



Modal and Probabilistic Analysis of Wind Turbine Blade

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ABSTRACT

A wind turbine is a device that extracts kinetic energy from the wind and converts it into mechanical energy. Therefore wind turbine power production depends on the interaction between the blade and the wind. The present paper deals with numerical analysis performed in the finite element code ANSYS in order to produce fluid-structure interaction analysis with pressure-based formulation, using modal analysis and the concept of multiple physics environments. The numerical results are obtained with two different approaches: deterministic and probabilistic followed by a numerical simulation of a blade subjected to air flow. Firstly it is used for frequency measurement in vacuum and in air, the second one is only used in air. Enhancement of the modelling possibilities within the ANSYS code is carried out with implementation of fluid-structure non-symmetric pressure/displacement formulations. The numerical results are deduced from a finite element approximation of the coupled problem.

KEYWORDS

Modal analysis, Fluid-structure interaction, Monte-Carlo, multiple physics environments.

Introduction

A wind turbine is a device that extracts kinetic energy from the wind and converts it into mechanical energy. Therefore wind turbine power production depends on the interaction between the blade and the wind [1].

In the aero-acoustic studies, the mechanism of interaction between an acoustic fluid and an elastic structure of paramount importance is important in many industrial applications. Indeed, when a resilient structure vibrates in the presence of a free flowing fluid, the effect of the fluid dynamics of the structure results in a phenomena of added mass, characterized by a more or less significant decrease of the eigen-frequencies of the coupled structures [2].

Modes are used as a simple and efficient means of characterizing resonant vibration. To better understand any structural vibration problem, the resonances of a structure need to be identified and quantified. A common way of doing this is to define the structure's modal parameters.

A modal analysis method avoids moving to the formal calculation that requires huge calculations, and allows for a simple and fast against rough calculation of own frequencies. So it can present relatively low influence of the air on the frequencies of a blade wind turbine. The goal of the study is to find the blade's natural frequencies, mode shapes and blade deflection under steady-state conditions.

Taking account in to uncertainties in the mechanical analysis it is necessary for optimal and robust structures design. Indeed, it is widely recognized that small uncertainties in the system settings can have a considerable influence on its vibratory behaviour expected [3].

We used probabilistic approach to improve the robustness of the design and estimate the impact of uncertainties of parameters on the vibration response of the blade. In addition the combination of probabilistic methods with simulation by finite elements allows not only to define the boundaries of the deterministic market approaches but also to improve by providing more information and an efficient use of data digital.

A load transfer coupled physics analysis is the combination of the analysis from different engineering disciplines that interact to solve a global engineering problem, such as steady-state

fluid-structure interaction. For convenience, this part refers to the solutions and procedures associated with a particular engineering discipline as a physics analysis. When the input of one physics analysis depends on the results from another analysis, the analyses are coupled. In this case, we use the two-way coupling, where the analysis requires iteration between the two simulations.

The present work proposes three numerical studies on a blade of wind turbine: a modal analysis and probabilistic one, followed by another analysis using load transfer coupled physics. Modal analysis presents a comparison of frequencies of a blade in vacuum and in air while the probabilistic study is implemented only for a blade in the air; finally the blade is subjected to air flowing to determine the pressure drop and blade deflection under steady-state conditions. These numerical studies are conducted using a finite element computer code ANSYS. A method of coupling finite element/finite element is used to model the coupled system fluid-structure, with a non-symmetric formulation in pressure/displacement.

Problem statement

A discretization of type finite element-based digital techniques allow solving the equations of fluid-structure interaction problems, these methods are applicable with general calculation codes. There is interest in this model to the vibration dynamic behaviour of an elastic structure coupled with a compressible fluid, on taking into account the vibratory phenomena in fluid. The problem studied is that an elastic structure (turbine blade) coupled with a compressible fluid (air in this case).

