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Review on Computational Fluid Dynamics and Fluid Structure Interaction of Wind Turbine Blade

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ABSTRACT- In today's rapid increase in energy demands and decaying fossil fuels availability, it is very important to investigate the different alternatives, renewable sources for energy generation. Wind energy is the biggest available source of energy which can easily be harnessed using the mechanical turbines; by converting wind energy into mechanical energy. A wind turbine is a rotary device that extracts kinetic energy from the wind. It has rotor blades mounted on the shaft which is connected to the generator through transmission devices. The blade profiles play an important role which decides the performance of the wind turbine. In this work, two blade profiles are simulated using CFD modeling and results are validated for coefficient of drag and lift. Further, the two profiles are compared for the flow separation point for different angle of attack. Optimization is performed between the two geometries for two different Re numbers using k-epsilon model for minimum drag. Coefficient of performance and critical angle of attack are also discussed for the two blade profiles. The pressure coming over the blade is used as input forces for structural analysis for calculation of displacement and structural parameters a like vomises stress and mode shapes. The study uses different shapes of blade to characterize the performance of these blades in wind turbine applications.

KEYWORDS**:** wind turbines, CFD simulation, fluid stracture interaction(FSI)

I. INTRODUCTION

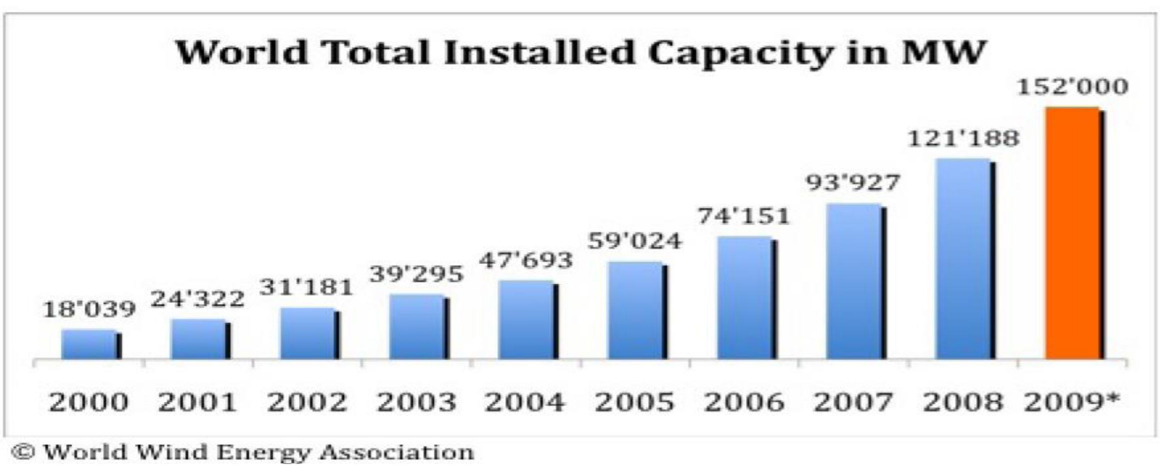

Fig.1 Wind Power developments

According to BWEA, the British Wind Energy Authority, in the UKcurrently there are 2896 large Wind turbines with installed capacity of 4532 MW, sufficient to supply over 2.5 million homes (based on annual household energy

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consumption of 4.7 MWh).Much attention has been paid recently to Renewables as a potential source of fuel. The rising oil price and the logistics in supplying fossil fuel to remote areas are the main drive to Renewables as well as the environmental incentive. In remote locations, stand-alone Renewable energy systems can be more cost-effective than extending a power line to the electricity grid. In addition, the environmental benefits under the current international concerns on global warming makes such project much more valuable and rewarding. The growth of renewable energy sources also stimulates employment, the creation of new technologies and new skills.The new Directive on renewable energy sets ambitious targets for all Member States, such that the EU will reach a 20% share of energy from renewable sources by 2020 and a 10% share of renewable energy specifically in the transport sector. It also improves the legal framework for promoting renewable electricity, requires national action plans that establish pathways for the development of renewable energy sources including bioenergy, creates cooperation mechanisms to help achieve the targets cost effectively and establishes the sustainability criteria for Biofuels.[1]

