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Noise Prediction of Wind Turbine and Low Noise Blade Design

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Summary

Noise reduction of wind turbines has recently become more important due to increasing large-scale turbine developments, stringent noise regulations, and installation of wind farms near residential areas. Wind turbine noise is mainly caused by broadband noise from the blades and can be reduced by an optimum design of blade using noise prediction technologies. We have developed a method to predict blade noise based on a computational fluid dynamics (CFD) approach and an empirical formula. This method can be used during the preliminary blade design and has been validated using an actual wind turbine. In this report, we present a less noisy blade that was developed by applying this approach at the design stage.

1. Introduction

Power production by renewable wind energy has risen sharply in recent years against a backdrop of demand for global warming reduction and energy security. Additionally, development of larger-scale turbines with higher output per unit has increased to ensure profitability and efficiency.

Fig 1 shows the relationship between the sound-power level of turbines and the rotor diameter. For larger-scale wind turbines, a longer rotor diameter results in higher sound-power levels, and the effects of the circumferential velocity at the blade tips induced by the longer blades surpass the effects of rotation frequency.[1] Therefore, increasing the rotor diameters is the main cause of increased sound-power levels.

As larger-scale wind turbines are built and more wind farms are constructed near residential areas with lower wind speeds, citizen complaints have increased, including in Japan, and environmental noise assessments at the planned sites have become more critical. Thus, predicting and reducing turbine noise has become more important during the planning phase of wind-power system developments.

Wind turbine noise is traditionally classified into two main sources: aerodynamic blade noise and mechanical noise from nacelles and towers. The former is dominant for the large-scale wind turbines (1-3 MW class) currently installed at many wind farms. Therefore, the aerodynamic noise generated at the blades must be minimized to reduce the total turbine noise. A blade-noise-prediction technology applicable at the design phase is essential.

To be practical, the prediction technology must be fast and accurate because the blade noise must be evaluated simultaneously with the blade performance and loads.

An unsteady computational fluid dynamics (CFD) approach is available for aerodynamic noise prediction, but it is not practical because large-scale wind turbines are too large as analysis targets and require too much computational effort. Another approach using an experiment-based two-dimensional (2D) blade empirical formula can predict noise in less time, but is not as accurate when applied to wind turbines. To improve the accuracy of the formula, it must be expanded to the whole blade to include blade-shape effects.
We have developed a practical approach to predict broadband blade noise by combining a steady CFD method that can provide good accuracy and calculation speed for blade design needs with an experiment-based empirical formula. In this report, we describe the new prediction approach and introduce a higher-performance low-noise blade design that was developed using it.

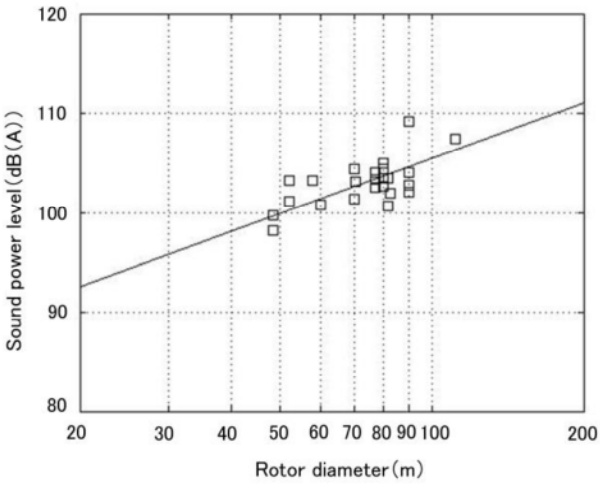

Fig 1 Variation in the sound power level of a wind turbine[1]

2. Noise prediction approach and validation

2.1 Noise prediction approach

Our noise-prediction approach, which combines steady CFD and an experiment-based empirical formula, uses the blade-noise prediction formula developed by Brooks et al. of NASA.[2] (BPM model) Here, we outline the BPM model based prediction method. The BPM model can predict the noise spectrum of 2D blade cross sections and can be used for the total turbine noise by dividing the blade into many sections to predict the noise spectrum of each section.[3]

To apply the BPM model to wind turbines, we developed an approach for broadband blade-noise prediction by including the following techniques to improve the accuracy and shorten the calculation periods.

- Consideration of the rotation effects of three blades revolving on the axis, i.e., changes in the diffusion distance and orientation due to the position change of the revolving blades.
- Consideration of the airfoil geometry, as the BPM model was derived for NACA0012 airfoils. The boundary thickness of each airfoil is estimated by CFD beforehand, assuming that the flow changes due to the airfoil are significant in the boundary layer thickness. This boundary-layer thickness is then supplied to the prediction formula.

