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ANALYSIS OF VIBRATION OF A VARIABLE BLADE LENGTH WIND TURBINE

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1. Abstract

In this paper, both flap-wise and edge-wise natural frequencies of vibration of a variable blade length wind turbine are calculated. A stepped beam with two portions has been used to approximate the blade. The two portions of the blade have been approximated by a hollow beam and a solid beam with rectangular cross section. As the outboard portion of the blade can be slid in and out of the inboard portion, ten different configurations of the stepped beam have been investigated. A MATLAB program has been developed for a finite element analysis of a one dimensional model of the stepped beam. Subsequently a three dimensional model of the stepped beam has been developed in the finite element program Unigraphics NX4. The results found using the MATLAB program have been compared with those found with NX4 and satisfactory agreement between these results has been found. Additionally, the influence of varying the blade length on the natural frequencies has been investigated.

2. Introduction

In order to attain the highest possible power output in conditions of widely varying wind speed, a variable blade length is proposed. The basic concept of this variable blade length wind turbine is to attain higher energy capture in low wind conditions by increasing the blade length and to minimize mechanical loads in high wind conditions by decreasing the blade length [1]. The wind turbine blade consists of a fixed portion and a moveable blade portion which can be slid inside the fixed portion.

Structural vibration problems present a major hazard and design limitation for a very wide range of engineering products. Vibration is important in wind turbines, because they are partially elastic structures, and they operate in an unsteady environment that tends to result in a vibrating response. The amplitude of the generated vibrations of a wind turbine blade depends on its stiffness [2]. One of the issues the variable blade length design presents to blade designers is that of structural dynamics. A wind turbine blade has certain characteristic natural frequencies and mode shapes which can be excited by mechanical or aerodynamic forces. This variable blade length design presents additional challenges because the stiffness and mass distribution change as the moveable blade portion slides in and out of the fixed blade portion.

Manufacturers of wind turbines are interested in studying and verifying both edge-wise and flap-wise vibrations (see Fig.1 below) of the turbine blade. The most visible and present source of excitation in a wind turbine system is the rotor.

- The constant rotational speed is the first excitation frequency, mostly referred to as 1P.
- The second excitation frequency is the rotor blade passing frequency: N_bP in which N_b is the number of rotor blades: 2P for a turbine equipped with two rotor blades, 3P for a three bladed rotor, etc

The structure should be designed such that its natural frequencies do not coincide with either 1P or N_bP. Otherwise a resonance may occur in the whole structure of the turbine, leading to vibrations with increasing amplitude which may eventually destroy the whole wind turbine [3].

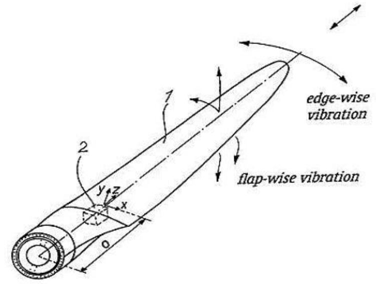


Fig.1 Edge-wise and flap-wise vibrations of the blade [4]

Dynamic analysis can be used to analyse and avoid the resonant vibration behaviour. Generally, research on the turbine blades focus on vibration frequencies and mode shapes. For simplification, a cantilevered beam can be used to replace the turbine blade [5]. Knowing the geometric shape and the material properties of the blade, the natural frequencies can be estimated using finite element analysis.

The purpose of the present study is to calculate both flap-wise and edge-wise natural frequencies for ten configurations of a stepped beam which represent the blade with its outboard portion in ten different positions. In this way, the influence of varying blade length on the natural frequencies has been investigated.

3. Methods

The fixed portion and the moveable portion of the variable blade length wind turbine have been approximated respectively by a hollow beam and a solid beam which can be slid in and out as shown in Fig.2.

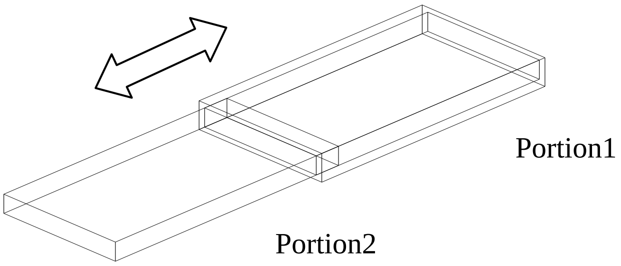


Fig.2 Stepped beam

The ten different configurations depending on the position of the second portion of the stepped beam are represented below.

