INVESTIGATIONS ON VIBRATION CHARACTERISTICS OF SMA EMBEDDED HORIZONTAL AXIS WIND TURBINE BLADE

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Abstract. Vibration induced in wind turbine blade is a solemn problem as it reduces the life of the blade and also it can create critical vibration onto the tower, which may cause serious damage to the tower. The aim of this paper is to investigate the vibration characteristics of the prototype horizontal axis wind turbine blade. Shape memory alloys (SMA), with its variable physical properties, provides an alternative actuating mechanism. Heating an SMA causes a change in the elastic modulus of the material and hence SMAs are used as a damping material. A prototype blade with S1223 profile has been manufactured and the natural frequency is found. The natural frequency is found by incorporating the single SMA wire of 0.5mm diameter over the surface of the blade for a length of 240 mm. Similarly, number of SMA wires over the blade is increased up to 3 and the natural frequency is found. Frequency responses showed that the embedment of SMA over the blade’s surface will increase the natural frequency and reduce the amplitude of vibration. This is because of super elastic nature of SMA. In this paper, when SMA wire of 0.5 mm diameter and of length of 720 mm is embedded on the blade, an increase in the natural frequency by 6.3% and reducing the amplitude by 64.8%. Results of the experimental modal and harmonic indicates the effectiveness of SMA as a passive vibration absorber and that it has potential as a modest and high-performance method for controlling vibration of the blade.

1. Introduction

Growth in domestic wind turbine system is clogged due to the pro-dominant noise and maintenance issues. The noise is caused due to the blade resonating at the flapwise mode of vibration of the blade. Noteworthy research has previously been carried out on determining the dynamic behaviour of wind turbine blades. Rauh and Peinke [1] studied the dynamic model of the wind turbine system.

Domestic wind turbine system has low blade length and radius, hence the edgewise vibration is considered to be negligible [2]. Sutherland [3] summarised the effect of using different materials in wind turbine blades and their fatigue properties. In order to increase the flexibility of the wind turbine system, the research carried out by Ahlstrom [4], suggested that there is a significant reduction in power production, with increase in flexibility of the wind turbine blade. Myriad of research has been performed on the fatigue properties and material selection of the wind turbine system [5-7].

Ronold and Larsen [8] studied the failure of a wind turbine blade in flapwise bending during normal operating conditions of the turbine. Murtagh and Basu [9] studied the influence of flapwise motion of wind turbine blades and their dynamic interaction with the tower in causing disastrous damage to the turbine system. They found that inclusion of the blade–tower interaction could lead to significant increases in the maximum blade tip displacement. A detailed study has to be performed on the usage

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of dampers in the blades to control the flapwise vibration induced dynamic behaviour of the system. Hence, the aim of this paper is to investigate the effectiveness of Shape Memory Alloys (SMA) in the vibration control of wind turbine blades. Investigation into the natural frequencies of rotating blades is also considered for different rotational speeds.

2. The Shape Memory Alloy and Vibration Control

Shape-memory alloys (SMAs) exhibit shape-memory effect and super elasticity, which are effective for usage in active vibration control system and tuneable dampers. Liang and Rogers [10-12] summarised the description on working of the SMA and the elastic properties of the SMA. In this study, the SMA Nitinol is opted to analyse the influence of shape memory effect in vibration control of wind turbine blades. Based on the increase in temperature, the crystal structure of SMA varies from martensite to austenite. At low temperature, i.e, in martensite state, the material has low elastic modulus and yield strength compared to the austenite state at higher temperature. The material stiffens with increase in temperature and the compressive stress thus produced can be used for actuation in active vibration control. The monograph on SMA, studied by Hodgson [13], provides elastic moduli at various crystal state of Nitinol. These values are shown in table 1, as given by Beer and Johnston [14]. SMA materials have been used in vibration control applications. Bazet al. [15] described the use of SMA actuators to achieve active control of the first mode of flexible beam. Liang and Rogers explored two different techniques for the SMA in vibration control [16, 17]. The first was active properties tuning (APT), where the change in the elastic modulus of SMA with heating was used to modify the dynamic characteristics of a composite plate in which the SMA wires had been embedded. This investigation on the effect of SMA in vibration control ensures development and testing of SMA based tuned vibration absorber.