Definition

Energy available in wind is basically the kinetic energy of large masses of airmoving over the earth's surface. Blades of the wind turbine receive this kineticenergy, which is then transformed to mechanical or electrical forms, depending onour end use. The efficiency of converting wind to other useful energy formsgreatly depends on the efficiency with which the rotor interacts with the windstream. In this chapter, let us discuss the fundamental principles involved in thiswind energy conversion process.[2]

Types of Wind Turbines

There are mainly two types of wind turbine: horizontal axis and vertical axis. The horizontal axis wind turbine (HAWT) and the vertical axis wind turbine (VAWT) are classified or differentiated by the axis of rotation the rotor shafts.[1]

Horizontal Axis Wind Turbines - Horizontal axis wind turbines, also known as HAWT type turbineshave a horizontal rotor shaft and an electrical generator which is both located at the top of a tower.[1]

Vertical Axis Wind Turbines - abbreviated as VAWTs, are designed with a vertical rotor shaft, agenerator and gearbox which are placed at the bottom of the turbine, and a uniquely shaped rotor blade that is designed to harvest the power of the wind no matterwhich direction is it blowing. The first is the Darrieus wind turbine, which is designed to look like a modified egg beater. These turbines have very good efficiency, but poor reliability due to the massive amount of torque which they exert on the frame. Furthermore, they also require a small generator to get them started.[1]

Fig.2 Wind Turbines, Some types

II. Introducing CFD

With Computational Fluid Dynamics we indicate the numerical solution of the differential governing equations of fluid flows, with the help of computers. This technique has a wide range of engineering applications. In the field of aerodynamic research this technique has become increasingly important and it is prominent for studying turbo machinery.[3]

A computational framework for the shape optimization of wind turbine blades is developed for variableoperating conditions specified by local wind speed distributions. The numerical workflow consists of a genetic algorithm based optimizer, a computational fluid dynamics based simulator and a 3D geometric modeller. The developed numerical workflow also implements the coupling of the process flows as well as passing data amongst the individual applications including the corresponding data mining. Several approaches to modeling 3D shapes are developed and employed by the workflow. They include parametric curves defining 2D curves lofted into 3D shapes in combination with applying computational geometry operators and full 3D parametric surface models which enable generic 3D shapes to be represented. The proposed definitions of excellence include annual energy production for given wind speed distributions and net-present-value and internal-rate-of-return based indicators as potential constituents of the fitness functions. Several case studies are presented with promising results towards theaspired custom-shaped wind turbine blades for optimum performance for any given specific location. The developed computational workflow can therefore be seen as a numerical device for custom optimization of performance of renewable energy systems.[4]

Case A: The CFD model for the Case A, uses the computationally simple first order upwind differencing scheme with the computational domain diameter of 1.6D. The optimization run was conducted for 25 generations with an initial population of 50 individuals. The respective optimization variables are the rotation and scale factor of the S809 airfoil at 3 blade sections, where only the outboard section is allowed the translational degree of freedom, which adds up to 7 optimization variables. Two robust optimizations were conducted with wind speed distributions associated with the Lastovo and Vis islands at the Adriatic, while single point optimization was conducted for the wind speed of 7.74 m/s. Another variant of robust optimization is Case A-Pitch, where the additional variables are the pitch curve parameterization coefficients providing the respective second order polynomial. In comparison with the Case A, the Case A-Pitch was run for only 10 generations with the initial population of 50. Therefore, there is total of four optimization cases with S809 airfoil as the base airfoil for shape optimization. The resulting blade shape for single point optimization is illustrated in Fig. 3, where the optimized shape is 3D-compared with the NREL blade.[4]