Our noise-prediction approach follows the steps outlined below.

- Calculate the inflow wind speed and angle of attack of each divided blade section based on the blade shape, wind speed, blade rotation frequency, and blade pitch angle.

- Predict the boundary-layer thickness of each section based on the inflow wind speed and angle of attack by using steady CFD.
- Predict the noise level of each section based on the blade shape, inflow wind speed, angle of attack, and boundary-layer thickness by using the BPM model.

It is considered that wind turbine has three main noise sources, (1) Turbulent boundary layer – trailing edge noise, (2) Trailing edge bluntness – vortex shedding noise and (3) Tip vortex formation noise. Empirical formulas of Brooks et al. shown as follows are applied to these noise predictions. Flow conditions which generate aerodynamic noise is shown in Fig 2.

(1) Turbulent boundary layer – trailing edge noise

$$SPL_p = 10\log\left(\frac{\delta_p^* M^5 L\overline{D}_h}{r_e^2}\right) + A\left(\frac{St_p}{St_1}\right) + (K_1 - 3) + \Delta K_1$$

(2) Trailing edge bluntness - vortex shedding noise

$$SPL_{BLUNT} = 10\log\left(\frac{hM^{5.5} L\overline{D}_h}{r_e^2}\right) + G_4\left(\frac{h}{\delta_{avg}^*}, \Psi\right) + G_5\left(\frac{h}{\delta_{avg}^*}, \Psi, \frac{St'''}{St'''_{peak}}\right)$$

(3) Tip vortex formation noise

$$SPL_{TIP} = 10\log\left(\frac{M^2 M_{\max}^3 \lambda^2 \overline{D}_h}{r_e^2}\right) - 30.5(\log St'' + 0.3)^2 + 126$$

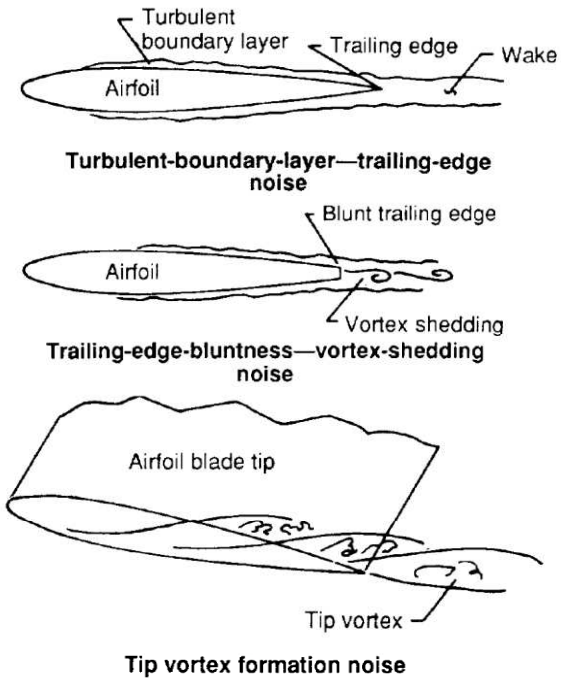

Fig 2 Flow conditions producing aerodynamic noise [2]

In this way, the time required for the noise prediction can be shortened substantially by using both the experiment-based BPM model and the steady CFD results, enabling the blade design and noise evaluation to be performed simultaneously.

During the design phase, various parameters such as the airfoil, code length, twist angle, and rotation frequency must be changed. However, our approach is suitable as a noise-evaluation method during this phase because it can predict noise values in short periods of time, even when these design parameters are changed.

2.2 Validation of prediction

Fig 3 compares the predicted and actual measured noise values for a real model. The plot illustrates the consistency between these values; the differences in the sound-power level of the turbine are within ±2 dB at each reference wind speed, showing the validity of our approach.

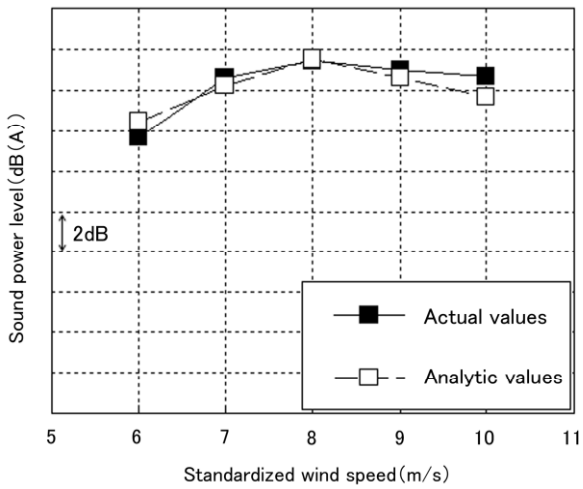

Fig 3 Actual and analytical values of the sound-power level

3. Development of high performance and low noise blades

3.1 Design concept of MWT102

MWT102 wind turbine which rotor diameter is 102m has been developed for the purpose of increase of capacity factor and correspondence for low wind speed region.[4] Design condition is Class 2A, and target capacity factor is more than 51% , target sound power level is less than 105dB(A). Design concepts are as follows.

