Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

Experimental and Theoretical Investigation into Aerodynamic Noise Sources of Large Upwind Horizontal-axis Wind Turbines

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PACS: 43.28.Ra

ABSTRACT

In this paper, the aerodynamic noise sources of upwind horizontal-axis wind turbines are experimentally and theoretically investigated. First, dominant noise sources on the rotor plane of wind turbines are localized by using the beamforming techniques. These visualized acoustic fields reveal the dominant source locations on the wind turbine. Then, theoretical predictions for identifying the dominant source locations are made by using the empirical noise prediction model of Brooks et al. (1989) for the airfoil self noise. Through the comparison of the predicted results with the experimental data, it is shown that predictions using the formula for laminar boundary layer vortex shedding (LBLVS) noise do not match the measurements, which urges the need for improving its present empirical prediction formula.

INTRODUCTION

With the urgent global need for developing renewable energy, the wind energy is considered as one of the best candidates. However, wind turbine noise is a major hindrance for the wider use of energy from wind turbines (WTs). Based on this situation, both developer/designer and other interested parties require applicable methods for the environmental assessment of wind turbine/farm noise. The sound power of wind turbine is requested to be reported according to the related regulations. Although the sound power of a wind turbine (WT) may be known before its installation, it is hard to represent noise level of the WT under all operating conditions because of expensive cost and complex environmental situation around the WT. For solving this problem, predicting WT noise is required as a supplemental method for the assessment.

Recently, to optimize the efficiency in generating energy from WTs, the size has been continually expanded. This tendency will cause more serious conflict between developer/designers and community near the wind farm because the noise also increases with growth of the size. For minimizing the conflict, proper assessment of the noise radiation from WTs is essential to satisfy both bodies.

With the continued decrease of mechanical noise of WTs, aerodynamic noise mostly contributes to total noise levels of WTs. Therefore, it has been regarded as dominant obstacle to develop WTs or wind farms. To accurately predict the noise radiation from WTs, the identification of dominant aerodynamic noise sources is essential.

In this paper, main aerodynamic noise sources of modern large upwind horizontal axis WTs (HAWTs) are investigated by using experimental and numerical approaches, which can assess relative importance of source mechanisms.

AERODYNAMIC NOISE OF UPWIND HAWT

The aerodynamic noise of rotating machines such as WTs can be categorized into tonal and broadband noise. Tonal noise of the rotating machine is generated at blade-passing-frequencies (BPFs). Due to lower rotating speed of the modern large HAWTs, its BPF Noise belongs to the infrasound. Therefore, broadband noise is a dominant component of the noise in the audible frequency range. Although many arguments about the effects of low frequency noise on the human health are still developing (Jung et al., 2008), our present work focuses on broadband noise sources.

Broadband noises from HAWTs are further divided into two mechanisms: broadband inflow-turbulence noise and airfoil self noise (Rogers et al., 2006). Broadband inflow noise (BIN) is originated from random loading on the rotating blades. The loading is generated by interaction between ingested atmospheric turbulence and the rotating blades. It is recognized as one of dominant noise sources in range of the audible frequency when WTs are operated. BIN is characterized by the noise spectrum of humped or peaked shape in the lower frequency range. It is caused by large scale components of ingested turbulence hit by rotated blade nearly periodically. Broadband airfoil self noise (BASN) is produced by self-generated turbulences which are originated by the interaction of laminar incident mean flow without turbulence with an airfoil. They interact with the trailing edge (TE) and/or the wing tip and then the noise is scattered to the surrounding space.

BASN is further divided into five detailed sources based on its generation mechanism (Brooks, 1989). Laminar boundary layer vortex shedding (LBLVS) noise is due to the interaction between vortex shedding in the laminar boundary layer (LBL) and the TE. A fluid dynamics process responsible for this phenomenon can be modelled as Tollmien-Schlichting instability waves which grow along the chord. In this process, acoustic wave propagates with the same frequency as it passes the TE (Thomas, 1978). These tonal noise components contribute to the formation of humped narrow band in the noise spectrum due to LBLVS noise, which was experimentally verified by Brooks et al. (1989). Trailing edge bluntness vortex shedding (TEBVS) noise is due to vortex shedding at the blunt TE and it also contribute to total spectrum as narrow band spectral hump. Lately, this noise has been successfully reduced by using sharp TE. Tip noise can be associated with formation of tip vortex separated at the tip of blade. It can be regarded as similar procedure of blade vortex interaction (BVI) noise of helicopter. However, the tip noise was shown that it makes negligible contribution to the overall noise level by the recent experiment (Oerlemans, 2007). The turbulence in the boundary layer passing over the TE generates the noise, which is called as turbulence boundary layer trailing edge (TBLTE) noise. As the attack angle of airfoil is increased, the flow in the turbulence boundary layer (TBL) is subject to separation near the TE, which induces the noise by scattering at the TE. It is referred to as separation and stall (SS) noise.