The structure occupies the area Ω_s , border $\partial\Omega_s$; the fluid occupies the area Ω_f , border $\partial\Omega_f$. The two areas are in contact on $\Gamma = \partial\Omega_s \cap \partial\Omega_f$. Frontiers elements $\partial\Omega_{s0}$, $\partial\Omega_{s\sigma}$, $\partial\Omega_{f0}$ et designates

$\partial\Omega_{fn}$ the portions of the field border structure imposed displacement required effort, and portions of the fluid field pressure and normal pressure gradient imposed border [4].

Without loss of generality, it is assumed that the required quantities (displacement, pressure) on the structure and fluid are void. The problem coupled acoustic fluid/elastic structure is described by the following equations:

- For the structure, the equations are:

$$-\omega \rho_s u_i - \frac{\partial \sigma_{ij}(u)}{\partial x_j} = 0 \text{ in } \Omega_s$$

$$u_i = 0 \text{ on } \partial\Omega_{s_0}$$

$$\sigma_{ij}(u)n_j^s = 0 \text{ on } \partial\Omega_{s_\sigma}$$

- For the fluid, it can be written as:

$$-\frac{\omega^2}{c^2} p - \frac{\partial^2 p}{\partial x_i^2} = 0 \text{ in } \Omega_F$$

$$p = 0 \text{ on } \partial\Omega_{F_0}$$

$$\frac{\partial p}{\partial x_j} n_j^F = 0 \text{ on } \partial\Omega_{F_\pi}$$

- The coupling conditions are:

$$\begin{cases} \sigma_{ij}(u)n_j^s = p n_i \\ \frac{\partial p}{\partial x_j} n_j = \omega^2 \rho_F u_i n_j \end{cases} \text{ on } \Gamma$$

The variational formulation of the problem is obtained by writing for all virtual δu displacement fields and any field pressure virtual δp eligible; it is written:

- For the problem structure:

$$\begin{aligned} & -\omega^2 \int_{\Omega_s} \rho_s u_i \delta u_i dv \\ & + \int_{\Omega_s} \sigma_{ij}(u) \varepsilon_{ij}(\delta u) dv \\ & = \int_{\Omega_s} p n_i \delta u_i dS \forall \delta u \end{aligned}$$

- For the fluid problem

$$\begin{aligned} & -\omega^2 \int_{\Omega_F} \frac{1}{c^2} p \delta p dv + \int_{\Omega_F} \frac{\partial p}{\partial x_i} \frac{\partial \delta p}{\partial x_i} dv \\ & = \omega^2 \rho_F \int_{\Gamma} u_i n_i \delta p dS \forall \delta p \end{aligned}$$

The discretization of the weak formulation of the problem by the M_s, K_s, K_r and R thus operators that mass operator M_f defined on the fluid domain Ω_f by:

$$\int_{\Omega_F} \frac{1}{c^2} p \delta p dv \rightarrow \delta P^T M_F P$$

We then get the following matrix problem:

$$\begin{pmatrix} -\omega^2 \begin{bmatrix} M_s & 0 \\ -\rho_F R & M_f \end{bmatrix} + \begin{bmatrix} M_s & R \\ 0 & M_f \end{bmatrix} \end{pmatrix} \begin{Bmatrix} U(\omega) \\ P(\omega) \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix}$$

Study of wind turbines

Wind turbine

Wind power is one of the most important sources of renewable energy. Wind power involves converting wind energy into electricity by using wind turbines [3]. The idea of taking energy from wind has been known and exploited for centuries in many countries. A wind turbine is composed of three propellers-like blades called a rotor. The rotor is attached to a tall tower. The tower looks like a very tall pole. On average wind towers are about 20 m high. The reason why the tower is so tall is because winds are stronger higher from the ground.

A modern wind turbine consists of a rotor (three blades) that drives a generator that produces electricity. The rotor and generator are installed at the top of a tower, which stands on a foundation in the ground or in the seabed. The turbine cap (nacelle) and the blades are controlled based on measurements of the wind direction and speed.

In simple terms, a wind turbine not only utilizes the wind's pressure on an obliquely positioned blade, but also utilises

the fact that the air current around the blade creates a negative pressure on the rear of the blade in relation to the wind. The force from this negative pressure produces a draught that causes the blades to rotate.

