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Investigation on the dynamic properties of propeller structure with different number of blades

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Abstract A propeller is mainly used for propelling the movement for an aircraft or ship. As it gives major contribution towards the performance of an aircraft or ship, study on propeller structure has become popular. In this study, the dynamic or modal characteristics of propeller structure with different number of blade of the same design are investigated. Modal properties of two blades, three blades and four blades propeller that are obtained through computational analysis are compared after validation of three blades propeller is conducted. It has been observed that the four blades propeller has the lowest nominal value of natural frequencies and shows most mode shapes deflection. The results confirm that as the propeller has more number of blades, it will produce more energy and hence has lower natural frequency.

1. Introduction

A propeller is a structure equipped with a rotating fan, which is used to propel a ship or a plane by generating thrust force from a power transmitted by the main engine. As the structure plays an important role in deciding the performance of modern ships and planes, topic of propeller design and performance has become a perennial subject of research. Most of the researches are focusing on the how the design of propeller blade can affect the performance of the propeller in creating thrust for more powerful movement [1–7]. For example, the study on several different configuration of propeller blades were conducted and the pressure field and thrust created from the propeller were analysed.

On the other hand, it has also been discussed that the dynamic behaviour of the blades may cause dangerous phenomenon such as resonance to the whole propelling system [5]. Generally, study of vibration on structure has always been an important topic of research as knowledge on the dynamic characteristic of a structure contributes to better structural design process. Specifically, for propeller structure, resonance may occur if the operating frequency of the propeller match its natural frequency. It also has been mentioned by reference [8] that propeller induces a pressure field due to the rotation movement and the thrust generated by the blades. Propeller also may be exposed to unstable vibration at a certain rotation speed as energy is absorbed from its surrounding [9]. Therefore, it is crucial to understand the effect of blades on the propeller towards the modal characteristics of the propeller.

Moreover, in practical application for designing propeller for airplane, modal properties of the propeller are crucial knowledge because of safety issues [10-11].

Consequently, there are studies that presented the analysis of propeller's modal properties under several approach. For example, the modal behaviour of propeller structure under different medium was investigated [12]. Hong et.al compared the free vibration characteristics of a marine propeller in air and water, and the influence of fluid inertial effect on the propeller was analysed. A study on modal characteristics of propeller blades of different material (metal and composites) was also investigated [13]. Other study on propeller structure that also concern the materials and damping element toward the modal characteristics of the propeller was also conducted by Morad et.al [14].

However, when concerning the effect of number of blades on propeller towards the performance of propeller, very little study was conducted. The study by Wang et.al shows how same number of blades with different skew angle contributes to the wake propelled by the propeller [7]. Similarly, study by Felli et.al. compares how different number of blades contributes towards the wake propulsion [15]. The subject of choosing number of blades on propeller mostly changed based on the design requirement of the propeller itself as there are many parameters that need to be considered as well.

This paper will provide the analysis and comparison of the modal properties of a propeller structure with different number of blades. The design of blades in terms of size and skew for each propeller remains constant.

2. Validation of modal properties of three blades propeller structure

2.1. Finite element analysis on three blades propeller structure

Initially, the propeller blade structure was modelled in SolidWorks software (see Figure 1) before being imported into a finite element analysis software (see Figure 2). Analytical frequency analysis was performed using MSC. Nastran/Patran software by utilizing the SOL103 which is the normal mode analysis. Finite element model of the propeller blade structure was created using 8-node tetrahedral elements which were selected during the meshing process. Isotropic material properties of steel were assigned to the model. The nominal values of the assigned material properties on the structure are as follows; Young's Modulus is 69 GPa, density is 2800 kg/m^3, and Poisson's ration is 0.3. No constraints were applied to the model which means the analysis was conducted under free-free boundary condition. The frequency range of interest was set between 10 Hz to 8000 Hz in order to avoid the calculation of rigid body modes during the analysis. In this study also, only first six modes were observed and analysed.

Figure 1. CAD model of three blades propeller structure.

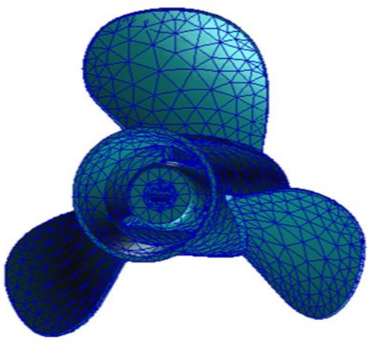


Figure 2. FE model of three blades propeller structure.