From previous study, it is shown that noise spectra of pitch-controlled HAWT are of negligible wind speed dependence (Lee et al., 2009). Since wind speed can be considered as sensitive factor of BIN, it can be inferred from this result that the BIN has negligible contributions to overall noise emission from this WT.

Above-mentioned mechanisms are investigated to assess its relative contribution. In the following section, the field measurement results by using beam-forming technique is described, which is followed by theoretical investigation for the validation and assessment of relative contributions of the aerodynamic sources of HAWTs.

MEASUREMENT

Methods and Equipments

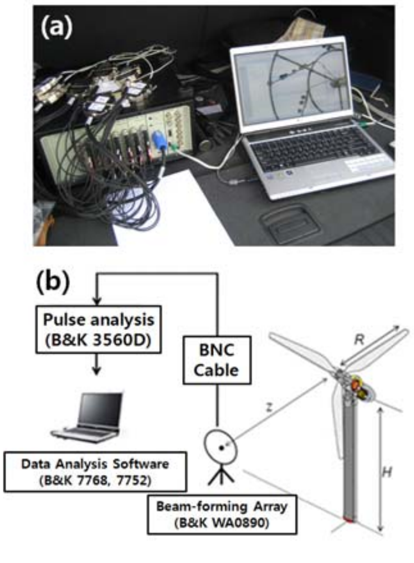

Figure 1 Experimental setup for the field test (a) and the schematics for the measurement system (b)

Among the wind farms in Korea, wind farms in Jeju islands are most suited for the field test. Measurement and evaluation of the noise emission from WTs have been carried out at the Hankyung and the Hangwon wind farms. In this study, the WT of the capacities 660 kW in the Hankyung wind farm is selected for the investigation. Detailed specifications of targeted WT and environmental conditions are described in the recent study (Lee et al., 2009).

Visualization of noise sources are carried out by using beam-forming system. This measurement system consists of 42 channel data acquisition unit (B&K 3560D), microphone array (42units) and the analysis software (B&K 7768, 7752). The beam-forming system is installed upstream from the WTs. The microphone is arranged in a planar array facing the centre of the object. Figure 1 shows the measurement system during the field test and its corresponding schematics.

Result

Figure 2 presents the typical result of visualized source distribution. Two important findings are observed in this result: the dominant noise source is located at right-bottom of the rotor plane when the blade rotates in the clockwise direction, and as the frequency increase, the dominant sources move radially outward and vertically upward..

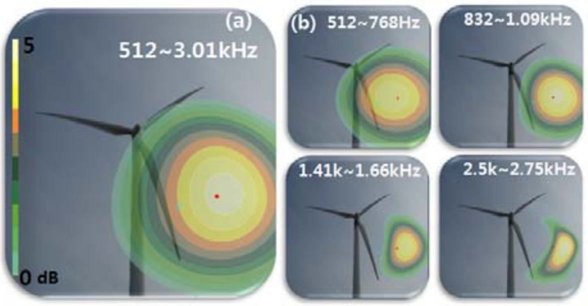

Figure 2 The visualized noise sources in the rotor plane using the Beam-forming techniques: (a) The Overall frequency band, 512 Hz to 3.01 kHz, (b) the function of band frequency. The measurement is taken in the position 60 m apart from the rotor hub in the upstream direction

PREDICTION

We have developed noise prediction algorithm based on Brook’s formula, which can be used to predict the noise emission levels and obtain its one-third-octave-band-spectrums of an upwind HAWT. This program is used to predict the source distribution on the rotor plane. Unfortunately, information on the detailed geometries of the blades of the WTs targeted in the experiment is not opened. Instead, blade design information of the other WT with the same capacity and power control method as the targeted WT are utilized, such as the distribution of chord, twist angles and airfoil shapes along the radial direction. In this analysis, tip noise model is not included because tip noise is known to be negligible in overall sound levels and it requires extensive information for the aerodynamic force distribution on blades in the radial direction.