The electricity production of a wind turbine depends on wind conditions. Obviously the wind does not blow constantly, and wind speed varies greatly from place to place and over time. On average, the wind blows more at sea than on land. Future wind turbines will generally be of megawatt scale. And as future turbines will be far more efficient, significantly fewer turbines will be needed for electricity production.

Vertical and horizontal axis turbines used for residential electricity generation. Wind comes from atmospheric changes; changes in temperature and pressure makes the air move around the surface of the earth; all of which is triggered by the sun. A wind turbine captures the wind to produce energy.

Modelisation

The NPS-100 prototype blade (a derivative of the ERS-100 blade) is a 9.0 meter all fiberglass blade manufactured for Northern Power Systems [5].

Modal simulation has been performed in order to determine the natural frequencies of this prototype blade model. The following paragraphs are a brief description of the necessary step for performing the model. Figure 1 shows the NPS-100 blade platform.

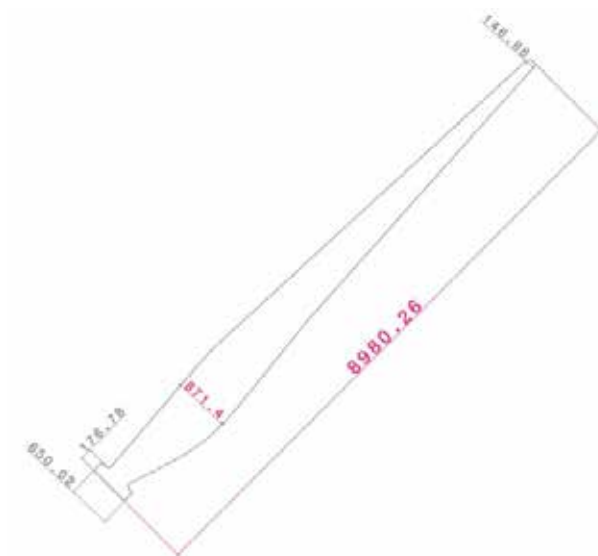


Figure 1. Geometry of a wind turbine blade

The calculation is implemented with the finite element code ANSYS. The modelling of the fluid-structure interaction problem is done by coupling the element structure SHELL63 and the fluid element FLUID29, meshed respectively with a four-node rectangular element.

Figures 2 and 3 respectively give a representation of the mesh of the pale in the case of the study in vacuum and the mesh of a pale of the wind turbine dived in the surrounding fluid.

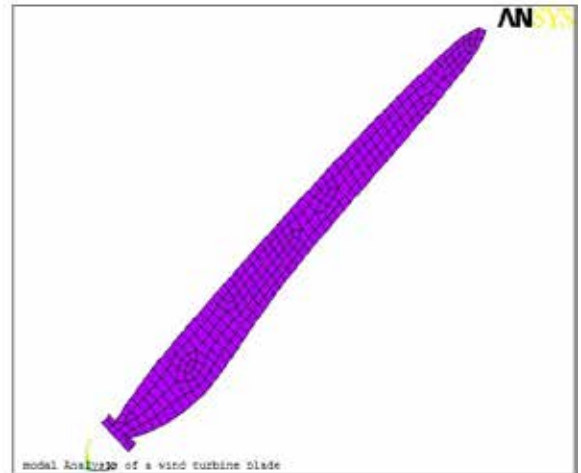


Figure 2: The mesh of a wind turbine blade

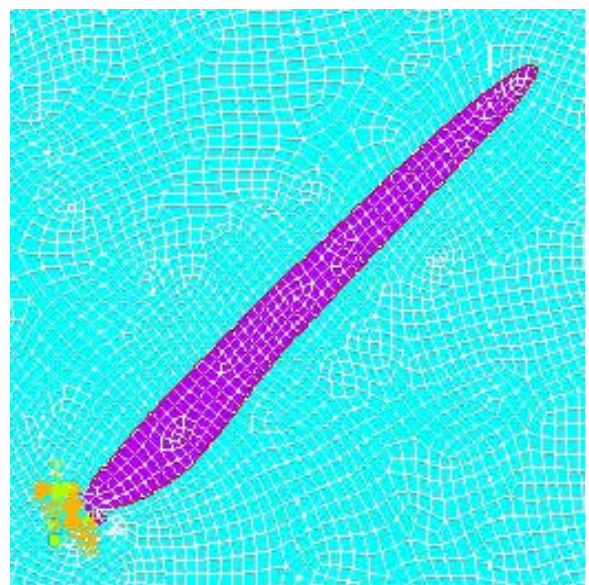


Figure 3: The mesh of a wind turbine blade in air

The performed modal analysis gives estimates of five natural frequencies. The natural frequencies, obtained from the modal analysis, are presented in Table 3.