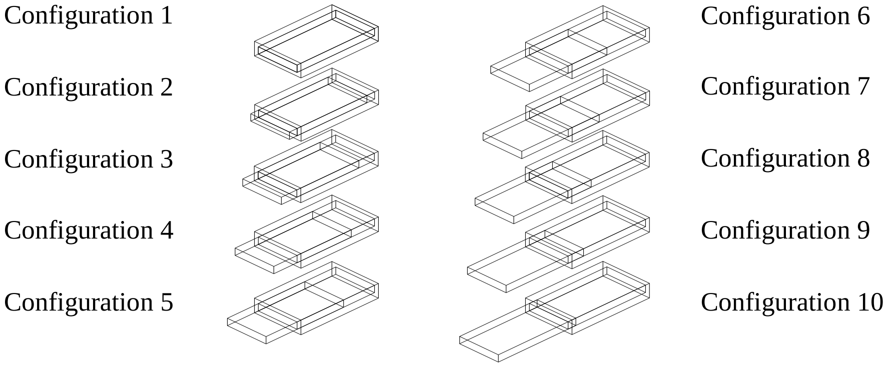


Fig.3 Ten configurations of stepped beam

Finite Element Analysis

In free vibration analysis, no loads are applied. The goal of the analysis is to determine at what frequencies a structure will vibrate if it is excited by a load that is applied suddenly and then removed. These frequencies are called natural frequencies and they are dependent on the fundamental characteristics of the structure, such as geometry, density and stiffness. These same characteristics can be included in a finite element model of a structural component. The finite element model can be used to determine the natural modes of vibration and corresponding frequencies. Once the geometry, density, and elastic material models have been defined for the finite element model, in the absence of damping, the dynamic character of the model can be expressed in matrix form as [6]:

$$[\mathrm{K}]\,\{u_i\} = \omega_i^2\,[\mathrm{M}]\,\{u_i\} \qquad (1)$$

Here [K] is the stiffness matrix, [M] is the mass matrix, ω_i is the natural frequency of vibration for a given mode and $\{u_i\}$ is the mode vector that expresses the corresponding mode shape. A finite element program uses iterative techniques to determine a set of frequencies and shapes that satisfy the finite element matrix equation.

MATLAB

A MATLAB program has been developed for a one dimensional model for the stepped beam. The geometry, material properties, vibration modes (flap-wise or edge-wise), number of elements and configuration of the stepped beam have been made as selectable parameters which allow us to analyse blades with different sizes and properties. Both flap-wise and edge-wise natural frequencies have been calculated for the ten different configurations.

NX4

A three dimensional model of a stepped beam has been developed in the commercial finite element analysis program Unigraphics NX4. This model is designed to capture three-dimensional behaviour. The blade has been modelled as a cantilever, therefore it is fully constrained at the end of the inboard portion (where it is attached to the turbine shaft/hub). The outputs of the simulation are the natural frequencies of vibration: the flap-wise, edge-wise and torsional natural frequencies as well as their mode shapes.

4. Results

Values of the material and geometric properties of the two portion stepped beam under investigation are given in Table 1.

Table 1 Material and geometric properties of the stepped beam

	Geometric properties				Material properties (Carbon fiber composite) [7]	
	L(mm)	W(mm)	T(mm)	Wh(mm)	E(mN/mm^2)	ρ (kg/mm^3)
Portion1	1000	60	20	5	230×10^{6}	1.8×10^{-6}
Portion2	1000	50	10	N/A	230×10^{6}	1.8×10^{-6}