Table 1. Elastic moduli of Nitinol

| Nitinol    | Elastic modulus (GPa) | Density (kgm$^{-3}$) | Poisson ratio |
|------------|-----------------------|----------------------|--------------|
|            | Martensite 28-41       | 6450                 | 0.33         |
|            | Austenite 83           |                      |              |

3. Selection of Blade Profile

Maximum lift force and minimum drag force are considered to be the parameter for an effective wind turbine blade. Hence, it is very significant to design our airfoil at an optimum angle of attack so that the $C_D/C_L$ ratio is the minimum. Geometric features of an effective airfoil are shown in figure 1.

![Figure 1. Important parameters of an airfoil](image)

In order to select the optimum airfoil section, three different airfoils NACA 0012, S809 & S1223 blade sections are chosen for the analysis. CFD analysis is performed on NACA 0012, S809 & S1223 blade sections for different angle of attacks for the chord length of 100 mm. Comparison of lift...
coefficients between NACA 0012, S809 & S1223 profiles for different angle of attack are shown in figure 2.

![Figure 2. Comparison of lift coefficient between NACA 0012, S809 & S1223 blade sections](image)

From the figure 2, it is clear that S1223 section is able to produce more lift coefficient than that of S809 and NACA 0012 sections. Comparison of lift and drag coefficients between NACA 0012, S809 & S1223 profiles for different angle of attack are shown in figure 3. The drag to lift ratio is an important parameter in measuring the airfoil performance which is depicted in figure 4.

![Figure 3. Comparison of lift coefficient between NACA 0012, S809 & S1223 blade sections](image)

![Figure 4. Variation of $C_d/C_L$ ratio with respect to at angle of attack ($\alpha$)](image)
When $C_D/C_L$ ratio is low it shows the lift coefficient has very high value. From figure 4 it is clear that $C_D/C_L$ ratio is low when angle of attack ($\alpha$) is 10º. Hence, it can be concluded that S1223 airfoil section is able to generate higher lift force than S809 and NACA 0012 airfoil sections, with an optimum angle of attack of 10º.

4. CFD Analysis for S1223 Profile

CFD analysis is performed on S1223 airfoil profile for the tip chord length of 10mm in order to analyse the flow phenomenon around the airfoil body and to calculate the lift and drag coefficients at laminar conditions with a 10º angle of attack [18]. The simulations were computed in the software ANSYS 15. Following formulas are used for analytical calculation and results are tabulated in table 2.

\[
\begin{align*}
\text{Drag force } F_D &= 0.5(C_D \rho AV^2) \\
\text{Lift force } F_L &= 0.5(C_L \rho AV^2) \\
\text{Total translational force } F_T &= (F_D^2 + F_L^2)^{0.5}
\end{align*}
\]