a) make blade length longer for an increase of the power output
b) thick blade for a reduction of weight
c) thin blade for a load reduction
d) twist blade near the tip for a noise reduction
e) prebend for ensuring a distance between blade and tower

Although longer blade increases annual energy production, the blades with existing airfoils does not satisfied with the target capacity factor. In addition to this, longer blade causes increase of noise, load, weight and deflection. These items should be compromised. However, it is difficult to achieve target by means of only compromise. Therefore, we have developed new airfoil for the purpose of higher power output and less noise. Airfoil code is MHI-Fxx (xx : thickness ratio[%]).

3.2 Development of airfoil MHI-F series

Aerodynamic characteristics

Desired aerodynamic characteristics of airfoil are as follows.

- High design lift coefficient (for high power output)
- Optimized design lift coefficient (for high power output)
- High max lift coefficient and max lift drag ratio (for high power output)
- Thin boundary layer thickness at trailing edge (for noise reduction)

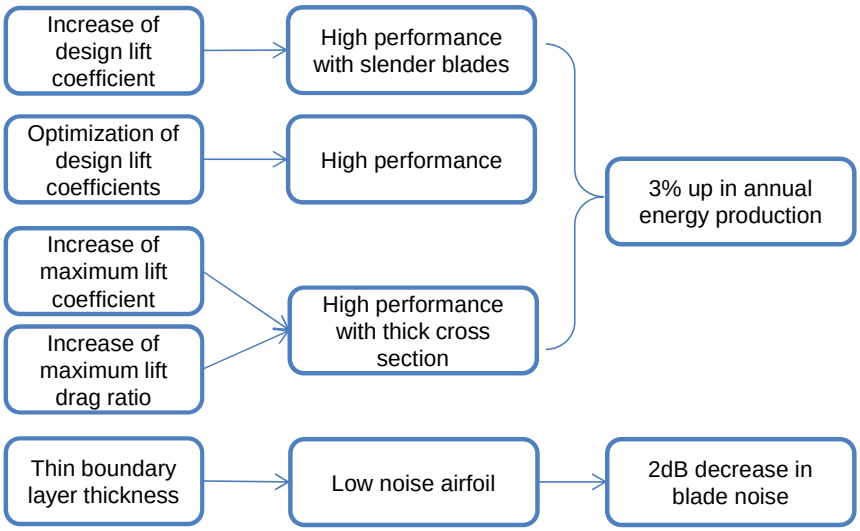

Fig 4 Design concepts of MHI-F airfoils

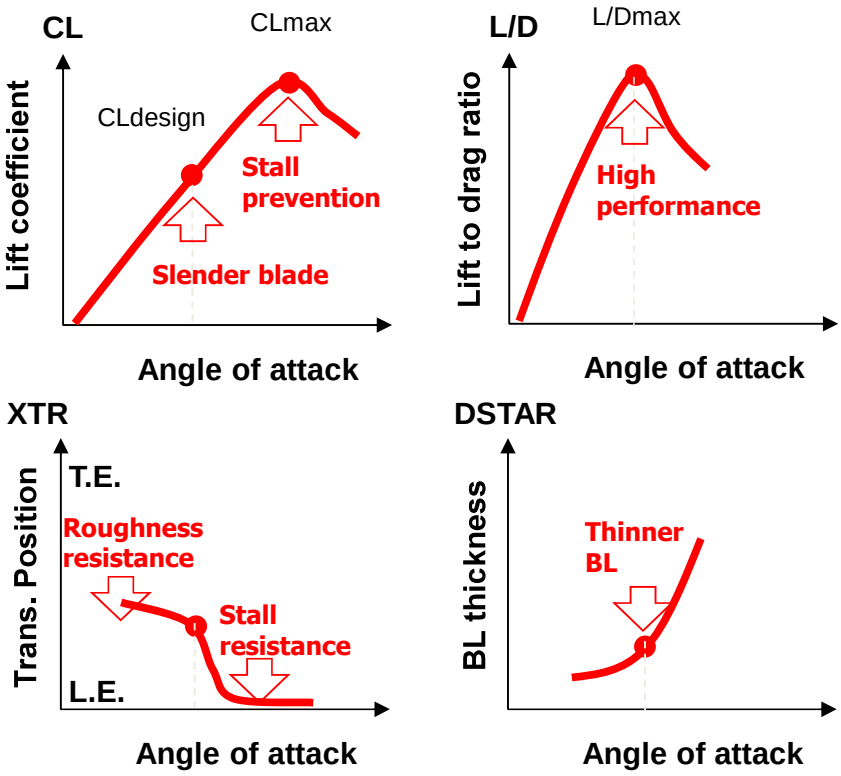

Fig 5 Definitions of aerodynamic characteristics of airfoils

1) Design lift coefficient

In general, increase of design lift coefficient is realized by high camber and location of maximum thickness moves front side. However, they has a risk for worse stall characteristic. Hence, target of design lift coefficient of MHI-F18 is 1.15 which has already accomplished by existing airfoils[5][6][7][8]. The airfoils of MHI-F21, 24, 30, 36 and 42 have design lift coefficients that are optimized to maximize blade performance (Fig 6), optimized design has conducted.

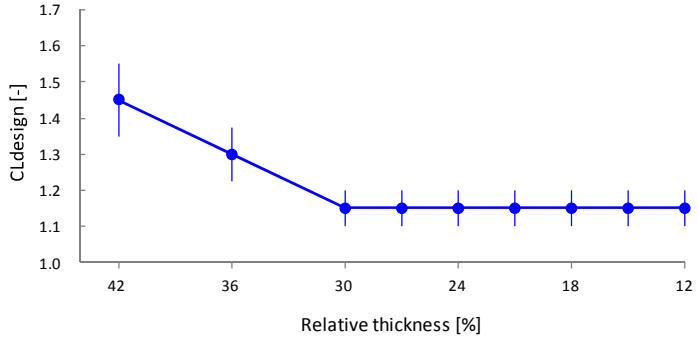

Fig 6 Design targets of design lift coefficients

2) Maximum lift coefficient