L: length

W: width

T: thickness

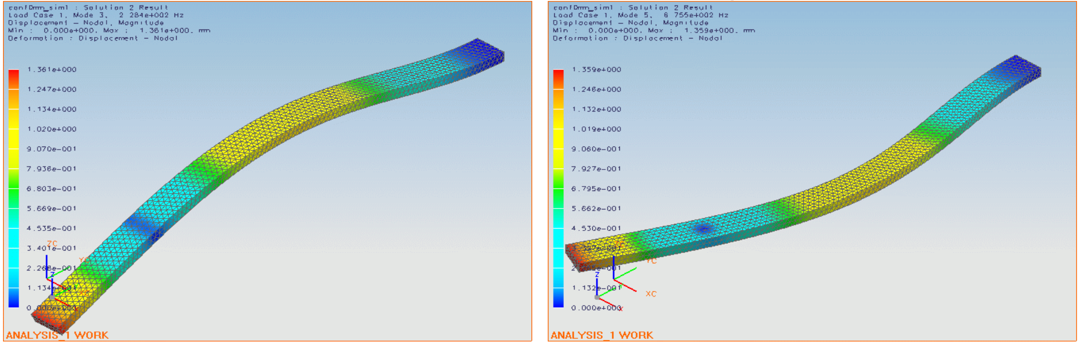
Wh: wall thickness

E: Young’s modulus

ρ : density

- NX4 results

This section contains examples of the results obtained with NX4 for three different configurations of the stepped beam. The flap-wise, edge-wise and torsional deflections are represented.


Mode 3 (Flap-wise)

Mode 5 (Edge-wise)

Mode 6 (Torsional)

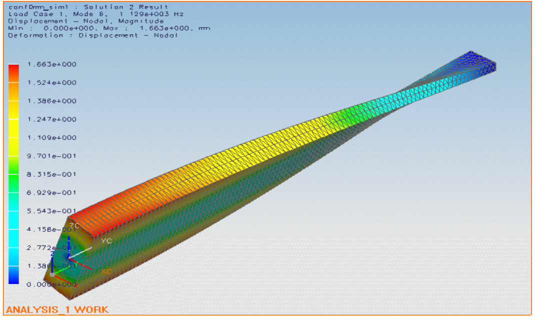
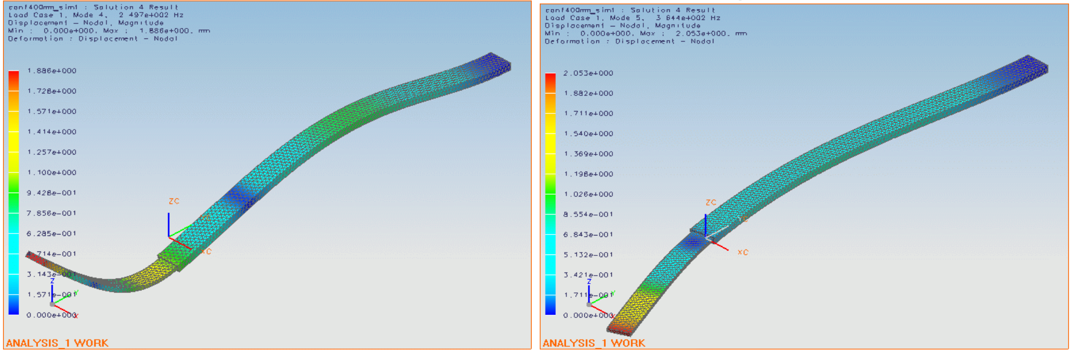


Fig.4 Flap-wise, edge-wise and torsional deflection for configuration1


Mode 4 (Flap-wise)

Mode 5 (Edge-wise)

Mode 9 (Torsional)

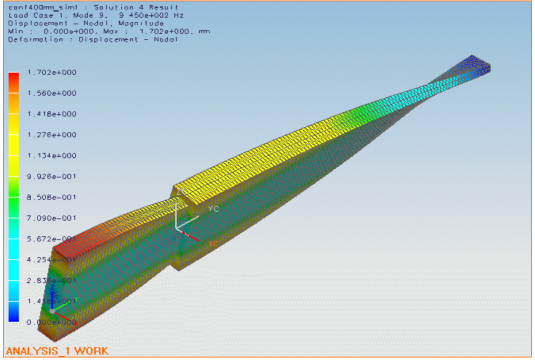
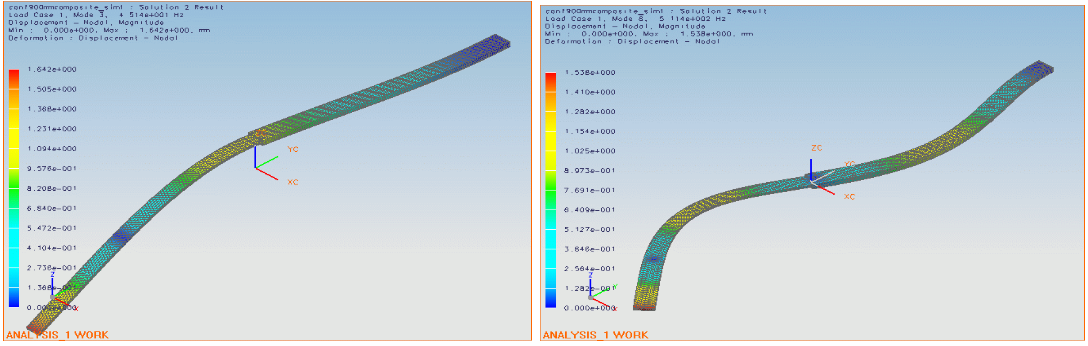