2.2. Experimental modal analysis on three blades propeller structure

Modal testing on the three blades propeller structure was conducted using impact hammer testing. One tri-axial accelerometer was used during the testing. The impact hammer test was performed by roving accelerometer method where the accelerometer was roved around to all measurement point while providing excitation on one single point only using an impact hammer [16]. The three blades propeller structure was labelled with 36 measurement points. The experimental model was sketch in a wire-frame model for the purpose of displaying the response collected by the structure at each of the measurement point during the testing (see Figure 3).The structure was placed in hanging position as shown in Figure 4 in order to portray the free-free boundary condition that was set during computational analysis [17].

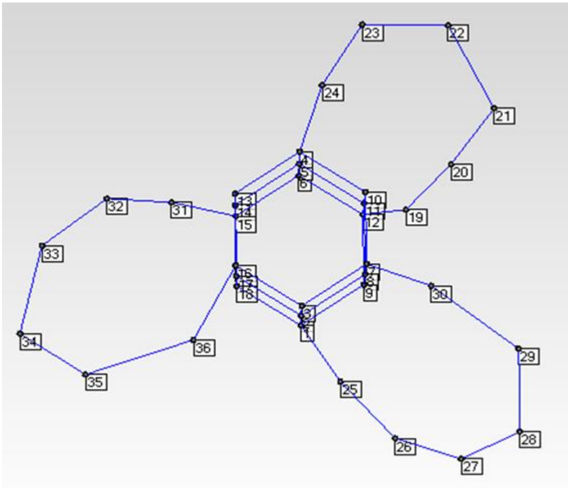


Figure 3. Experimental model of the three blades propeller.

Figure 4. Three blades propeller hanging from test rig.

2.3. Correlation of natural frequencies of three blades propeller structure

Correlation of the output gathered in both analysis (experiments and analytical) intends to validate the data obtained through computational analysis. This is owing to the reason that data obtained through computational analysis is based from assumption and need to be validated experimentally before trusting its reliability for providing accurate results [18]. Figure 5 provides the curve of natural frequencies of the three blades propeller structure for the first six modes, that are obtained through impact hammer test (experimental) and normal mode analysis (analytical/computational). Based on the figure, the values of natural frequency obtained computationally are well correlated with the values obtained during experimental works. It is clearly shown that in most modes such as 2nd, 3rd, and 4th mode, the values of natural frequency are very well correlated and shows almost no error. Therefore, the model of the three blades propeller structure is considered as validated and reliable enough for further prediction analysis.

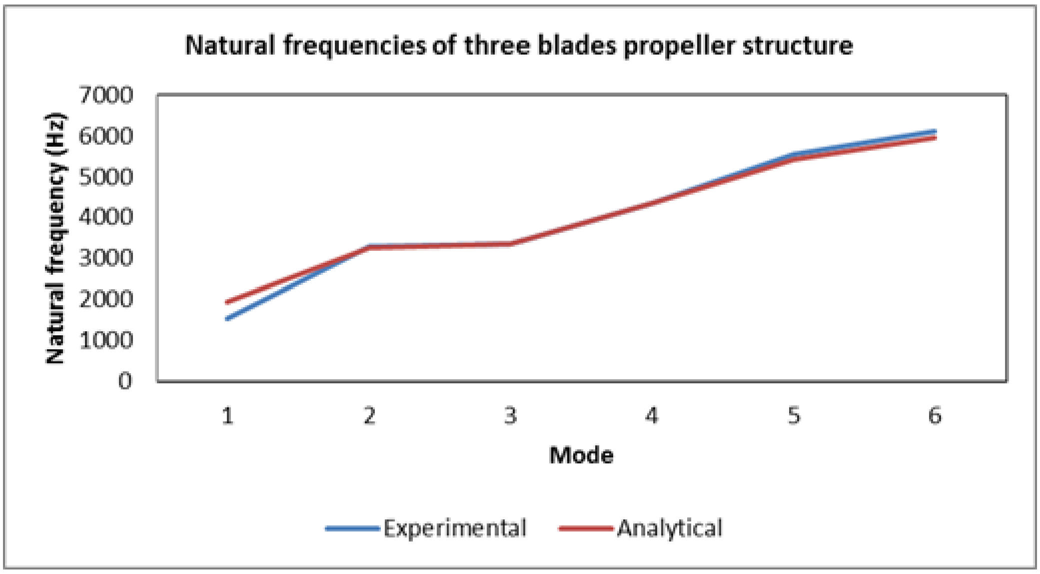


Figure 5. Correlation of natural frequencies obtained through experimental and computational analysis of the three blades propeller structure.