Deterministic result

Numerical modal analysis has been performed on blade of wind turbine respectively in vacuum and in air, to extract natural frequencies. The performed modal analysis gives estimates of natural frequencies. The results are based on the calculation performed on blade of wind turbine as described above.

Table 1 et 2 give respectively material's properties of the structure and the fluid.

Young's modulus [N/m ²]	Poisson's ratio	Density [Kg.m ⁻³]
3790E6	0.34	2600

Table 1. Material's properties of the structure.

Density [Kg.m ⁻³]	Speed of sound [m.s ⁻¹]
1.3	1100

Table 2. Material's properties of the fluid.

This modal analysis is used to determine the vibration characteristics of a structure or a machine component while it is being designed. It can also serve as a starting point for another, more detailed, dynamic analysis, such as a transient dynamic analysis, a harmonic response analysis, or a spectrum analysis.

The present modal analysis is used to determine the natural frequencies and mode shapes of a structure. The natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions. They are also required if you want to do a spectrum analysis or a mode superposition harmonic or transient analysis. The natural frequencies, obtained from the modal analysis, are presented in Table 3.

Mode	vacuum	Air
1	14.633	14.131
2	17.259	15.932
3	26.530	20.114
4	28.150	21.821
5	36.556	30.465

Table 3. Numerical modal analysis in vacuum and in air.

Probabilistic approach

This part aims to contribute to the discussion of advantages of probabilistic design compared to traditional deterministic design. The focus however will be regarding the beneficial gaining that are associated with probabilistic modelling of vibration of a blade wind turbine compared to a regular deterministic approach using partial safety factors and characteristic values. The deterministic design approach requires great knowledge and a precise description of the blade parameters, which is often a difficult task to determine.

It appears inevitable that the industry, as well as many other industries, will eventually incorporate probabilistic analysis methods to some degree. Probabilistic structural analysis methods, unlike traditional methods, provide a means to quantify the inherent risk of a design and to quantify the sensitivities of design variables.

Monte Carlo simulation is a method that is widely used in probabilistic approaches. MCS is to generate set of random samples. The mechanical model is run for each of these samples. The results obtained are then used to calculate the estimator of the response. Front of the complexity of the problem, we have chosen to consider only the sources of uncertainties related to the material properties and we will be limited to the study of a single blade in air. Table 4 contains the means of random variables used in this study and the distributions laws chosen.

Parameters	Means	Standard deviation	Distribution
Young's modulus [Pa]	3790E6	1895E4	Gaussian
Structure's density	2600	1300	Uniform
Fluid's density	1.3	0.65	Uniform

Table 4. Moments and distribution laws of the parameters.

Table 5 gives the results of deterministic and probabilistic computation for blade of a wind turbine.

Frequencies	Deterministic	Probabilistic
1	14.131	12.146
2	15.932	16.883
3	20.114	22.048
4	21.821	24.999
5	28.710	26.368

Table 5. Means of the frequencies for a blade of wind turbine in air.

Bladesubject of air flow

We can perform multi-physics analyses with a single ANSYS database and single set of nodes and elements for the entire model. What these elements represent are changes from one physics analysis to another, based on the use of the physics environment concept. We use coupled analysis (i.e. the input of one physics analysis depends on the results from another analysis) and a single database with two physics environment; physics environment of fluid and physics environment for structure and also we demonstrate mesh morphing. The program moves nodes and elements of the "field" mesh to coincide with the deformed structural mesh.

