that in an unstable atmosphere, as claimed in Ref. [12].

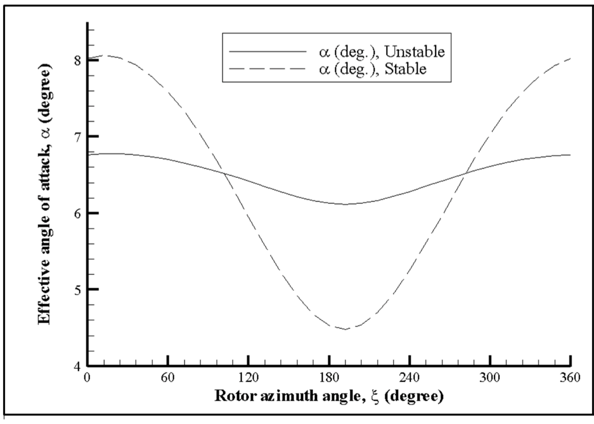

Figure 3. Sectional effective angle of attack of the blade at r/R=0.82

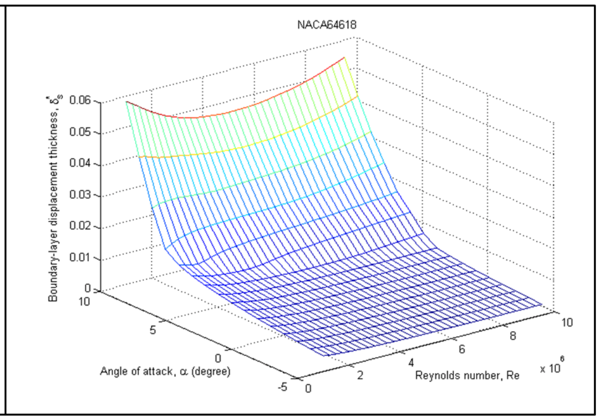

Figure 4. Boundary-layer displacement thickness of the suction side of NACA64618

2.4 Noise prediction method

In order to predict turbulent-boundary-layer trailing edge noise and turbulence ingestion noise, 2D semi-empirical noise models are applied for each section [7, 8, 15]. However, since the directivity function used in ref. [7] is derived by assuming the plate as semi-infinite, it becomes inaccurate near the angle $\theta_e = 180°$ [6, 7]. To relieve this effect theoretical noise directivity function is modified as (Fig. 5)

$$\bar{D}_{h,m} = \begin{cases} \bar{D}_h & (\theta_e < 180-\theta_c,\ \theta_e \geq 180+\theta_c) \\ \bar{D}_h \times \cos\left[\left\{\theta_e - (180-\theta_c)\right\} \times 90/\theta_c\right] & (180-\theta_c < \theta_e \leq 180) \\ \bar{D}_h \times \cos\left[\left\{(180+\theta_c) - \theta_e\right\} \times 90/\theta_c\right] & (180 < \theta_e \leq 180+\theta_c) \end{cases} \tag{3}$$

where $\bar{D}_h$ is theoretical directivity function, and θ_c is a cut-out angle.