3. Computational modal analysis on propeller structure with different number of blades

Normal mode analysis was performed on the model of three propellers with different number of blades (2 blades, 3 blades and 4 blades) of the same design as shown in Figure 6. The set up for analysis for all three models of propeller were the same with the one conducted for the three blades propeller as described in previous section. The data for material properties remains unchanged as well as the boundary condition and the mode of interest.

The nominal value of the first six natural frequencies for propeller of different blade number is as shown in Table 1. The computational data presented in Table 1 indicates that when propeller has lower number of blade, the natural frequencies of the propeller is significantly higher. Figure 7 shows the natural frequencies curve for propeller models with different blade number. It shows that the two blades propeller has higher value of natural frequencies in each mode. This is owing to the reason that more number of blades contribute to more mass to the propeller structure, and therefore decrease its frequency.

On the other hand, the mode shapes of the first six natural frequencies for two blades, three blades and four blades propeller is tabulated in Table 2, Table 3 and Table4 respectively. Understanding the mode shapes is important in order to understand the behaviour of the propeller under resonance. Therefore, enhancement such as stiffeners may be added in order to fortify the propeller design for better operation [19]. Based on the computed mode shapes, the higher the number of blades on the propeller, the more it experiences deflection on each blades compared to the propeller with smaller number of blades. The two blades propeller shows deflection in all blades only in the first mode. The three blades propeller shows deflection in all blades in third and sixth mode. The four blades propeller shows deflection in all blades in the first, second, fourth and sixth mode. This agrees with some findings that discussed that more blades on propeller produced more thrust and therefore contains more energy [20]. Thus, resonance is more likely to occur in propeller with more blades.

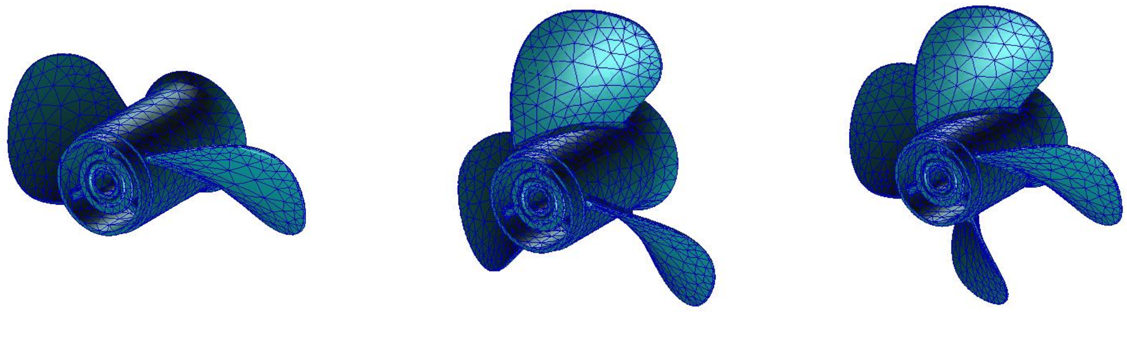


Figure 6. Finite element model of propeller structure with (a) two blades, (b) three blades and (c) four blades.

Table 1. Comparison of first six natural frequencies for propeller with different number of blades

Mode		1	2	3	4	5	6
Natural frequencies of propeller (Hz)	2 blades	2072.1	4451.2	5451.0	5510.9	7606.3	8086.8
	3 blades	1926.2	3233.1	3360.1	4353.1	5425.6	5953.2
	4 blades	572.95	2636.2	2677.4	3096.8	4346.3	4793.1

