Fourth International Meeting on Wind Turbine Noise
Rome Italy 12-14 April 2011

Integrated Airfoil/Blade Aeroacoustics Modeling and Validation

Sidney Xue, JingShu Wu, and Matthew Summers
Vestas Technology R&D Americas Inc., Houston, Texas
sixue@vestas.com

Abstract

The most effective and cost saving solution to control and reduce wind turbine noise is in the design stage. An integrated wind turbine rotor modelling and analysis tool validated with measured data for aero-acoustics modelling capabilities is needed. This tool will be utilized to perform turbine optimization through advanced airfoil/blade design and rotor control. A strategy and frame work for an integrated wind turbine model, including VTS (Vestas Turbine Simulation), CFD (Computational Fluid Dynamics), and CAA (Computational Aero-Acoustics) utilizing the state-of-art technology to model the airfoil/blade and rotor aero-acoustics, is laid out in Figure 1 and 2. The computed airfoil and rotor noise in both time and frequency domains due to the airfoil and rotating blade, as seen in Figure 3-12, were presented and compared to available wind tunnel data with anechoic chamber acoustic measurements and the new acoustic array field measurement for validation and correlation.

Objectives

When a wind turbine or wind farm is installed near a populated residential community, its noise impact on the community, especially at night, is a great concern and can be a major market entry factor. International Electro-technical Commission (IEC) 61400-11 specifies the acoustic noise measurement standards. The objective of this research effort is to develop a validated and integrated rotor simulation with the state-of-the-art aero-acoustic model that can be utilized in rotor design and control for quieter wind turbine technology. The dominant aerodynamically generated noise for large wind turbines will be modeled and studied. The research work here also represent largely collaborated efforts with Sandia National Laboratory, National Renewable Energy Laboratory, Pennsylvania State University, commercial CFD software vendors and Riso National Laboratory for Sustainable Energy in Denmark; together we want to develop the advanced modeling methods with validations, and developed the advanced testing methods and measurements as well as design concepts. The ultimate goal is to develop and demonstrate how the state-of-art integrated aero-acoustic modeling/simulation technology with validation can be utilized for quieter wind turbine design and rotor control process, so that the

noise generated from a wind turbine and wind farm can be reduced and controlled by an improved installation.

Methods

It is expected that the wind turbine noise reduction should not be achieved through loss of wind turbine performance in term of energy production. At the same time, it is understood that wind turbine aero-acoustic sources have strong coupling with wind turbine aerodynamics and blade dynamics including elastic effects. Thus the following integrated rotor modeling and simulation should be utilized and validated with various fidelity models [Ref 1]. The Figure 2 shows the development process and frame where it is shown that airfoil noise should be validated by wind tunnel test inside anechoic chamber, and wind turbine rotor aero-acoustics should be validated with field test such as acoustic array. The Figure 3 shows the integrated airfoil/blade/rotor modeling and design optimization diagram with the key tool module.