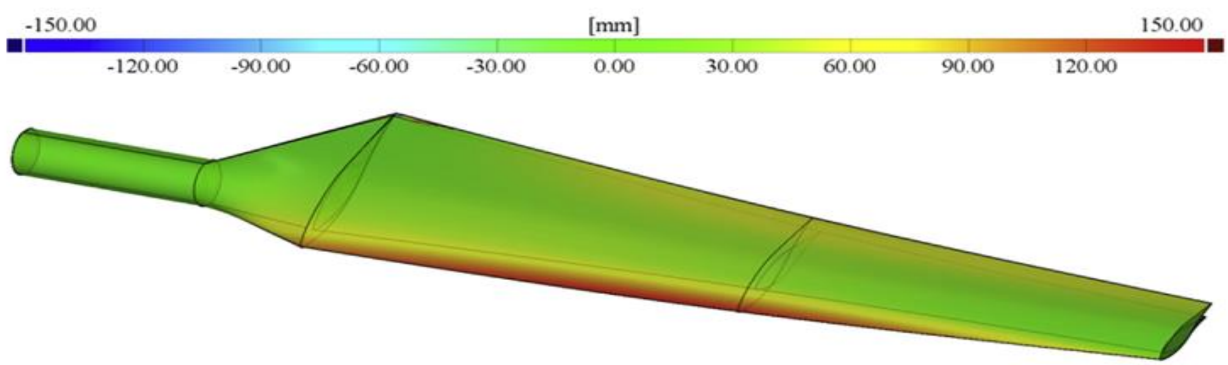

Fig. 3 .Case A-Single point, optimized geometry deviation from NREL Phase VI experimental rotor

CASE B: The preliminary CFD prediction for the WT power, i.e. the power coefficient in the range of low wind speeds was too close to the Betz limit. The CFD model was subsequently modified by introducing a higher differencing scheme and increasing the global computational domain and consequently a more realistic prediction was obtained. The predicted power maximum (35 kW) is significantly higher than the NREL one, however at a much higher wind speed (16 m/s). The airfoil for the B case is the same along the active span of the optimized blade but its shape is the result of optimization. The optimized airfoil is more cambered when compared to S809. It is not as thick as the S809, but the curvature of the leading edge is almost the same. Close to the trailing edge, the pressure side is concave as for the S809. The optimized blade is less tapered due to longer the tip chord but the twist distribution is like for the NREL one, Figs.4.

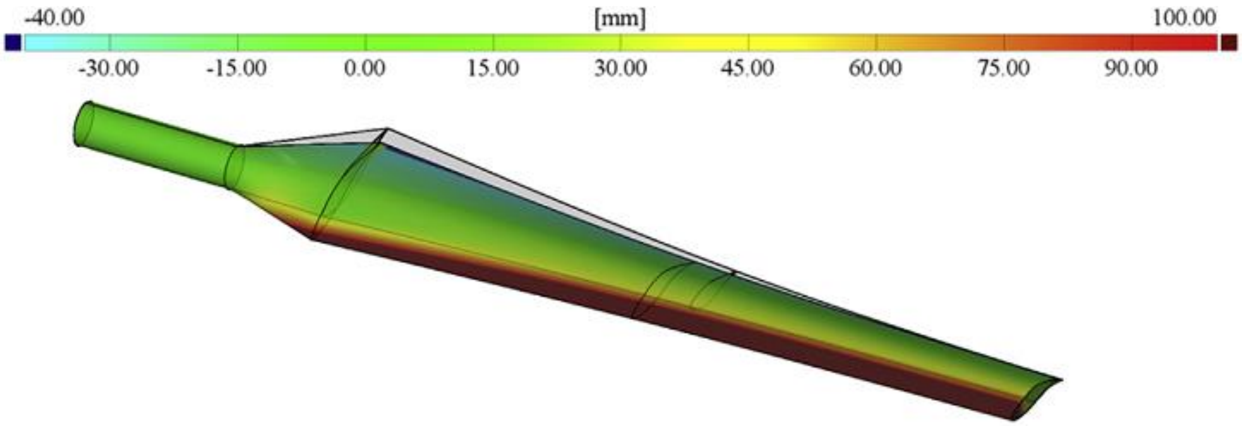

Fig. 4.Case B-Single point, optimized geometry deviation from NREL Phase VI experimental rotor. [4]