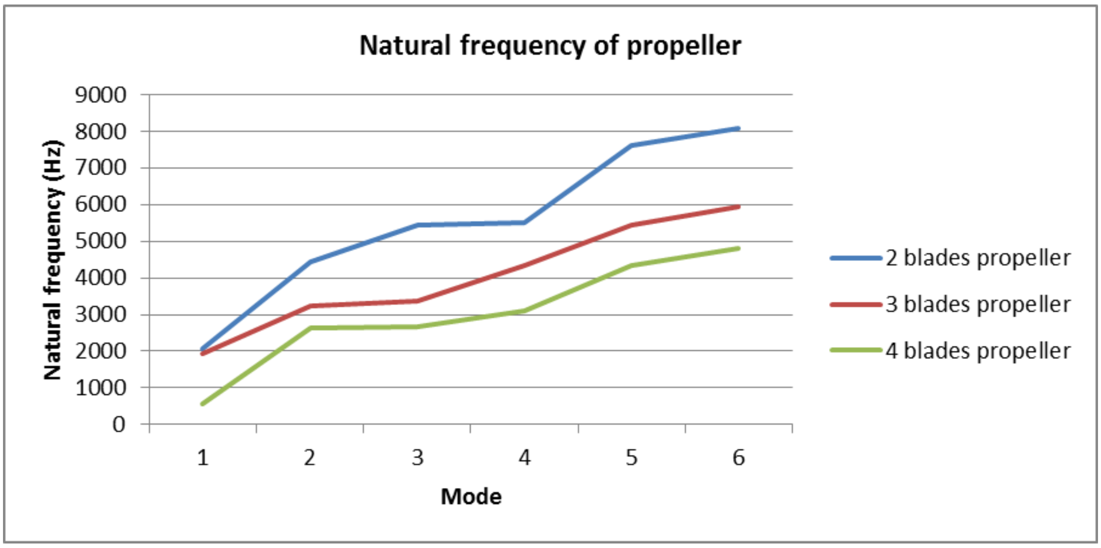


Figure 7. The natural frequencies curves of propeller with different number of blade.

Table 2. Comparison of mode shapes for two blades propeller

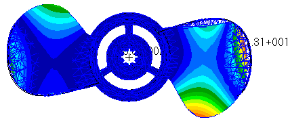
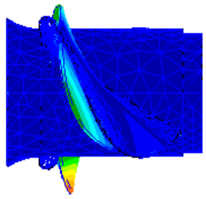
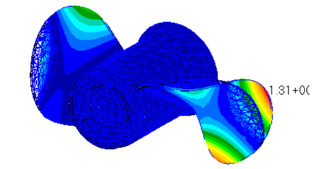
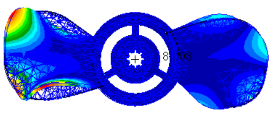
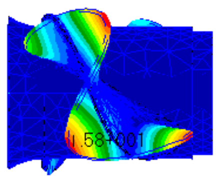
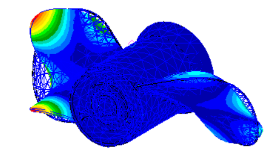
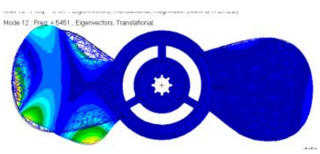
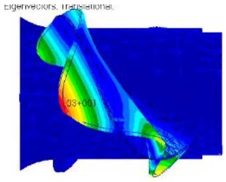
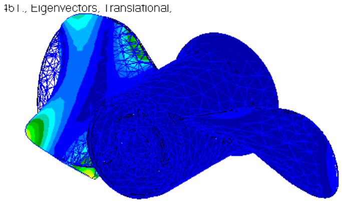
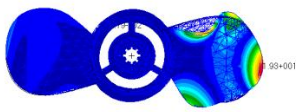
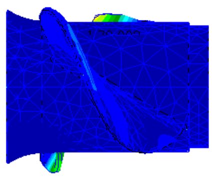
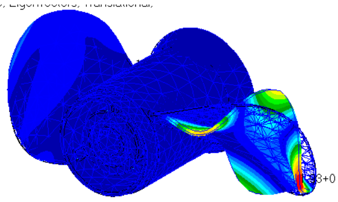
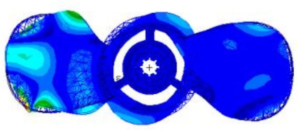
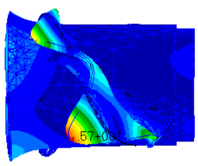
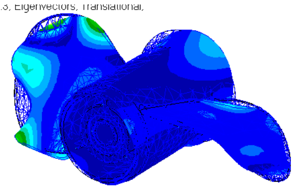
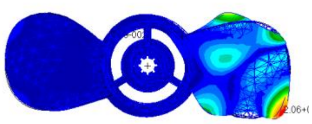
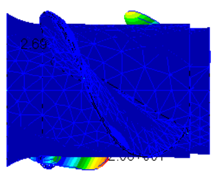
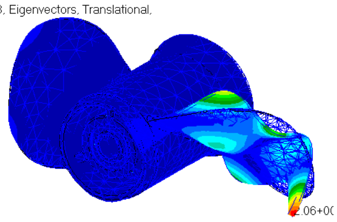
Mode	Mode shapes		
1			
2			
3			
4			
5			
6			