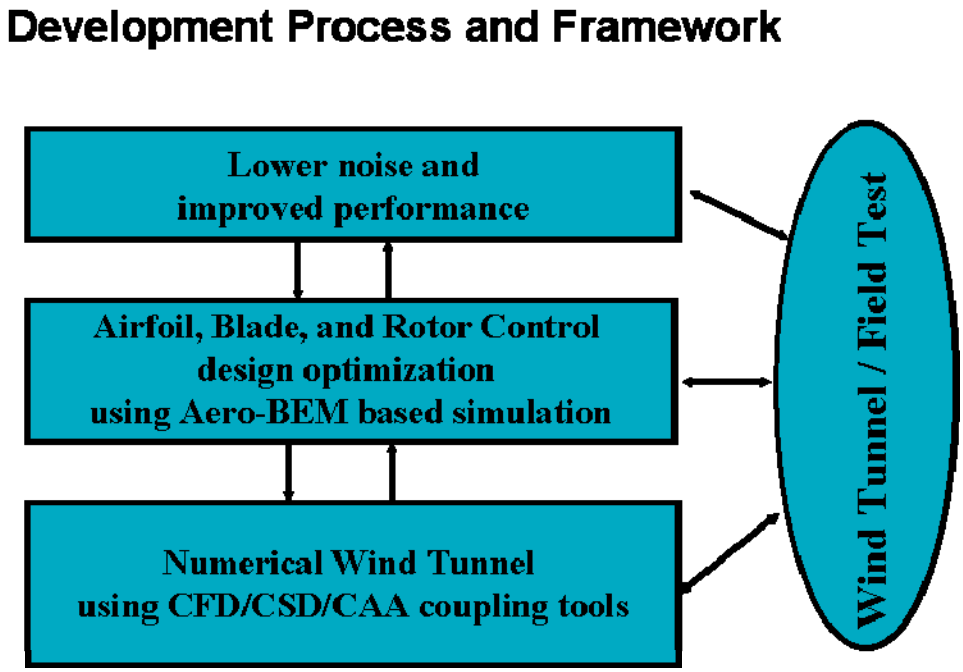

Figure 1. Development Process and Framework

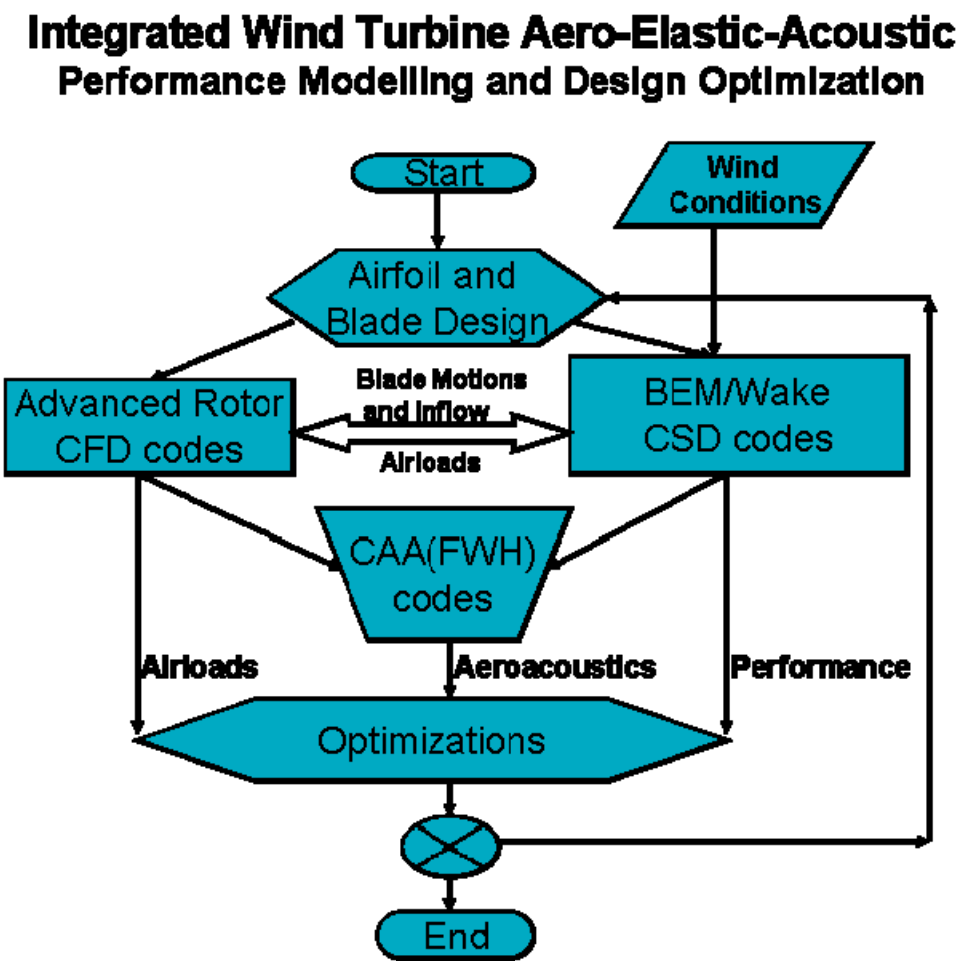

Figure 2. Integrated Aero-acoustic Modeling

Tool selection for each module in the system is based on a rigorous literature review, trial evaluation, bench marking and validation among various commercially-available software codes or though government and university support. It is found that each software have its own advantages and limitations; therefore tool selection should depend on the specific objective.