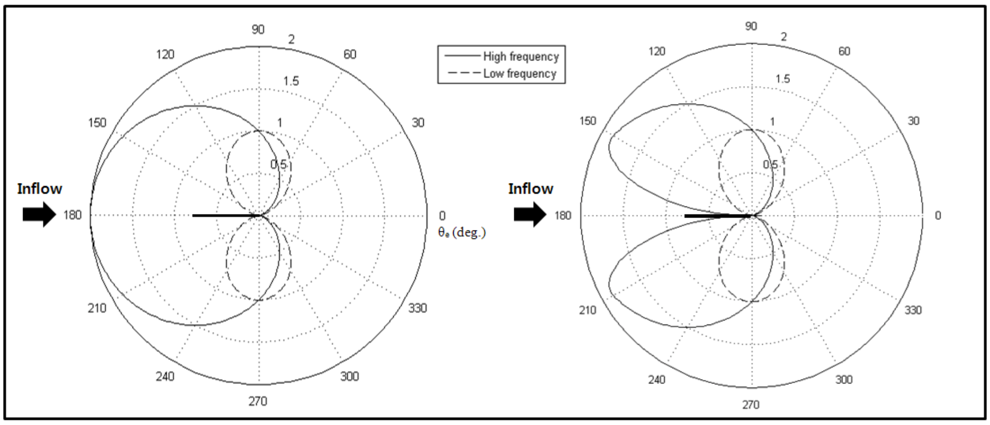

Figure 5. Theoretical (left) and Modified (right) flat plate noise directivity

The cut-out angle is determined as $\theta_c = 30°$ by comparing with the theoretical high frequency noise directivity for a finite chord airfoil [16]. Using this method, a one-third octave band spectrum is obtained by summing over all the noise spectra of the blade sections with respect to retarded time. Furthermore, an overall sound pressure level is determined by summing up this frequency spectrum, and modulation depth is defined as the difference between the maximum and the minimum overall sound pressure levels.

3. Prediction result

Fig. 6 and Fig. 7 plot predicted overall sound pressure level and modulation depth of the wind turbine noise in an unstable and a stable atmospheric conditions. In both atmospheric conditions predicted overall sound pressure level is a maximum on the axis line and a minimum in the plane of rotation, whereas modulation depth is a maximum in the plane of rotation and a minimum on axis. This result is consistent with the previous work of ref. [6]. From this result, it can be concluded that the amplitude modulation can be observed irrespective of the atmospheric stability condition.

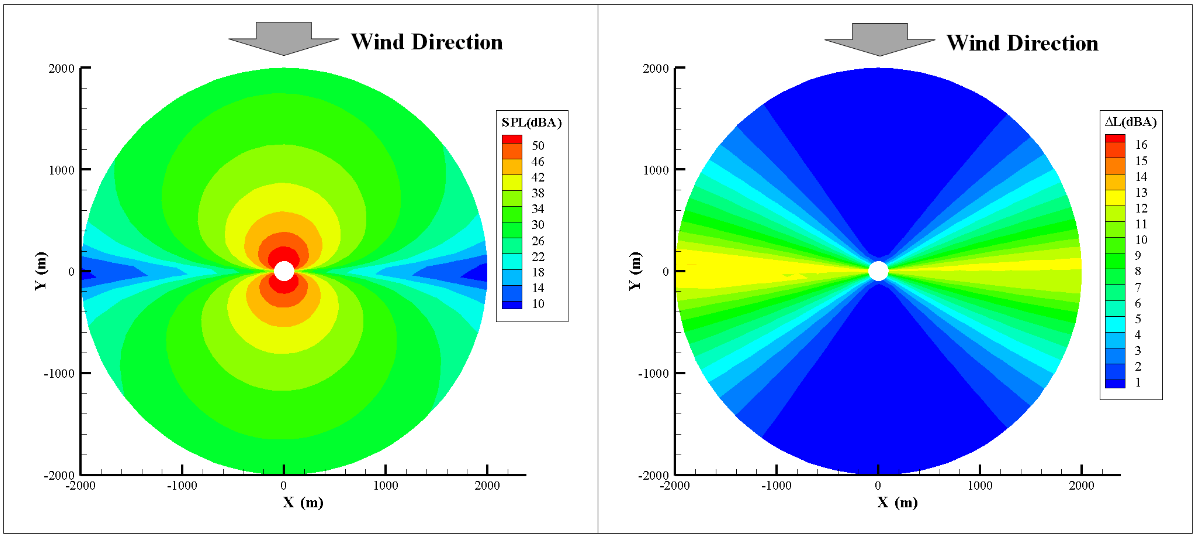

Figure 6. Overall sound pressure level (left) and modulation depth (right) in an unstable atmosphere