Table 3. Comparison of mode shapes for three blades propeller

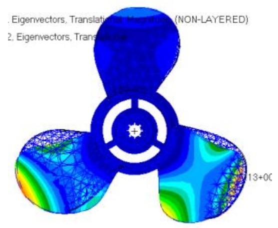
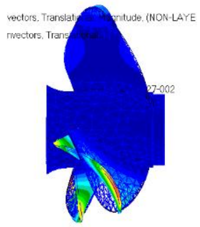
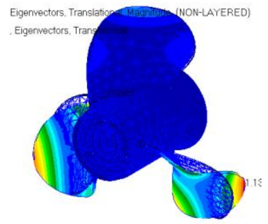
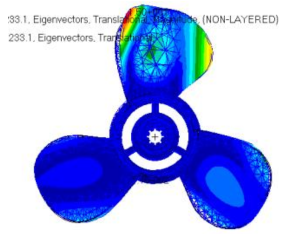
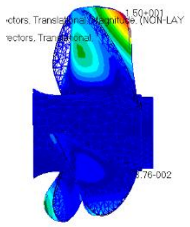
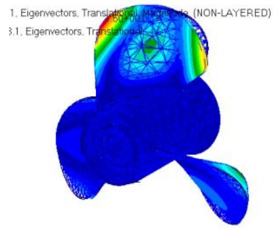
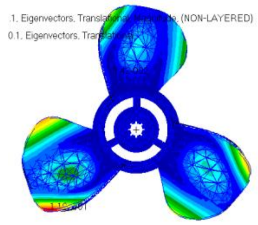
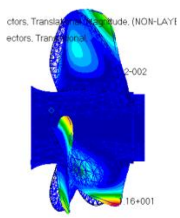
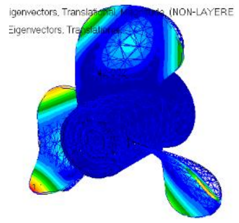
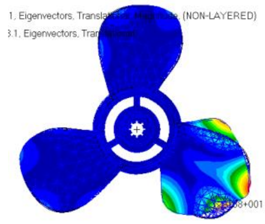
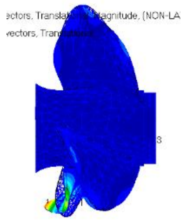
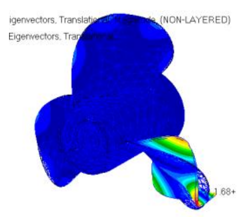
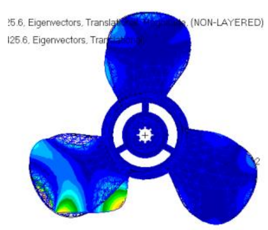
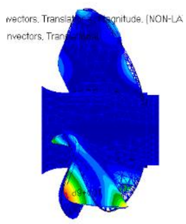
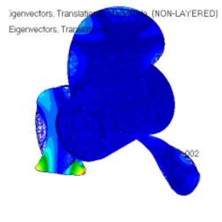
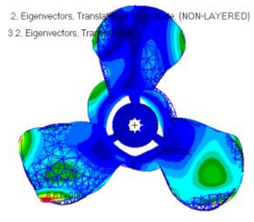
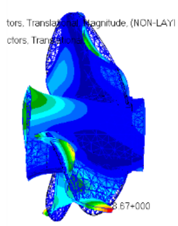
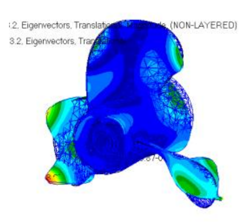
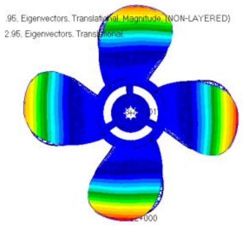
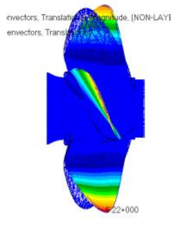
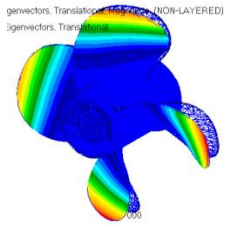
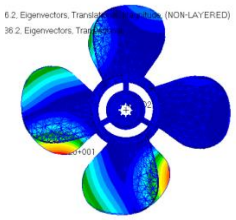
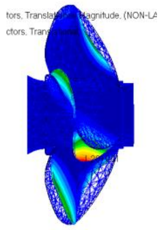
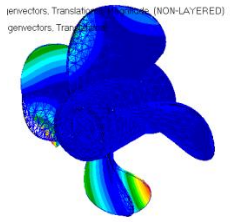
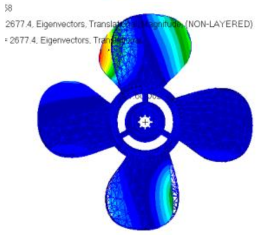
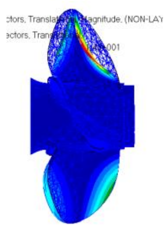
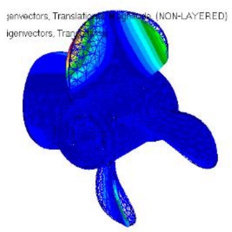
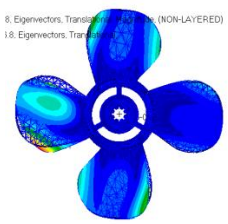
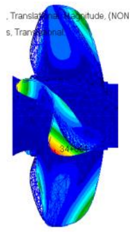
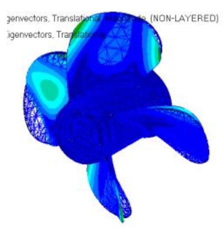
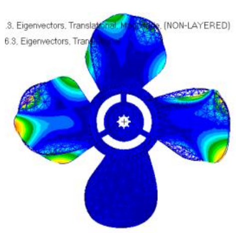
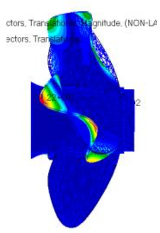
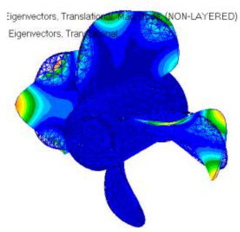
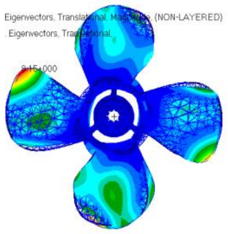
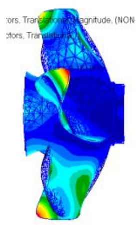
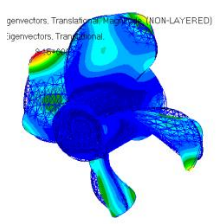
Mode	Mode shapes		
1			
2			
3			
4			
5			
6			