**Table 2.** Translation force for various velocity of wind

| Velocity (ms\(^{-1}\)) | Max velocity (ms\(^{-1}\)) | Pressure (MPa) | Co efficient of drag ($C_D$) | Co efficient of lift ($C_L$) | Drag force ($F_D$) (N) | Lift force ($F_L$) (N) | Total Translational Force ($F_T$) (N) |
|------------------------|-----------------------------|----------------|-----------------------------|-----------------------------|------------------------|------------------------|----------------------------------|
| 4                      | 6.2                         | 19.71          | 0.0219                      | 0.0572                      | 0.0009                 | 0.0025                 | 0.0026                           |
| 5                      | 7.55                        | 27.58          | 0.0301                      | 0.1646                      | 0.002                  | 0.0113                 | 0.0114                           |
| 6                      | 9.26                        | 39.8           | 0.0433                      | 0.2247                      | 0.0043                 | 0.0223                 | 0.0227                           |
| 7                      | 10.81                       | 52.2           | 0.0558                      | 0.3199                      | 0.0075                 | 0.0433                 | 0.0439                           |
| 8                      | 12.35                       | 66.01          | 0.0695                      | 0.4337                      | 0.0122                 | 0.0767                 | 0.0776                           |
| 9                      | 13.9                        | 81.55          | 0.0843                      | 0.5662                      | 0.0188                 | 0.1268                 | 0.1281                           |
| 10                     | 15.45                       | 98.47          | 0.1                         | 0.718                       | 0.0276                 | 0.1985                 | 0.2004                           |
| 11                     | 17                          | 116.88         | 0.1167                      | 0.8889                      | 0.039                  | 0.2973                 | 0.2998                           |
| 12                     | 18.59                       | 136.42         | 0.1346                      | 1.1052                      | 0.0535                 | 0.44                   | 0.4432                           |
| 13                     | 20.13                       | 158.11         | 0.1527                      | 1.2904                      | 0.0713                 | 0.6029                 | 0.6071                           |
| 14                     | 21.7                        | 180.91         | 0.1719                      | 1.5213                      | 0.0931                 | 0.8243                 | 0.8295                           |
| 15                     | 23.27                       | 205.18         | 0.1919                      | 1.7728                      | 0.1193                 | 1.1028                 | 1.1092                           |

The section lift coefficient, drag coefficient and deflection of tip of the blade for S1223 airfoil are obtained by analysing the measured pressure distribution on the airfoil surface and analytical formulas for the wind velocity varying from 4 ms\(^{-1}\) to 15 ms\(^{-1}\) which is shown in table 2.

5. Prototype blade development

For predicting the vibration characteristics of actual wind turbine blade, before actually manufacturing, prototype of the blade is manufactured with scaled down model of 1:10 as shown in figure 5 and tests are performed on it to obtain the desired information. The prototype blade is manufactured in such a way that it has geometric similarity, kinematic similarity and dynamic similarity with actual wind turbine blade.
Material and shape of the rotor blade are the key design aspects. The selected material should be stiff, strong, and light. Glass fibres for composites have a good combination of properties: moderate stiffness, high strength, and moderate density. Hence blade is made up of Glass fibre reinforced plastics (GFRP) material with S1223 profile for the length of 240 mm.

6. Modal analysis of a single blade
In order to control the vibration amplitude of the blade, it is necessary to determine the natural frequency of the blade. Modal analysis has been conducted for a single blade experimentally and the numerical model is validated using the experimental results.

6.1. Experimental modal analysis
In order to determine the natural frequency of the blade experimentally, a uniaxial accelerometer of 10.22 mV/g sensitivity, DAQ and PC with interfacing software are connected as shown in figure 6.

Initial disturbances are given by impact hammer and 5 samples of Frequency Response Functions (FRF) are taken by fixing the accelerometers at tip of the blade, middle of the blade and root of the blade. The FRF curve obtained from experimental modal analysis is shown in figure 7.
From the FRF it is found that the first natural frequency of the single blade is obtained as 67 Hz. In order to find out effect of SMA, 0.5 mm diameter SMA wire is kept over the surface of the blade for the length of 240 mm and clamped rigidly by means of transparent duct tape such a way that SMA wire and blade will act as a single spring mass system. A uniaxial accelerometer of 10.22 mV/g sensitivity, DAQ and PC, with interfacing software are connected as shown in figure 8. Similarly, FRFs are taken for 2 SMA wires and 3 SMA wires.

It will be convenient to understand the behaviour of the system considering volume fraction to be a design parameter.

Volume of SMA wire (0.5 mm diameter and 240 mm length) = 47.12 mm$^3$
Volume of prototype blade (From numerical analysis) = 26480 mm$^3$
Volume fraction when 1 SMA wire is embedded = 0.00274
Volume fraction when 2 SMA wire is embedded = 0.00542
Volume fraction when 3 SMA wire is embedded = 0.00822

The FRFs obtained for the different volume fractions are shown in figure 9.
Figure 9. Frequency response of the blade for different volume fractions

From the figure 9, with increase in volume fraction, the increase in natural frequency of the system can be visualised. In order to identify the influence of SMA wires over the damping ratio displacement response is taken which is shown figure 10.