The blade is subjected to air flowing with an inlet velocity of 30 m/sec. The object of this part is to determine the pressure drop and blade deflection under steady-state conditions. For this part, we model three regions: (a) the blade, (b) a small fluid region around the blade that requires mesh morphing, and (c) the remaining fluid region. The blade will deform due to the fluid pressure.

The blade will deform due to the fluid pressure. The deflection may be significant enough to affect the flow field. By solving a structural analysis in the structural region, you obtain the blade displacements. We then use the morphed mesh in a subsequent fluid analysis.

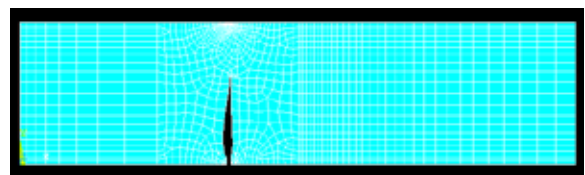


Figure 4: Mesh morphing in the small fluid region around the blade

The fluid-structure solution loop was executed until the convergence criteria were met. In the Fluid Structure interaction loop, the number of iterations was set to 100 for the remaining FLOTRAN runs.

Figure 5 depict the streamlines near the blade for the deformed geometry and figure 6 indicate fluid pressure contours. Qualitatively, the results will look similar for the undeformed (first analysis) and deformed (final analysis) cases.

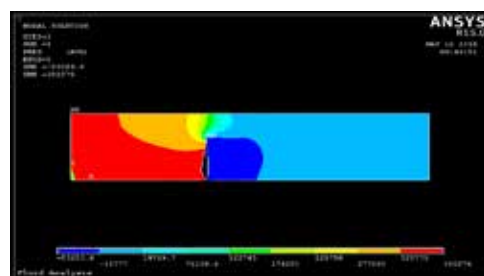


Figure 5: streamlines near the blade for the deformed geometry

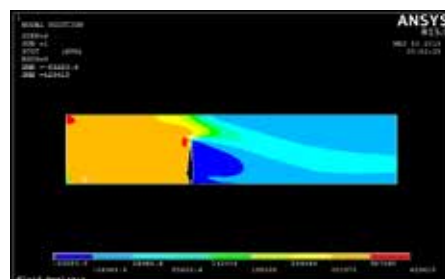


Figure 6: Pressure Contours

Finally, Figure 7 shows the Von Mises stress obtained in the final analysis.

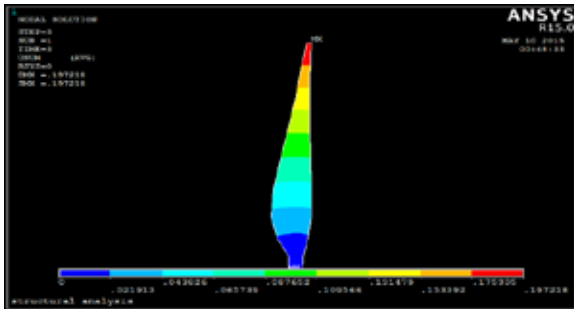


Figure 7: Von-Mises stress in blade.

Conclusion

The kinetic energy extracted from the wind is influenced by the geometry of the rotor blades. Determining eigen-frequencies of a wind turbine blade is an initial step for a more complicated study (e.g. aerodynamics). Where determining the aerodynamically optimum blade shape, or the best possible approximation to it, is one of the main tasks of the wind turbine designer.

The vibration analysis of wind turbine blade was performed using different analysis methodologies including classical deterministic or probabilistic approaches and blade deflection was determined under steady-state conditions. We have presented in this work a numerical modal analysis of a light wind in vacuum and in air, as well as a probabilistic study of the air, followed by another analysis using load transfer coupled physics to determine the blade displacements that you need to morph the small region around the blade.

In these analyses was shown first, a low influence of the air to rest on the blade of wind turbine, subsequently were performed a probabilistic analysis to assess the effect of the mechanical properties distributed randomly on the frequencies of the light wind, finally we present the maximum displacement of blade when is subjected to air flow. These results allow us to, subsequently, move to a possible optimization of the pale of wind turbine study.

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