For CFD (Computational Fluid Dynamics) tool, evaluation was based on bench marking AcuSolve, CFX/Fluent, STARCCM+, and CFD++. We found each code has significant aerodynamic modeling capabilities with its own Pros and Cons depending on the objective.

For CAA (Computational Aero-Acoustics) tool, we have evaluated Fluent-CAA, CFD++/CAA++, PSUWOPWOP, NREL NAFNOISE and FAST, and Riso HAWTOPT. It is found that using PSUWOPWOP code which was developed for helicopter industry [Ref 2, 3 and 4] is a very efficient way to compute the far-field low frequency noise when it is coupled with a rotor aerodynamics and dynamic modeling based on Blade-Element Method (BEM), while NAFNOISE is a very efficient tool [Ref 5] in evaluating typical airfoil broadband noise, such as laminar/turbulence boundary layer noise, trailing edge separated flow noise, trailing edge bluntness vortex shedding noise, and turbulence inflow noise, which are very important wind turbine

aerodynamically generated noise. It should be noted that NAFNOISE for airfoil and FAST for 3D rotor noise are the semi-empirical aero-acoustic noise prediction codes that compute the noise in frequency domain, which should be validated in new airfoil noise simulation. On the other hand, the CAA code such as PSU-WOPWOP and Fluent-CAA (FWH), based on Ffowcs Williams-Hawkings (FWH) equation solution method, is a time domain aero-acoustic noise prediction code, and is more deterministic time domain solution that can be utilized for high fidelity modeling when it is coupled with CFD using LES turbulence model or NLAS (Non-Linear Acoustic Solver) model. VTS (Vestas Turbine Simulation code) is our most efficient comprehensive wind turbine simulation code which includes airfoil/rotating blade aerodynamics, dynamic with elastic modes, nacelle and tower that include transmission, generator and rotor controller. VTS was utilized in this study to couple with PSU-WOPWOP for the far-field aero-acoustic rotor noise simulation, followed by parametric study to identify the key wind turbine aero-acoustic noise sources.

Validations with Wind Tunnel and Field Acoustic Array Tests

For the airfoil noise model validation, we did bench marking and validated our airfoil noise modeling using both NAFNOISE and FLUENT-CAA simulations on classic NACA0012 airfoil and validated the modeling against NASA wind tunnel test with acoustic measurements inside anechoic chamber where its results was published in NASA Reference Publication 1218 [Ref 5]. Figure 3 shows our high fidelity computed acoustic pressure result in time history using Fluent (Large Eddy Simulation) at microphone located at about 5 chords above airfoil suction side. Its 1/3 Octave frequency spectrum was shown in Figure 4 in comparison with NASA wind tunnel acoustic test data and low fidelity tool NAFNOISE computation result. The Figure 5 shows the airfoil noise source contribution to the total noise from NAFNOISE. Figure 6 shows the wind tunnel with anechoic chamber and acoustic array facility that we might want to use for future airfoil noise study.