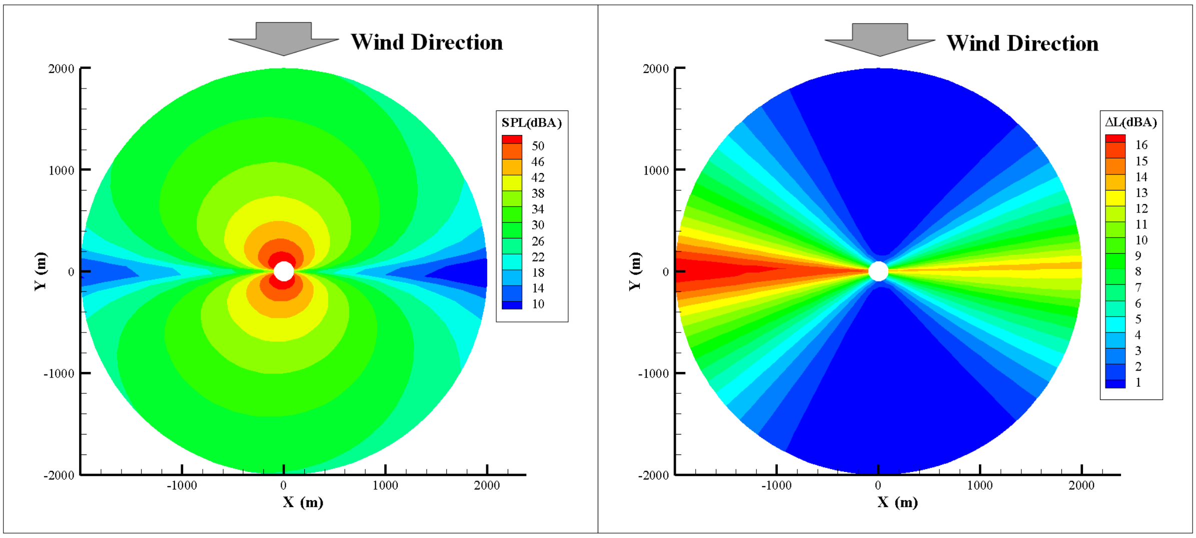

Figure 7. Overall sound pressure level (left) and modulation depth (right) in a stable atmosphere

However, as can be seen by comparing Fig. 6 and Fig. 7, the modulation depth in a stable atmosphere is higher than that in an unstable atmosphere, especially in the plane of rotation where the blades move downward. Fig. 8 illustrates the noise directivity and the modulation depth with respect to azimuth angle; 1~3dB increase of the modulation depth is observed in a stable condition. On the other hands, overall sound pressure level is relatively low in a stable atmosphere, but this is due to a low turbulence intensity in stable conditions, which leads to a low level of turbulence ingestion noise.

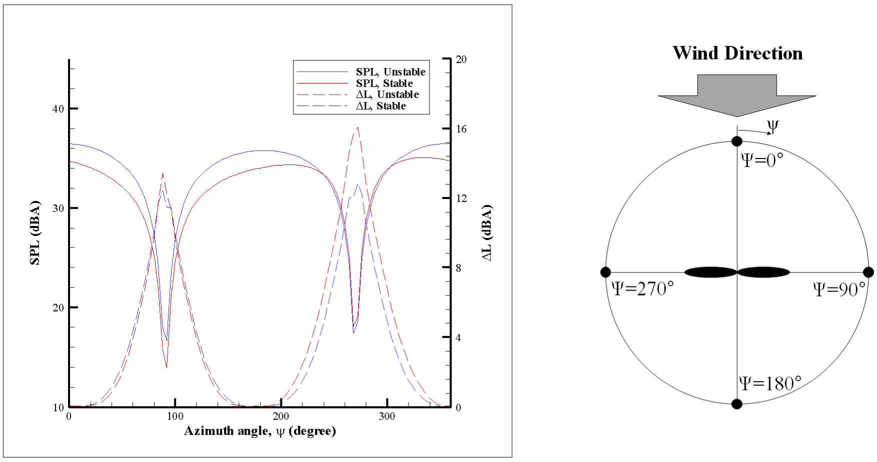

Figure 8. Noise directivity and modulation depth with respect to azimuth angle (R=1000m)

It is also worthy of notice that for far field the modulation depth (ΔL) is consistent with the distance between the noise source and an observer point, while the overall sound pressure level (OASPL) decreases by 6dB per distance doubling, as shown in Fig. 9. The reason is that the peak and the trough of the sound pressure level decrease at the same rate (6dB per distance doubling).