Table 4. Comparison of mode shapes for four blades propeller

Mode	Mode shapes		
1			
2			
3			
4			
5			
6			

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However, in determining the right number of propeller blades that should be used, it depends on several other factors such as the engine power, operating frequency for the propeller, performance requirements and many more. As more blades produce higher thrust with drag which may contributes to the loss of fuel efficiency. Therefore, in determining the optimum number of blades a propeller should have depends on combination of many factors which will vary depending on where and with how much power the propeller will work [8].

4. Conclusion

The modal characteristics of propeller with different number of blades, which are two blades, three blades, and four blades were investigated. The value of natural frequency for each propeller together with their mode shapes were obtained computationally and analysed later on. The following findings were pointed out:

- Computational and experimental analysis on the three blades propeller structure shows good correlation in most of the mode. Even though the results is well correlated, there are still room for improvement. A method call model updating is very recommended for reducing the available discrepancies between analytical and experimental results.
- When the propeller has less number of blades shows higher value of natural frequency. The two blades propeller has the highest value of natural frequency in every first six mode than the three blades and four blades propeller. This is owing to the fact that less blade means less mass. As the value of natural frequency is inversely proportional to the mass of a structure, the two blades propeller which has the lowest mass has the highest value of natural frequency.
- The mode shapes for all propellers were computed and analysed. For the four blades propeller was observed to show the most deflection in its mode shape. This situation suggested that , resonance is more likely to occur in propeller with more blades.

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