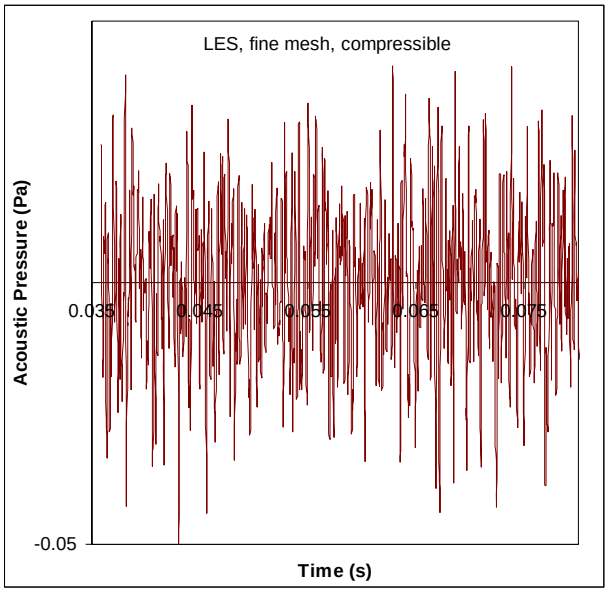

Figure 3 CFD LES/CAA simulation of Airfoil Noise

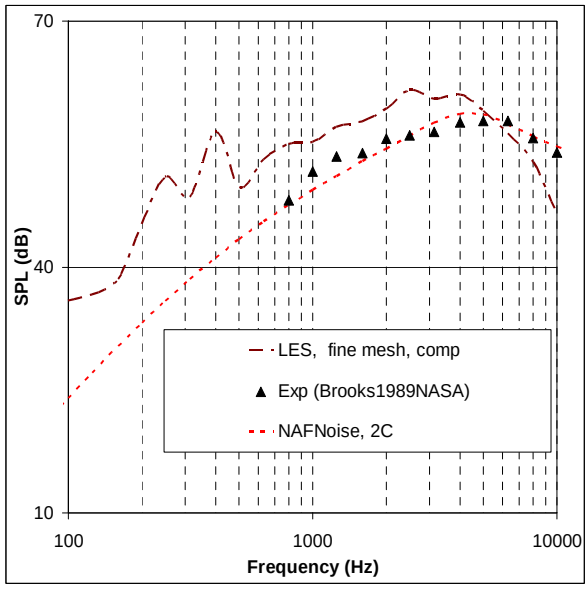

Figure 4 LES/CAA and NAFNOISE simulation of Airfoil Noise in comparison with Experiment

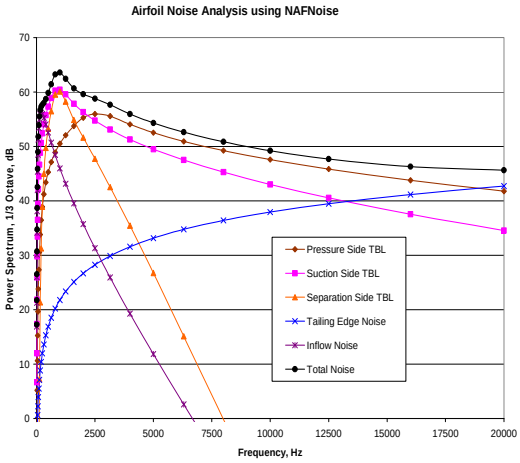

Figure 5 NAFNOISE prediction of Airfoil spectrum

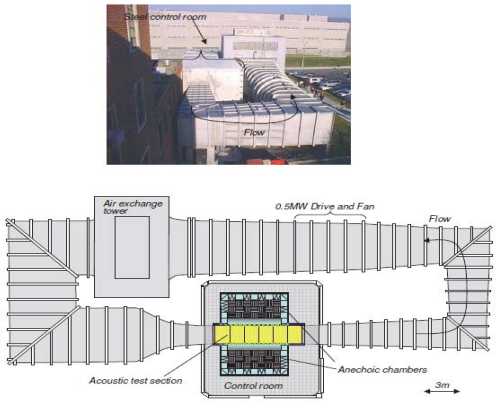

Figure 1. Photograph and plan view schematic of the Virginia Tech Stability Tunnel in anechoic configuration. Photo shows connection to Randolph Hall through metal building at center of picture. This pressure sealed steel room contains both the test section and operating console.

Figure 6 Wind Tunnel in Anechoic Chamber

For the rotor aero-acoustic noise modeling validation, we did integration the VTS coupled with PSUWOPWOP then combined with the airfoil noise modeling result into the final wind turbine aero-acoustic noise simulation. The computed wind turbine rotor noise with sound pressure contribution contour using VTS+PSUWOPWOP in Figure 7 is compared with B&K Acoustic Array test data measured in the similar condition for the same turbine model with result showing the sound pressure contribution level contour in Figure 8. The validation is also done with different wind speeds between our modeling results and IEC 61400-11 test results for the same turbine as shown in Figure 9. For the field acoustic test development, we are working with Bruel and Kjar Sound and Vibration as the partnership. It is understood that the high background noise is a big issue for the conventional IEC 61400-11 standard test as well as to separate the rotor aero-acoustic noise and nacelle mechanical noise. Thus, for the first time, we worked with B&K on the acoustic array test using B&K 30 microphones array system as shown in Figure 10. It is found through the field test that wind turbine aero-acoustic noise has modulation in its character. Thus, it is important to model the rotor acoustic in time domain; Figure 11 shows our first effort to simulate the rotor aero-acoustic in time domain which clearly shows the each blade rotating noise and blade tower interaction effect. Figure 12 shows the acoustic array test result in the similar condition after post-data processing focused on rotor downdraft aero-acoustic noise, this confirms the rotor aero-acoustic has modulation in its nature.