An increase of maximum lift coefficient is important from the aspect of improvement of performance at high wind speed and prevention of stall for gust. Wind variation affects variation of angle of attack, its effect at blade root is higher than other part of blade. Therefore, target near the blade root is higher than outer part.

3) Maximum lift drag ratio

An improvement of maximum lift drag ratio is important for the performance at variable rotational speed condition. It can be realized by high camber, thin blade thickness near the trailing edge and location of maximum thickness moves front side.

4) Boundary layer thickness

The cause of aerodynamic noise of modern wind turbine is turbulent boundary layer – trailing edge noise. For the purpose of noise reduction, the boundary layer thickness is reduced by means of optimization of suction side shape between maximum thickness point to trailing edge. The concept of the optimization is that dY/dX between maximum thickness point to trailing edge shows S shape.(Fig 7)

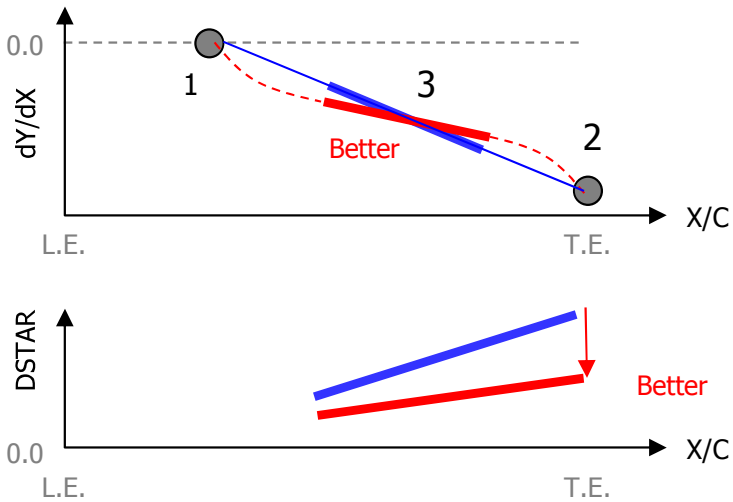

Fig 7 Relationship between suction shape and boundary layer thickness

The shape of airfoils

For the purpose of high design lift coefficient, maximum thickness point is located to front side and thickness near the trailing edge is reduced. Maximum thickness point near the front side leads to increase of design lift coefficient, maximum lift drag ratio and reduction of boundary layer thickness. It has been optimized considering the strength of the trailing edge. Maximum camber point near the front side leads to increase of maximum lift drag ratio and reduction of boundary layer thickness. However, it also leads to decrease of maximum lift coefficient. Therefore, it has been optimised considering these characteristics. Thick airfoil has a possibility of separation at pressure side when the suction side becomes too thick. Hence, separation has been avoided by the optimization of concave shape of pressure side near the trailing edge.