CASE C: Optimization of the blade using the arbitrary surface shape model provides a further increase in the maximum power compared to the A and B cases, nevertheless it is achieved at a slightly lower (rated) wind speed of 12 m/s. Being optimized for the same (design) wind speed, the leading edge of the blade is More 'pointed' and the pressure side is turning into a flat shape near the blade tip. Fig. 5 illustrates the blade geometry deviation with respect to the NREL blade. The location of the blade section with maximum camber follows this trend with a certain shift towards the leading edge for the outboard cross sections. The C rotor solidity is higher due to 10-20% increase of the blade chord length, but it is less twisted than the B-rotor blade.

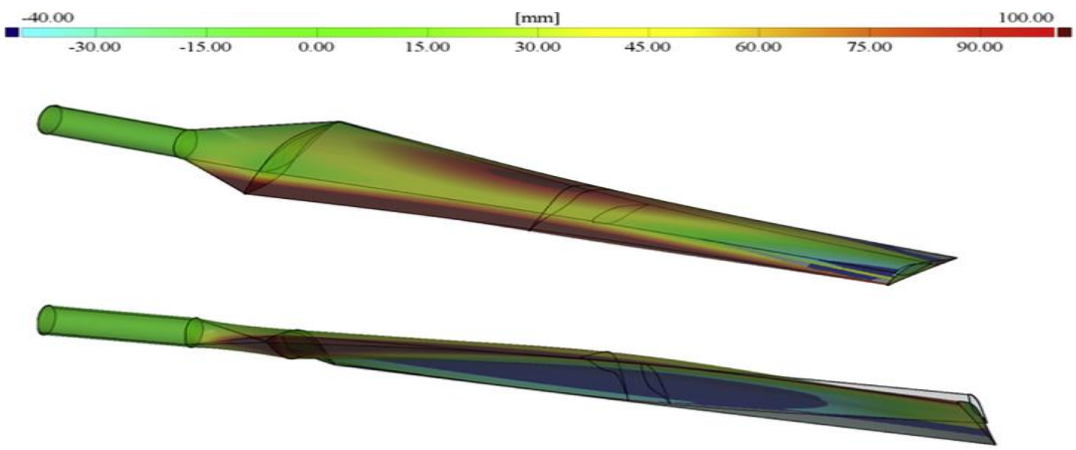

Fig. 5 Case C-Single point, optimized geometry deviation from NREL Phase VI experimental rotor. [4]

III. AERODYNAMIC OF WIND BLADE AND WIND TUNNEL

The wind loading is one of the most general external loading conditions which any structure will experience during their service time. Usually these structures are designed to minimize the aerodynamic wind load. These works are geared towards saving structural material and produce optimized economical structural design. In contrast to general structural system, the wind blade is designed to maximize the aerodynamic load. A turbine system is a mechanically rigid multi-body system which converts the wind energy to rotating torque energy. In order to produce maximum efficiency, large-scale structural systems of wind turbine with tower and base foundation are needed. The fundamental power generation and control system are also essential. The complexities and difficulties come from these highly technical assemblies. Among all the components of a wind turbine system, the shape sensitive rotating wind blade is the most important part to increase the power generation rate (power coefficient).