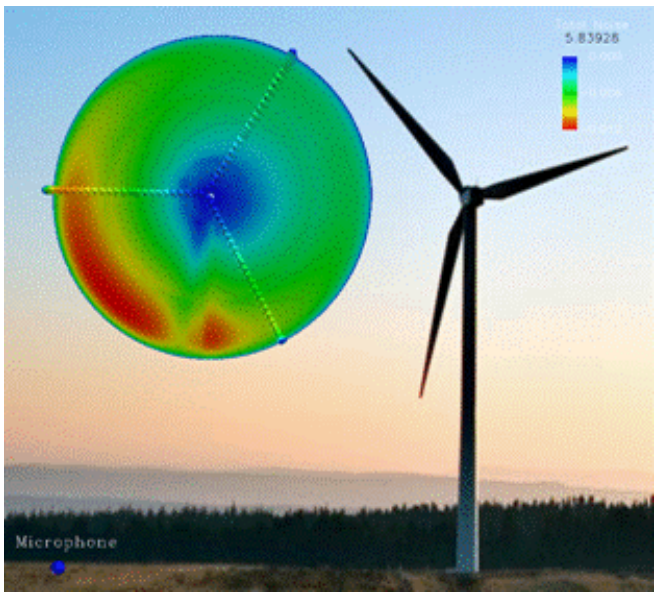

Figure 7 Modelling Noise Rotor Map

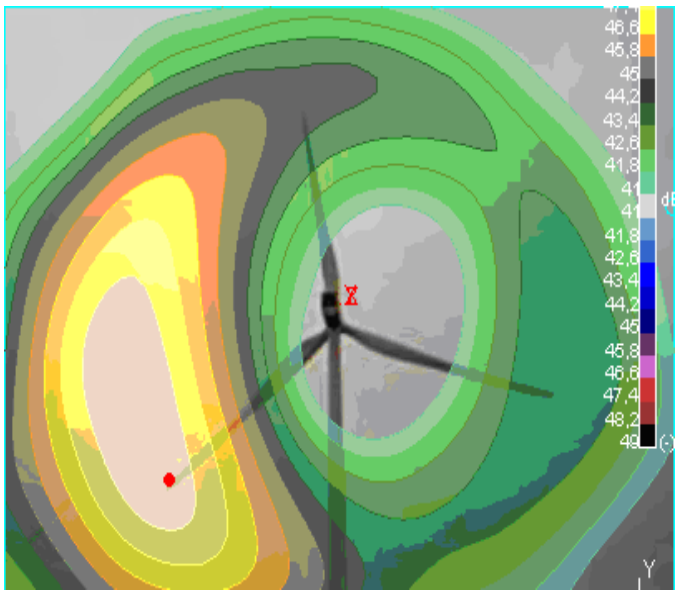

Figure 8 Acoustic Array Test Result

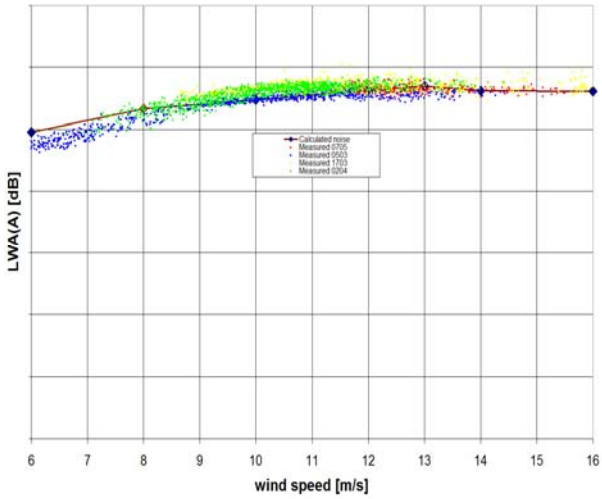

Figure 9 Modeling vs Test results

Figure 10 B&K Pentangle Acoustic Array

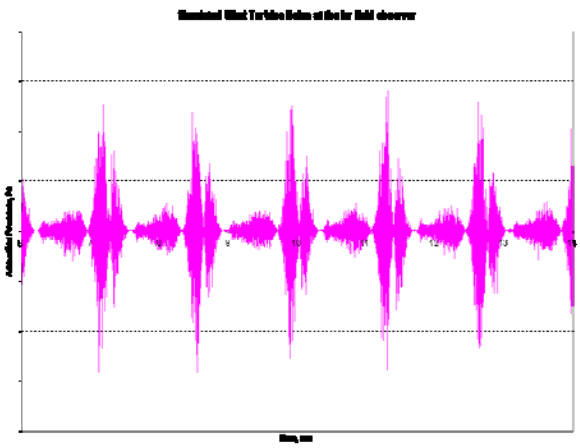

Figure 11 Modelling Rotor Noise

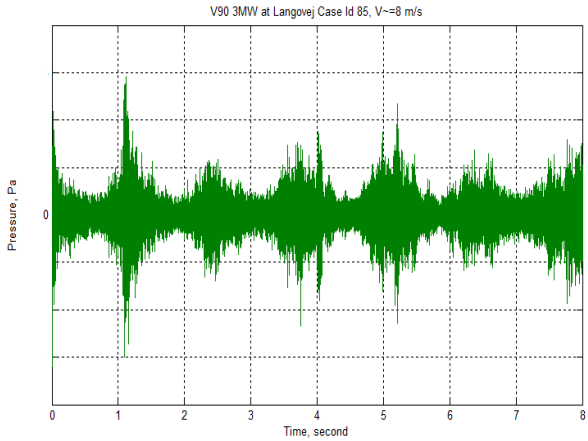

Figure 12 Acoustic Array Test Rotor Noise

Conclusions

Comprehensive wind turbine aero-acoustic simulation system is developed and correlated with wind tunnel test for airfoil noise and acoustic array field test for rotor aero-acoustic noise. The key wind turbine aero-acoustic noise generation mechanisms including RPM, blade-tower interaction, airfoil broadband noise, blade design such as swept tip, rotor control inputs, and atmospheric turbulence were evaluated through subsequent parametric studies. It is found that wind turbine aero-acoustic noise has strong coupling with aerodynamics and rotor dynamics including elastic modes necessitating the use of integrated wind turbine simulation that includes both wind turbine aerodynamic performance and aero-acoustics noise. Thus the wind turbine aero-acoustic noise reduction can be achieved with rotor design and control optimization while considering both wind turbine performance and noise at the same time. It is also found the acoustic array testing technology is an effective tool to suppress background noise and separate the rotor aero-acoustic noise versus nacelle mechanical noise, which we would like to continue working in this technology.