Visualized noise source

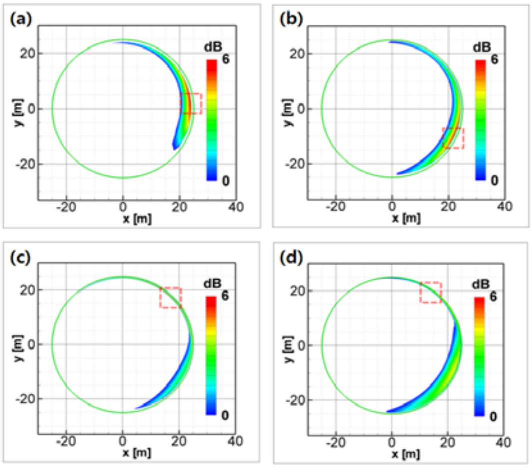

Figure 3 Predicted source contributions on the rotor plane for the targeted pitch controlled WT at the various frequencies: (a) 630 Hz, (b) 1000 Hz, (c) 1600 Hz, (d) 2500 Hz

In Figure 3, regions where the noise contributes dominantly to observer are marked by red rectangles at each frequency. These results are obtained by using only semi-empirical formulas (Brooks, 1989) with aerodynamic information at each airfoil segment of blade obtained from CFD computation using the XFOIL (Drela, 1989). Due to the difference of computational algorithm between the beam forming and the prediction, overall shape of the source distribution is different for each other. Through the comparison of these results in Fig. 3 with the experiment in Fig. 2, however, it can be seen there are good agreement between two results in terms of dominant source regions. However, detailed investigation into source distribution in Fig. 3c and 3d reveals that the strongest source regions is located in the right-upper part of the circles, which cannot be observed in the experiment.

For further analysis on these strange results, the localization of individual noise sources including TBLTE, TEVVS, SS and LBLVS is made. As Figure 4 show, source of predicted LBLVS noise is found to be located at upper part in the right side. It indicates that the strange result observed in Fig. 3c and d is due to this LBLVS noise. It can be inferred from this result that the LBLVS does not contribute to overall noise of the WT.

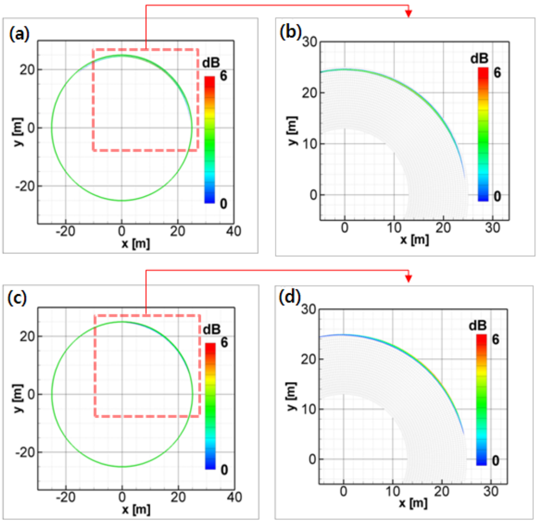

Figure 4 Localized source of predicted LBLVS noise at each frequency: (a) 1600 Hz, (b) detail result of (a), (c) 2500 Hz, (d) detail result of (c)

CONCLUSION

Aerodynamic noise sources of upwind HAWT using the pitch control are localized by using experimental and theoretical approaches. Through the comparison between experimental and theoretical results, sources for predicted LBLVS noise have been found to be located at the strange region which does not match to experiments. It can be inferred from this observation that LBLVS noise negligibly contribute to the radiated noise of the WT. The reason for this may be that LBL on the rotor blade easily changes to TBL due to the environmental conditions such as ingested turbulent gust and rough surface of the blade. Therefore, direct application of LBLVS noise model of Brooks et al. (1989) can induce the over-predictions of radiated noise levels of WTs, which raise the need to improve LBLVS noise model for the accurate prediction of overall WTs noise.

ACKNOWLEDGMENTS

This subject is supported by Ministry of Environment of the Republic of Korea as “The Eco-technopia 21 project”.

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