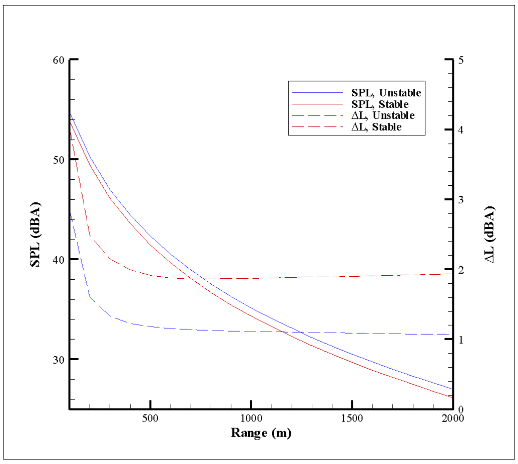

Figure 9. OASPL and ΔL (ψ=225°)

4. Perception of amplitude modulation

Aerodynamic noise from wind turbines is a broadband sound, and it has similar character to typical background noise such as wind induced noise. Thus, if wind turbine noise has no amplitude modulation, it is difficult for an observer to perceive this noise even though in a low background noise environment. However, if the noise is amplitude modulated, it can be easily perceived regardless of the sound level. According to psychoacoustics [17], for a modulation frequency of 1Hz, just-noticeable degree of amplitude modulation of white noise is always 5% ($\Delta L \approx 1dB$) when the sound level is higher than 30dB. This means that even though the noise level is low enough (e.g. 30~40dB), amplitude modulated noise from wind turbines can be perceived if the modulation depth is more than 1dB.

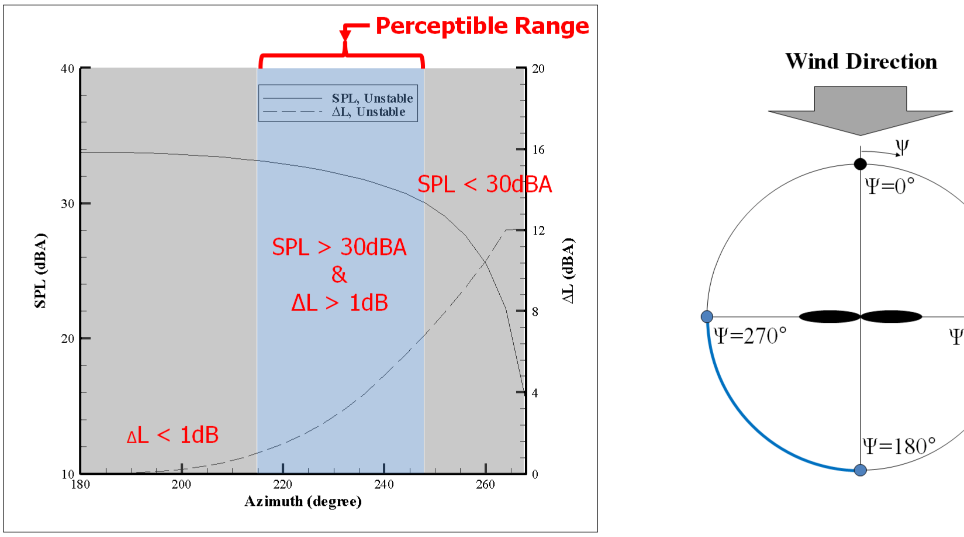

Figure 10. Perceptible range with respect to azimuth angle (R=1200m)