Acknowledgement

The authors would like to acknowledge and thank tremendous support from B&K team with acoustic array testing and post data processing. The authors would like to thank Carsten Westergaard, Jan Johansen, Bryan Edwards and Jens Jakob Wedel-Heinen for their great support and interest through out the test process. Thanks are also due to our management and project support.

References

1. S. Xue and et al from Bell Helicopter Textron Inc “Integrated Aero-Acoustics Rotor Simulation and Design Optimization”, 27th AIAA Aero-acoustics Conference, May, 2006
2. K. Brentner and F. Farassat, “Modeling aerodynamically generated sound of helicopter rotors”, Aerospace Sciences 39, pp 83-120, 2003
3. T. Samuels and S. Xue “Helicopter Noise Prediction and Validation: First look at Combined Main and Tail Rotor”, 64th American Helicopter Society Annual Forum, April 29, 2008.
4. S. Xue and A.S. Lyrintzis,”Rotating Kirchhoff Formulation for 3D Blade Vortex Interaction for Hovering Rotor”, AIAA Journal, Vol. 32, No. 7, July 1994.
5. P. Moriarty and P. Migliore, “Semi-Empirical Aero-acoustic Noise Prediction Code for Wind Turbines”, NREL, Technical Report, Dec. 2003
6. T. Brooks NASA Langley Research Center and et al, “Airfoil Self-Noise and Prediction”, NASA Reference Publication 1218, 1989.