Wind tunnel test

Wind tunnel tests of MHI-F18,21,24 and 30 have been conducted to validate the airfoil design.(Fig.8) Measurement results of aerodynamic characteristics are shown in Fig.9,10. Design lift coefficient, maximum lift coefficient and maximum lift drag ratio are improved compared to existing airfoils. Because of these improvements, it becomes possible to maintain high performance with slender blade which is needed for extension of blade length and load reduction. In addition to this, because design lift coefficients of these airfoils are almost satisfied with the optimized design lift coefficient which is shown by a dashed line in Fig.9, it becomes possible to achieve maximum efficiencies at all span-wise locations. Maximum lift drag coefficient of thin airfoils which is used for root section is highly improved. For this reason, high performance can be achieved when thick airfoil is used for the purpose of reduction of weight. From the point of view of noise, boundary layer thickness of MHI-F18 is thinner than existing airfoils(NACA63,NACA64 and DU). It will lead to the less noisy airfoil comparing to the same tip speed. Additionally, noise reduction caused by decrease of tip speed is expected because slender blade can be designed without increase of design tip speed due to high design lift coefficient.

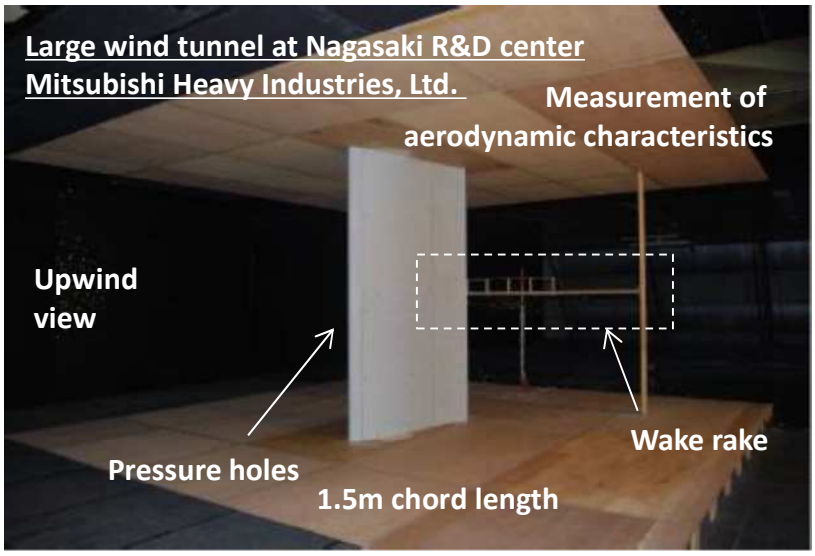

Fig 8 Wind tunnel test of MHI-F airfoils(Re=2×10^6)
at large wind tunnel at Nagasaki R&D center, Mitsubishi Heavy Industries, Ltd.