A wind blade shares the aerodynamic theory with airplane wing and helicopter blade. These systems utilize the higher lifting force to rotate and to lift. The airplane wing stays stationary when it is in operating condition. The wind blade is closer to the rotating helicopter blade. However, the high speed rotating helicopter blade should be thin and should have small angle of attack. As a result, there are little unsteady turbulent phenomenon compared with wind blade system. To determine the optimized wind blade shape which generates the maximum power in low operating inflow wind speed, we need to evaluate the aerodynamic force coefficient which will rotate the wind blade about primary axis. Airplane wing has constant sectional airfoil shape along the span-wise dimension because of nearly constant angle of attack around it.[5]

However, the wind blade rotates in induced angular velocity and hence it has linearly varying rotating velocities. The calculated angles of attack along the span are shown to have nonlinear values. The wind blade may also have nonlinear twist angle to minimize the angle of attack and turbulence around the blade wall along the span. Since the blade is rotating and has nonlinear twist angle, the surface stream on the suction surface flows toward the direction of the tip from the root side. Because of the reported2D airfoil wind tunnel test data for various angles of attack are shown to have noticeable errors compared with 3D wind tunnel test data, the wind blade cannot be designed based on2D aerodynamic theory and design codes. These codes are based on 2D wind tunnel tests and 2D BEM formulations. Comprehensive 3D aerodynamic data should be taken into account in wind blade design process. To meet these requirements, the real scale 3D wind tunnel studies are essential. The NREL Phase VI wind blade is a well known publicly accessible 3D wind tunnel test project. From these rigorous experimental wind tunnel tests, accurate quantitative aerodynamic and structural measurements on a full scale wind turbine blades were performed to provide the needs of accurate 3D aerodynamic forces which takes into account the inflow turbulence and shear across the rotor plane.BEM is frequently preferred in wind blade design code because of its simplicity and overall accuracy.

However, it depends on the aerodynamic force coefficients from 2D or 3Dwind tunnel test data and has limitation only for asymmetric cases. It shows difficulties when taking into account the unsteady and nonlinear transient rotor yaw and rotating wake flow effects like any other numerical methods. VM is anon going active research area, which considers the 3Dunsteady flow effects. Even though they have appeal innumeric advantages, the aerodynamic coefficient of 3D wind tunnel test data should be used for evaluating the accuracy of aerodynamic analysis and application. Even though CFD has a similar difficulties and limitations, it can easily be applied to the change of shapes of wind blade around a reference shape.[5]

IV. CONCEPT OF FLUID STRUCTURE INTERACTION

The FSI are used in wide range of multi-physical problem in which the fluid effects are dominant but difficult to evaluate for structural part. Especially high curvature free shape of 3Dwind blade is a challenging problem to apply on the FSI simulation, because of its difficulty in evaluating the aerodynamic force of the surface.

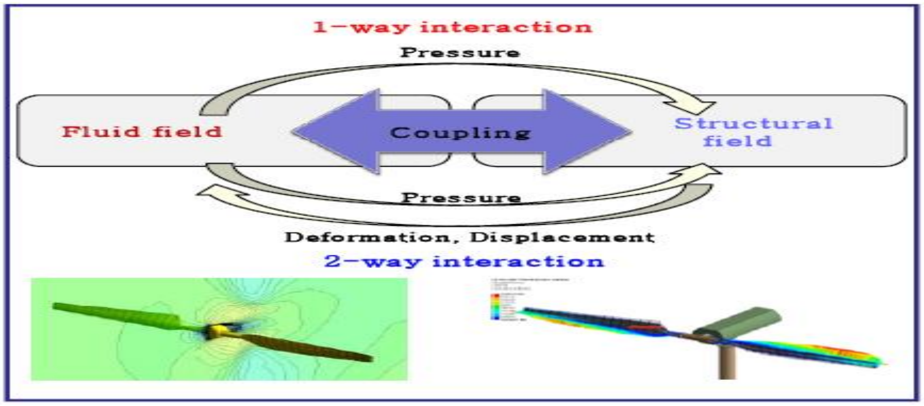

Fig. 6. Concept of fluid structure interaction.