By utilizing the result of ref. [17], it is roughly assumed that amplitude modulated noise can be perceived if the overall sound pressure level is higher than 30dB and the modulation depth is more than 1dB. It is also assumed that the background noise is extremely low. Using these assumptions perceptible range of amplitude modulated sound is estimated with respect to azimuth angle at a distance of 1200m from the noise source, as shown in Fig. 10. The result indicates that amplitude modulation is perceived only in the range of 35 ~ 65° from the axis line; near the axis line ($\psi \approx 180°$) the modulation depth is too low to perceive amplitude modulation, whereas near the plane of rotation ($\psi \approx 270°$) the overall sound pressure level is too low to perceive this noise. Moreover, Fig. 11 presents estimated maximum perceptible distance of the amplitude modulation in both atmospheric stability conditions. It shows that amplitude modulated noise from the wind turbine can be perceived at a distance of up to 1600m, in the range of about 30 ~ 60° from on axis.

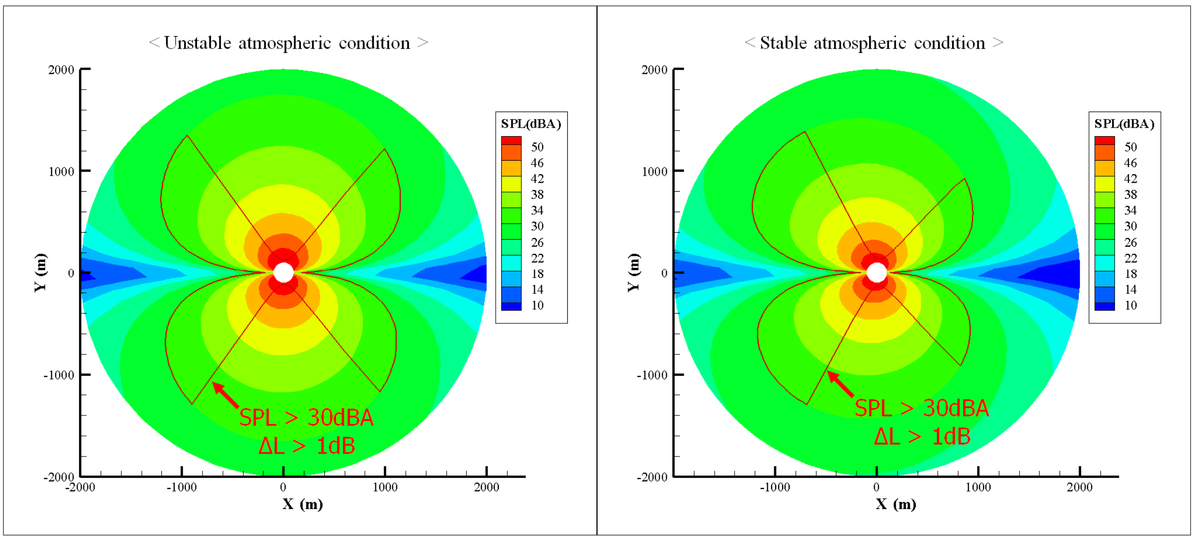

Figure 11. Maximum perceptible distances in an unstable (left) and stable (right) atmosphere

5. Conclusion

This study predicted the overall sound pressure level and the modulation depth of the wind turbine noise from a 2.5MW generic wind turbine model. The result showed that the amplitude modulation is observed regardless of the atmospheric stability condition, but the modulation depth in a stable atmosphere is 1~3dB higher than that in an unstable atmosphere, especially in the plane of rotation where the blades move downward. Moreover, maximum perceptible distance of the amplitude modulation is estimated in this study. The result indicates that the wind turbine noise can be perceived at a distance of up to 1600m in the range of about $30 \sim 60°$ from the axis line in a low background noise environment. This result implies that residents living at a distance of up to 1.6km from wind turbines may feel annoyance due to the perception of amplitude modulation.

6. Acknowledgements

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