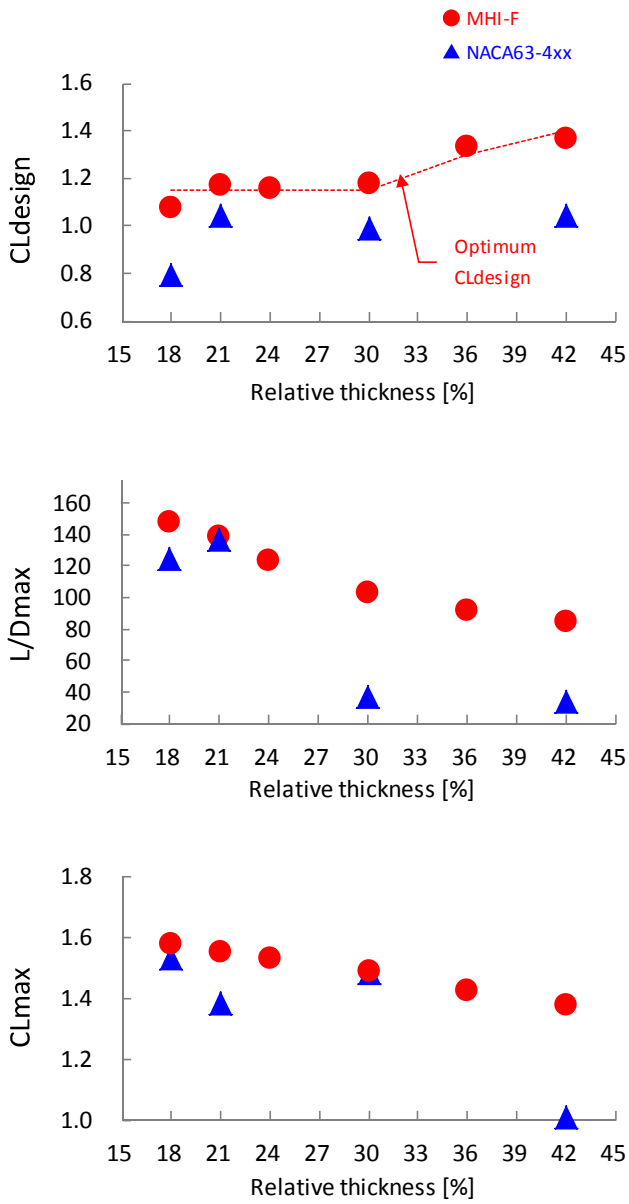

Fig 9 Aerodynamic characteristics of MHI-F airfoils (convert to Re=2×10^6)

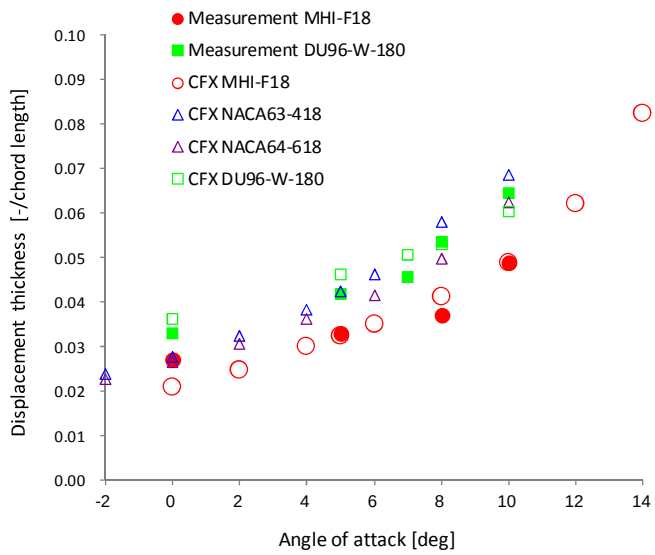

Fig 10 Boundary layer displacement thickness of MHI-F airfoils (convert to Re=2×10^6)

4.2 Blade design with noise reduction

To reduce the generated noise, it is important to understand and analyse the noise characteristics and identify the noise frequencies. Our approach has the benefit of predicting the frequency characteristics of the generated noise. Fig 11 presents an example plot obtained using our approach, showing the aerodynamic noise spectrum of each noise source in a wind turbine. The major noise components are the turbulent boundary-layer noise and trailing-edge bluntness noise; these occur at frequencies of 200 Hz-1 kHz and 2-3 kHz, respectively. Based on the frequency characteristics, the target noise source that must be addressed can be identified.

In this noise-prediction approach, the blade is divided into several sections so that the noise level of each section can also be identified. This allows us to focus on a particular blade section to reduce the total noise efficiently. Figure 12 shows an example of the noise predictions for each blade section. There is a higher noise contribution at the blade tip because the turbulent boundary layer noise is the major component of the spectrum (as shown in Figure 12) and the noise level increases with the circumferential velocity. These results show that the noise source to be addressed primarily is the turbulent boundary layer noise generated at the blade tip. This allows us to focus on noise reduction by identifying the noise types and locations during the design phase and develop less noisy blades efficiently without degrading their performance. Using this approach, We succeed in developing a less-noisy blade that was 2 dB or more quieter compared with conventional blades.