The fundamental pre-requirements for FSI are the verification of pressure loading value from CFD and the definition of interface between fluid and structural domain. As shown in Fig. the interface transfers data from fluid to structure or structure to fluid. These interactions are called as1-way. If the interface transfers the data to both sides sequentially, we call it as 2-way. Fluid domain transfers the pressure or temperature to the structure and structure transfers usually the displacement to the fluid. From these interactions, the fluid domain updates the domain mesh from structural deformation. The structural part deforms due to the pressure or temperature load from the fluid domain. Unlike the BEM or VM methods, the structural part can be modeled using FEM procedure. The response of the structure relies on the material and solid modeling quality. The surface of structural part should share identical topology with CFD domain.

The rotating wind blade is vibrating with its frequency to the direction of first Eigen-mode shape which is independent to the wind flow direction but dependent to the local axis. The Vibrating frequency of wind blade is dependent on the stiffness and mass of blade. If the tower is considered, the vibrating model of tower will be coupled with blade. Lift causes bending in the flap-wise direction while air flow around the blade cause edge-wise bending. Flap-wise bending involves tension on the pressure (upwind) side and compression on the suction (downwind) side. Edgewise bending involves tension on the leading edge and compression on the trailing edge. Hence, 3D wind blade may experience the unsteady transient of fluctuation and vortex shedding. CFD is one of the options to capture these unsteady effects, even though it has numerical difficulties and limitations. To consider the time dependent unsteady effect of fluctuation and vibration in numerical method, the fluid domain must be changed along with structural vibration intransient analysis. Hence, to simulate these problems, the interface should take into account the interaction of both sides using 2-way FSI. The 1-way FSI is used for steady static problem and 2-way is for unsteady transient problem.[5]

V. INTRODUCTION OF CFD AND FSI

The design of wind blade is highly dependent on the evaluation of aerodynamic wind load. To increase the wind turbine power coefficient, it should extract more wind kinetic energy. Hence the understanding of the aerodynamics around the blade is that much important to obtain the optimum wind blade shape. There are well known approaches to calculate the aerodynamic load of wind blade. Wind tunnel tests are considered as the most exact and practical method and are sought for validation by researchers. However, it needs comprehensive equipment's and knowledge to perform the test.The researchers can utilize the publicly reported 2D airfoil wind tunnel test results to design their wind blade. The practical and more important data of 3D wind blade wind tunnel test is very difficult to obtain and rarely available. Moreover, the wind blade is highly shape sensitive especially for the twist angle and the varying span-wise sectional shape. The 2D airfoil aerodynamic coefficients such as lift and drag, with various angles of attack do not correspond to the 3D results. The idea of using 2D wind tunnel test data for 3D simulation and design is not desirable. The alternatives are to use computational methods like Blade Element Momentum method (BEM) [1], Vortex method (VM) and Computational Fluid Dynamics (CFD) to calculate the aerodynamic load of 3D wind blade.

However, BEM and VM are basically dependent on the accuracy of wind tunnel test data until now.Even though, CFD is known to be very difficult to apply in the unsteady aerodynamic phenomenon, it can calculate the sectional airfoil aerodynamic coefficient independently using high end computational software and hardware with comprehensive turbulence models. Verifications of CFD results are necessary though before applying to practical projects. Also, the surface pressure obtained from CFD can be directly applied as the structural load using an interface to connect fluid flow and structural analyses called as Fluid Structure Interaction (FSI) [9].In this study, we introduce a process of FSI where results from CFD are directly applied to structural analyses and vice versa with the use of an appropriate interface. The interface between the two physical domains can transfer the mutually needed data. Through this systematic FSI analysis process, the aerodynamic effects of the fluid domain on the structure can be easily seen. The structural analysis and design are performed through the interface by explicitly loading the aerodynamic loads to the FEM structural model automatically without calculating any sectional aerodynamic coefficients. [5]

VI. CFD FOR FLUID STRUCTURE INTERACTION

The wind loading is one of the most general external loading conditions which any structure will experience during their service time. Usually these structures are designed to minimize the aerodynamic wind load. These works are geared towards saving structural material and produce optimized economical structural design. In contrast to general structural system, the wind blade is designed to maximize the aerodynamic load. A turbine system is a mechanically rigid multi-body system which converts the wind energy to rotating torque energy. In order to produce maximum efficiency, large-scale structural systems of wind turbine with tower and base foundation are needed. The fundamental power generation and control system are also essential. The complexities and difficulties come from these highly technical assemblies. Among all the components of a wind turbine system, the shape sensitive rotating wind blade is the most important part to increase the power generation rate (power coefficient).[5]