Figure 10. Displacement response

From the displacement response which is shown in figure 10, damping ratio ($\varepsilon$) has been found out for different volume fractions of SMA and values are tabulated in table 3.

| Volume fraction of SMA wire | Frequency (Hz) | % increase of frequency | Damping ratio ($\varepsilon$) |
|----------------------------|----------------|-------------------------|-------------------------------|
| 0                          | 67.07          | -                       | 0.0100                        |
| 0.00274                    | 68.26          | 1.774                   | 0.0145                        |
| 0.00542                    | 70.31          | 4.83                    | 0.0162                        |
| 0.00822                    | 71.68          | 6.873                   | 0.0202                        |
From the table 3, it is clear that when volume fraction of SMA increases, the natural frequency and damping capacity of the system increases. This result shows that SMA can be used as good structural damper.

6.2. **Numerical modal analysis**
In order to verify the experimental values, the 3-D solid blades are modeled and modal analysis is performed in ANSYS 15.0. Three dimensional solid blade with S1223 profile is shown in figure 11.

![Figure 11. Three Dimensional solid blade](image)

The material properties of the blade are given as mentioned in table 4.

| Name          | Blade | Material  |
|---------------|-------|-----------|
| General       |       | GFRP      |
| Mass density  |       | 1992.95 kgm$^{-3}$ |
| Yield strength|       | 299.991 MPa  |
| Ultimate tensile strength | | 480.013 MPa  |
| Young's Modulus|     | 34.4117 GPa |
| Poisson's ratio|    | 0.22      |
| Stress        |       | Shear modulus | 14.1032 GPa |

Since the first bending mode plays a crucial role in generating flapwise vibration of the blade, first natural frequency and first bending mode shapes are noted down and is shown in figure 12.

![Figure 12 First mode shape of the blade](image)
Table 5. Comparison of Numerical and Experimental Results

| Volume fraction of SMA wire | Frequency by experimental (Hz) | Frequency by numerical (Hz) | % deviation |
|---------------------------|-------------------------------|----------------------------|-------------|
| 0                         | 67.07                         | 72.93                      | 8.856       |
| 0.00274                   | 68.26                         | 73.26                      | 7.326       |
| 0.00542                   | 70.31                         | 74.21                      | 5.544       |
| 0.00822                   | 71.68                         | 75.76                      | 5.697       |

Table 5 shows a good agreement between experimental and numerical methods with less than 9% deviation.

7. Harmonic analysis
Harmonic analysis is performed to find out effectiveness of amplitude reduction when SMA wire is embedded and the non-dimensionalised amplitude parameter are shown in figure 13 and table 6.

![Figure 13. Comparison of Harmonic Response](image)

Table 6. Reduction depicted in Harmonic Analysis

| Volume fraction of SMA wire | Frequency by numerical (Hz) | % reduction of amplitude at blade’s natural frequency 72 Hz | Maximum amplitude ratio |
|---------------------------|----------------------------|----------------------------------------------------------|-------------------------|
| 0                         | 72.93                      | -                                                        | 8.649                   |
| 0.00274                   | 73.26                      | 41.8                                                     | 5.009                   |
| 0.00542                   | 74.21                      | 47.51                                                    | 4.539                   |
| 0.00822                   | 75.76                      | 68.87                                                    | 2.6918                  |

8. Conclusions
In order to demonstrate the use of smart materials, such as SMA in altering the blade stiffness properties, SMA wires are embedded over the composite blade. The natural frequency changes due to increase of blade’s stiffness properties and a significant increase in the damping property of the blade, after embedding the SMA wires is evident through experimental investigations as reported. There is a noticeable increase in the natural frequency of the composite blade due to embedment of SMA wires, and this strategy has a potential for horizontal axis wind turbine blade vibration control. The actuation provided by the SMA wire could be used for active vibration control, as the excitation frequency is random. SMA wire embedded wind turbine blade could provide excellent damping and provide way for active vibration control of small wind turbine system.
9. References

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