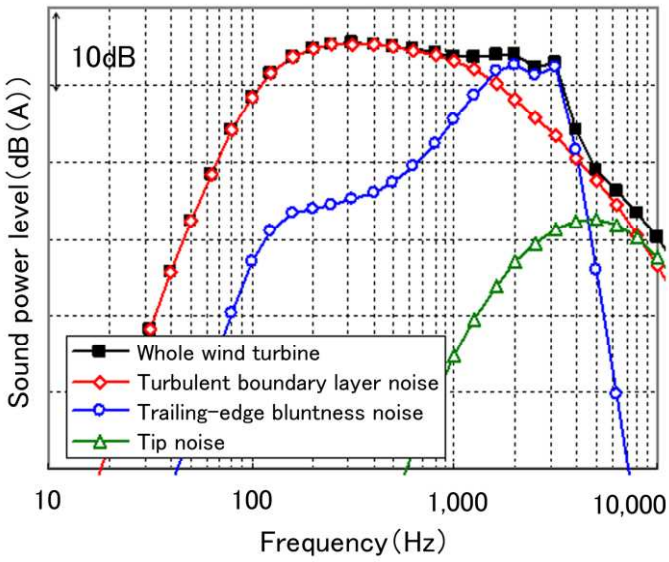

Figure 11 Predicted spectrum of each sound source

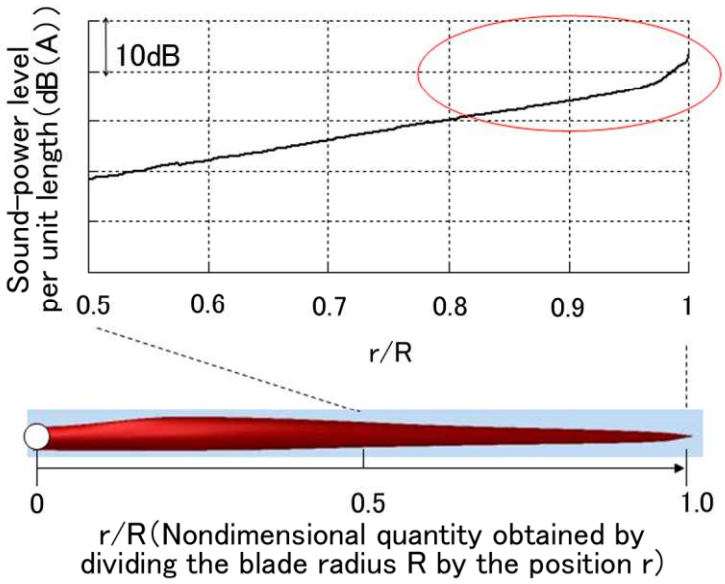

Figure 12 Noise distribution in the blade-length direction

5. Field test of MWT102

We have designed new blades for MWT102 with these airfoils and the noise reduction technologies. Blades are designed to make cross section thick for weight reduction and to make chord slender for the purpose of load reduction. Fig13 shows the comparison of the new blade (102m diameter) with our existing blade (95m diameter). The evaluation of performance has been conducted by the blade element momentum theory and three dimensional computational fluid dynamics. The evaluation of noise characteristics has been conducted by use of the method which is shown in section 2. Target capacity factor 51% and sound power level 105dB(A) has been achieved in these evaluations, actual blades have been produced and the field test of MWT102 has been conducted. A measurement of performance and noise has been conducted by the certification organization.(Fig 14) The measurement results are shown in Fig.15. The capacity factor converted in the condition which the annual average wind speed is 8.5m/s and air density is 1.225kg/m^3 is 51.1%, the maximum sound power level is 104.9dB(A).