Fig.5 Flap-wise, edge-wise and torsional deflection for configuration5

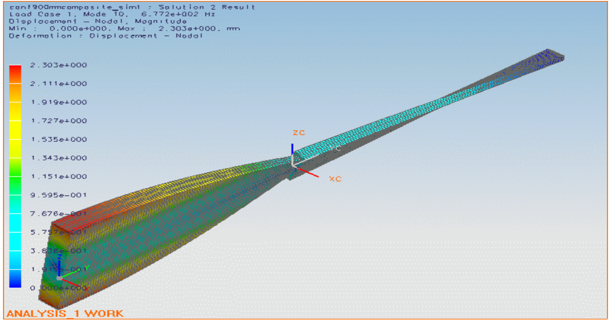


Mode 3 (Flap-wise)

```
conf900mmcomposite_sim1 : Solution 2 Result
Load Case 1, Mode 3,  4 514e+001 Hz
Displacement - Nodal, Magnitude
Min :  0.000e+000, Max :  1.642e+000, mm
Deformation : Displacement - Nodal
```

Mode 8 (Edge-wise)

```
conf900mmcomposite_sim1 : Solution 2 Result
Load Case 1, Mode 8,  5 114e+002 Hz
Displacement - Nodal, Magnitude
Min :  0.000e+000, Max :  1.538e+000, mm
Deformation : Displacement - Nodal
```



Mode 10 (Torsional)

```
conf900mmcomposite_sim1 : Solution 2 Result
Load Case 1, Mode 10,  6.772e+002 Hz
Displacement - Nodal, Magnitude
Min :  0.000e+000, Max :  2.303e+000, mm
Deformation : Displacement - Nodal
```

Fig.6 Flap-wise, Edge-wise and Torsional deflection for configuration10

- NX4 & MATLAB results comparison

In this section, we compare the results found using the MATLAB program and NX4. The first nine natural frequencies (flap-wise and edge-wise) of the stepped beam are calculated successively for three different configurations. Torsional natural frequencies obtained with NX4 have been ignored due to the fact that the MATLAB program can only calculate flap-wise and edge-wise natural frequencies.

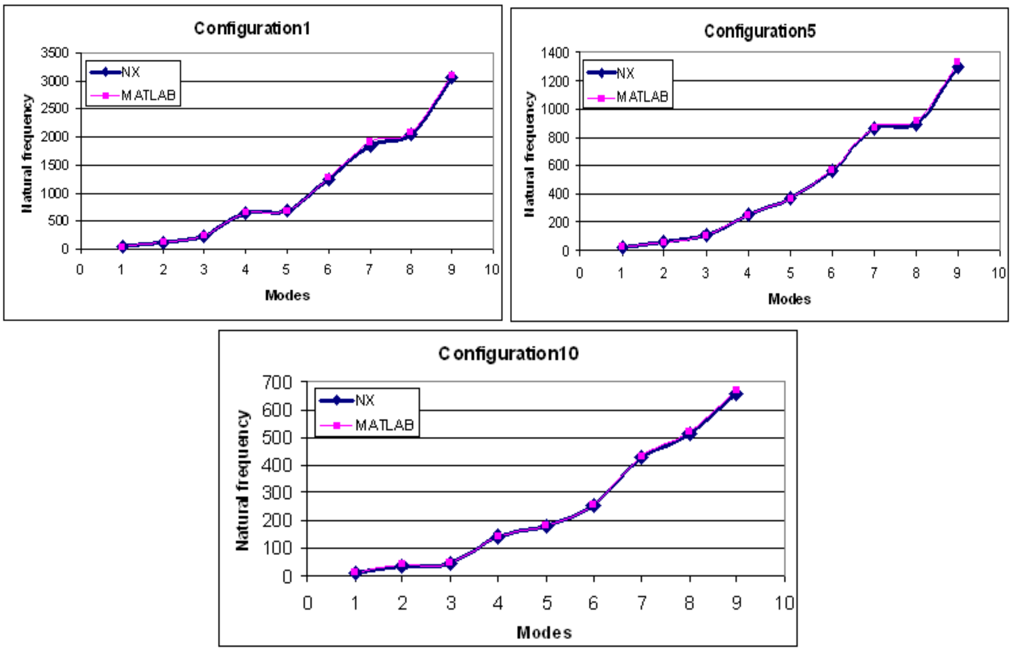


Fig.7 MATLAB and NX4 results comparison

- Influence of blade length variation

The influence of varying the blade length has been studied and the results are shown in Fig.8 for the first five natural frequencies related to the configurations of the stepped beam. Table 2 provides values of these five first natural frequencies calculated for each configuration of the stepped beam shown in Fig. 3.