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Fig. 7 and Fig. 8 show the 1-way and 2-way FSI simulation process respectively. The verified CFD results are used for wind blade pressure load and transferred to the structural surface load. Only the interaction of wind blade surface considered to verify the wind blade aerodynamic load. The static and transient structural responses were tested using1-way and 2-way FSI respectively. In 2-way FSI simulation, as shown in Fig. 8(a) simultaneous interactive calculating processes are performed to match the interface domain. Hence, the FSI simulation is strongly related to each other in 2-way case.[5]

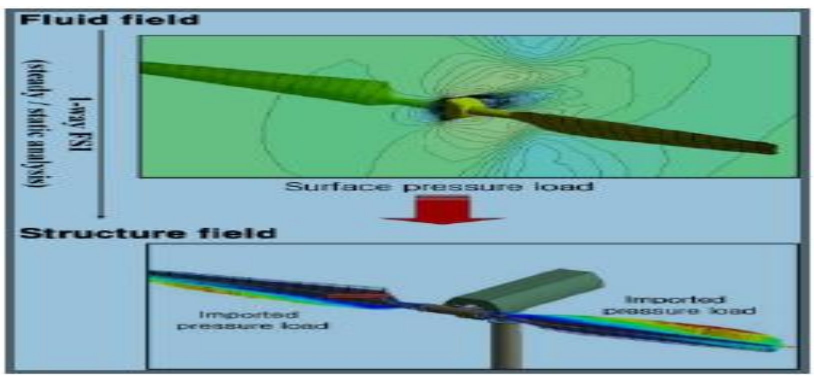

Fig.7 way FSI process: steady state fluid/static structure.

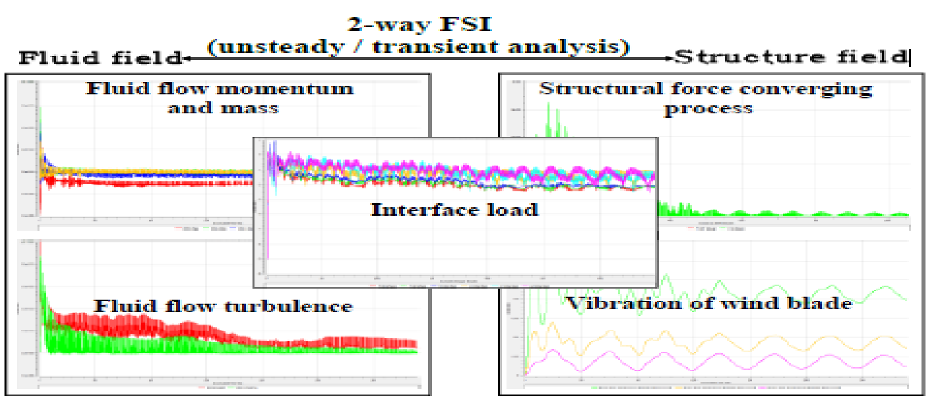

Fig.8(a). 2-way FSI process.