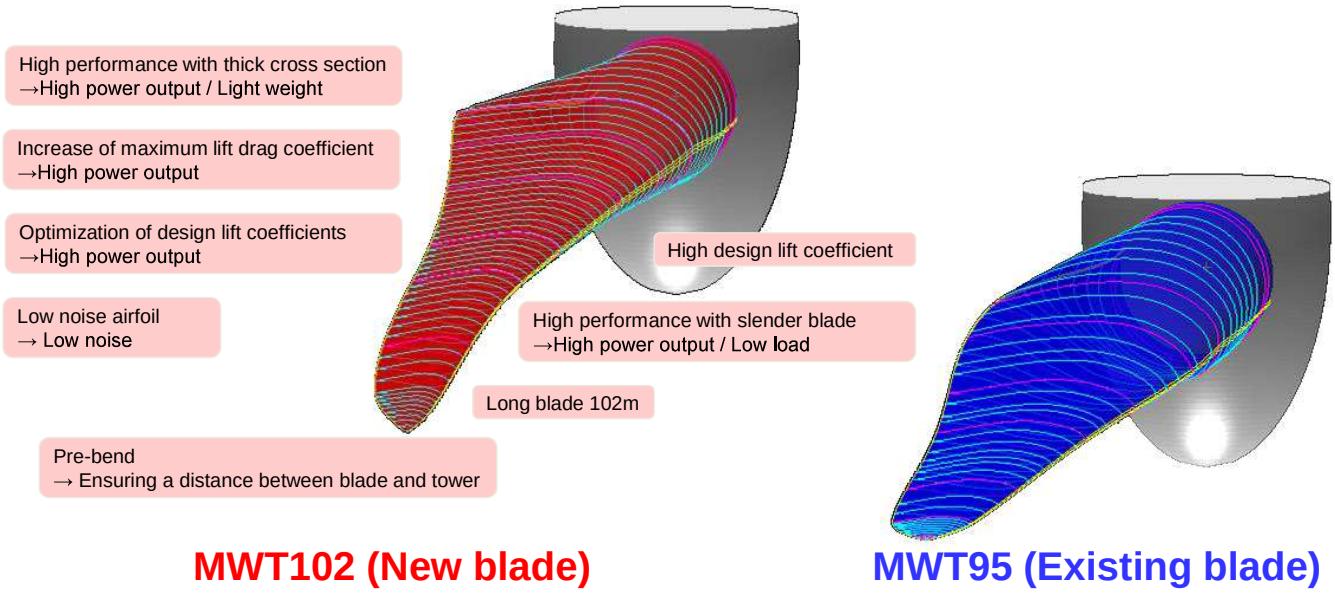

Fig 13 Comparison of blade shapes

Fig 14 MWT102/2.4 wind turbine (United States)

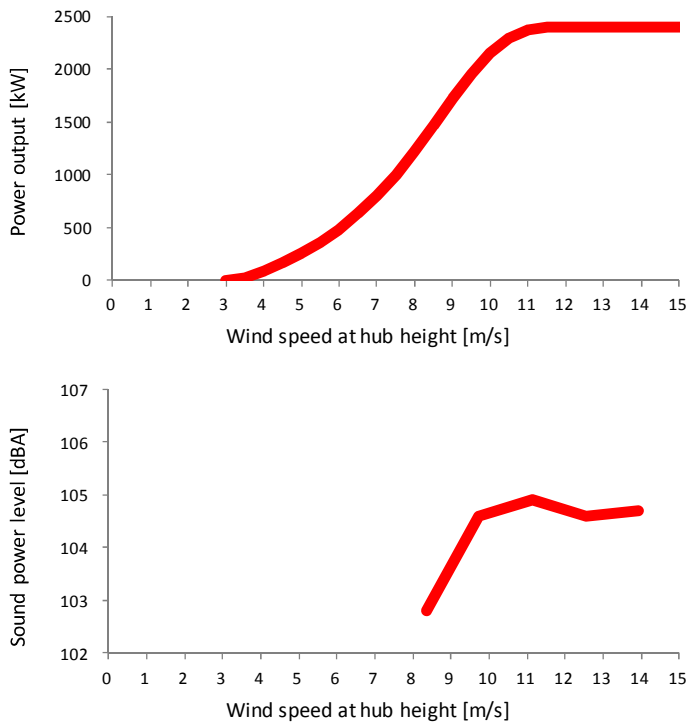

Fig 15 Measurement data of MWT102/2.4 wind turbine(measured by certification organisation)

6. Conclusions

Wind turbine noise reduction has become more important from the viewpoint of environmental assessments, and further noise reduction has been demanded. To develop quieter blades, it is important to identify noise sources and their locations to reduce the noise during the design phase. A prediction method to evaluate noise quickly and accurately during the design phase is essential. In this report, we presented a practical noise-prediction method for wind turbine blades that can exploit current computational capacities and keep the speed of blade development. This method has allowed to develop the less noisy blades of MWT102 wind turbine with high-performance. This method is also applied to our offshore wind turbine in order to improve the performance and reduce the load. These turbines will provide effective natural energy use with a less environmental load.

References

[1] Velser L. et. al(2005) *Wind Energy 2005* BWE-Service GmbH.
[2] Brooks T.F. et. al(1989) *Airfoil Self-Noise and Prediction* NASA RP-1218
[3] Grosveld F.W. (1984) *Prediction of Broadband Noise from Large Horizontal Axis Wind Turbine Generators* AIAA-Paper 84-2357
[4] Fukami K. et.al (2012) *Aerodynamic Design for Large-Sized Wind Turbine Blade* Proceedings of Japan Wind Energy Symposium
[5] Abott, et.al (1956) *Theory of Wing Sections* Dover
[6] Timmer and van Rooij (2003) *Summary of the Delft University Wind Turbine Dedicated Airfoils* Journal of Solar Energy Engineering, vol.125, pp.488
[7] Tangler, et.al. (1995) *NREL Airfoil Families for HAWTs* updated AWEA 1995.doc
[8] Fuglsang and Bak (2004) *Development of the Riso Wind Turbine Airfoils* Windenergy, July, 2004, pp.151