Table 2. Computed natural frequencies (NX4)

Configuration number	Computed natural frequencies (Hz)				
	Mode1	Mode2	Mode3	Mode4	Mode5
1	36.5	109	228	638	675
2	32.8	93.8	203	556	586
3	29.4	82.1	174	421	510
4	26.4	72.6	140	301	435
5	23.6	64.6	107	249	364
6	21.0	57.7	83.5	224	305
7	18.6	51.7	67.6	205	259
8	16.4	46.5	57.0	184	224
9	14.5	41.8	49.9	162	198
10	12.7	37.7	45.1	141	178

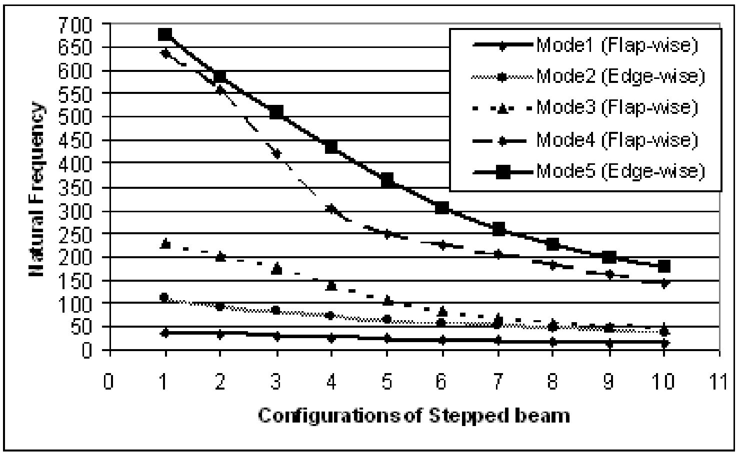


Fig.8 Natural frequencies

5. Discussion

During design of a wind turbine blade, the 1st flap-wise, 2nd flap-wise, 1st edge-wise and the 1st torsional natural frequencies shall be determined as a minimum [8]. It can be seen (Fig.7) that there is good agreement between the MATLAB and NX4 results for the first nine natural frequencies

- in configuration1 : natural frequency ≤ 3000 Hz
- in configuration5 : natural frequency ≤ 1300 Hz
- in configuration10 : natural frequency ≤ 650 Hz

It should be noted that only the frequency range between 0.5 Hz and 30 Hz is of relevance to wind turbine blades. In that range, the MATLAB and NX4 give the same results. Torsional natural frequencies have been calculated using NX4. The lowest torsional natural frequency (configuration10) determined is 677 Hz.

The study of influence of blade length on natural frequencies represented in Fig.8 has shown that with increasing the blade length, the natural frequency decreases. This is probably due to the fact that the blade becomes more flexible as its length increases. The excitation loads are concentrated in the interval 0.5 Hz-30 Hz. The natural frequencies included in the interval 12.7 Hz-36.5 Hz may coincide with these excitation frequencies. Therefore the first mode may be subjected to excitation.

Finite element analysis has been used as a preliminary computational tool to precede an experimental modal analysis. As future work, experimental modal analysis will be performed on the blades being designed by a colleague. The experimental results will be compared with those obtained from the finite element analysis.

6. Conclusions

- Good agreement between results obtained with one dimensional model (MATLAB) and three dimensional model (NX4) has been found at lower frequencies, especially in the band of interest.
- Results found in table 2 have shown that natural frequencies are function of configuration number.
- Increasing blade length reduces the natural frequencies.
- The excitation energy is concentrated in the frequency band of interest, typically in a range between 0.5 Hz to 30 Hz. Therefore, the first mode (flap-wise natural frequency) may coincide with a forcing frequency.
- The model includes some approximation. The result shows that further research with a more accurate model is needed.

7. References

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