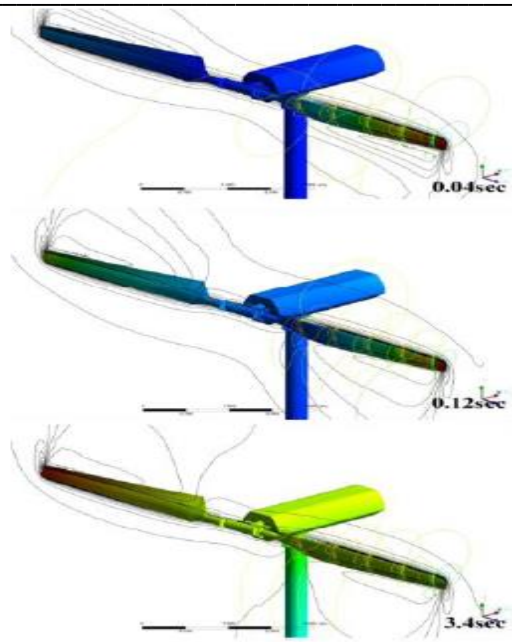

Fig.8 (b) Isometric view. 2-way FSI results :pressure and velocity contour

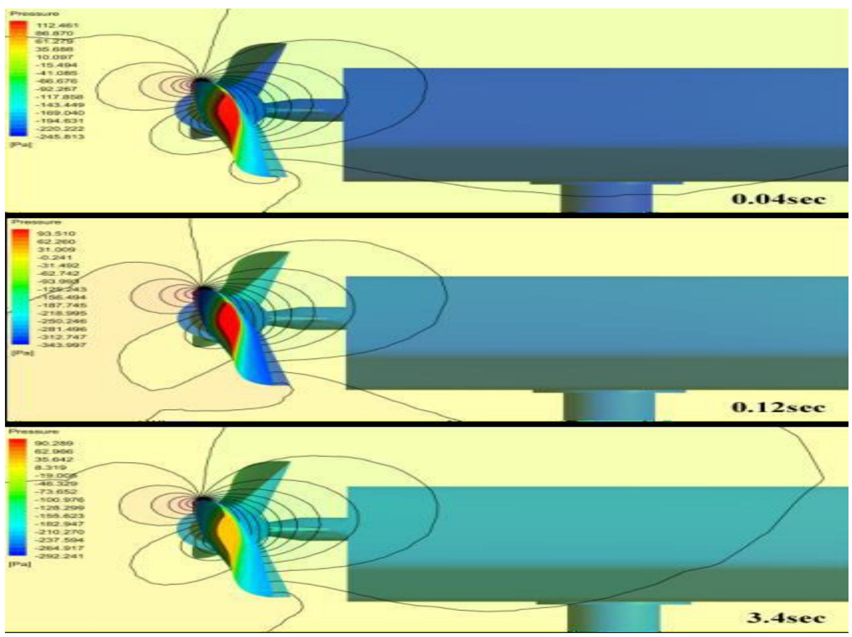

Fig.8 (c) Side view of 2-way FSI results :pressure and velocity contour

Only 7m/s wind speed case is considered with 72 rpm rotating velocity to show the numerical characteristics of this study. From the mesh-sensitivity parametric studies, the wind power coefficient or torque value of wind blade is found to be highly dependent on the fluid mesh characteristics. The static structural responses using 1-way FSI are found to be in good agreement with the results obtained by using sectional aerodynamic force which is based on the BEM formulation. The supporting tower has little effect on the overall stability but it increases the displacement for static and transient cases. The time dependent vibration of wind blade shows the mode composition of natural frequency. However, the fundamental vibrating motion of wind turbine is dominant to that of tower not wind blade because of lightweight nature of wind blade.[5]

VII. CONCLUSION

As moving forward the contribution of wind energy is increasing taking into consideration the present status quo or global scenario renewable energy has huge importance in this reviewthe evaluation of aerodynamic interaction of NFEL PhaseVI wind blade using FSI is presented. The CFD results are shown to be in excellent agreement with wind tunnel test data using k-wSST turbulence model. The assumed structural FEM model produced similar natural frequency on the experiment. From the 1-way and 2-way FSI simulation for static and transient analysis respectively, the dominant vibrating motion of overall turbine blade is not blade but tower, and the time dependent transient vibrating motion of wind blade finally converged to the static motion. The FSI interface transferred the surface pressure to the structure and structural displacement to the fluid accurately and successfully. The wind power coefficient of wind blade is highly affected by the fluid mesh quality. The structural mesh characteristic was important in mapping process of CFD aerodynamic load to the structure.

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