

PREDICTION OF MODAL BEHAVIOUR OF A ROTATING BOAT PROPELLER

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Publication Date
30 January 2024

Summary:

This report analyses the modal properties of a rotating three-bladed boat propeller. It predicts the Campbell diagram, maximum stresses, and displacements at various propeller speeds.

The main results can be summarised as follows:

- There are 12 natural frequencies below 1250 Hz, occurring in triples and corresponding to blade modes. The natural frequencies are not highly sensitive to rotational speed within the propeller's operational speed range. The largest frequency increase is observed for the first three natural frequencies and is approximately 10%.
- The maximum stress of 80 MPa occurs at the blade root at the maximum rotor speed. This stress is well below the yield stress, with a safety factor of 2.68.
- The maximum blade extension at 6000 rpm is 0.012 mm, which is less than 0.01% of its length.

Based on these findings, the propeller is acceptable. No redesign is recommended.

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1 Introduction

The objective of this report is to predict the modal properties of a rotating boat propeller, as well as the maximum stress and displacements experienced at the highest rotational speed.

The geometry of the analysed three-bladed propeller is shown in Figure 1.

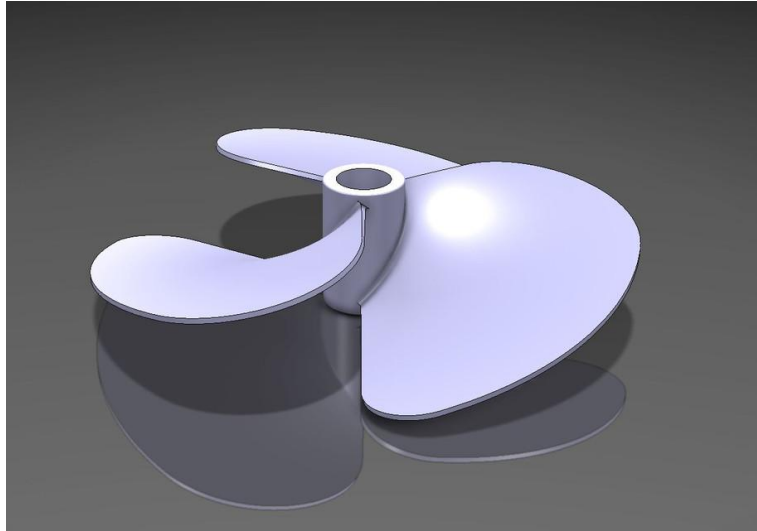


Figure 1: Boat propeller analysed in this report

The propeller is made from 304 stainless steel, with the material properties summarised in Table 1.

Material Property	Value and Units
Modulus of Elasticity	$E = 193\text{e}9 \text{ Pa}$
Poisson's Ratio	$\nu = 0.29$
Density	$\rho = 8000 \text{ kg/m}^3$
Yield Stress	$\sigma = 215\text{e}6 \text{ Pa}$

Table 1: Material properties of 304 stainless steel

The propeller's normal operational speed does not exceed 6000 rpm.

2 Methodology

The computational assessment was performed using finite element analysis (FEA). The model was prepared using a tetrahedral mesh. A convergence analysis of the natural frequencies of the non-rotating propeller was performed to ensure that the resulting modal properties were not dependent on mesh density. The results of the convergence analysis are reported in Section 3.1.

The computation of the modal properties of the rotating propeller was performed in two steps. First, the propeller was loaded by the centrifugal force proportional to the rotational speed. In the second step, the modal properties of the loaded propeller were computed. Rotor speeds from 0 to 6000 rpm were applied in increments of 1000 rpm so that the Campbell diagram, i.e. the relationship between modal properties and rotational speed, could be plotted. Gyroscopic and non-linear effects were not considered, which is justified by the small size of the propeller and the small displacements experienced during rotation. The stresses and deflections caused by the centrifugal forces were also evaluated.

3 Results

The results are presented in three parts: first, the outcome of the mesh convergence analysis is shown; next, the Campbell diagram is discussed; and finally, the maximum blade displacement and stresses are presented.

3.1 Mesh convergence analysis

The mesh convergence analysis of the natural frequencies was performed by varying the mesh density and element type, using either linear or quadratic elements. The results are shown in Figure 2. The horizontal axis shows different mesh sizes in mm, and the quadratic mesh is indicated by “q”. It can be seen that, as the number of elements increases and the mesh size decreases, the natural frequency converges towards a stable approximation. Introducing quadratic elements further improves the analysis accuracy. Since the variation in natural frequencies for quadratic meshes with sizes of 0.003 mm and 0.002 mm is less than 1%, the analysis was not continued, and the quadratic mesh with a 0.002 mm mesh size was used in all further studies. Further mesh refinement would have little impact on the modal properties while having a detrimental effect on computational time.

This graph also shows that the natural frequencies appear in triples. This is because they correspond to the blade natural frequencies. The corresponding mode shapes are shown later in Section 3.2.

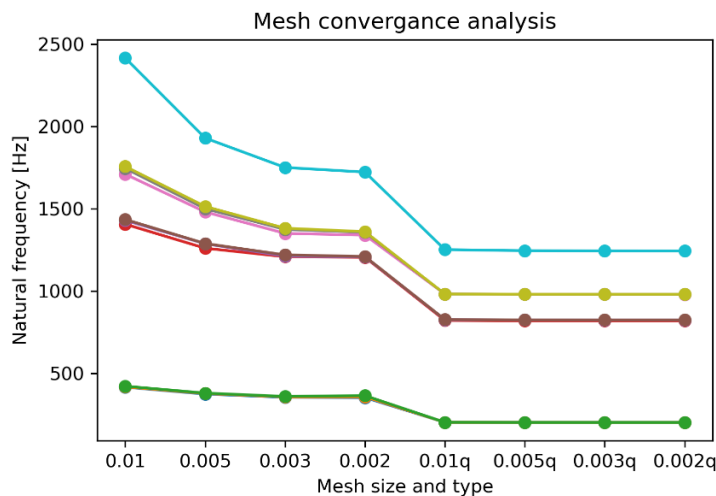


Figure 2: Mesh convergence analysis: impact of mesh size and type on the natural frequencies of the non-rotating boat propeller

3.2 Campbell's diagram

Having selected the mesh for the analysis during the convergence study, the Campbell diagram was computed, as shown in Figure 3. The natural frequencies are not strongly dependent on rotational speed. However, they do increase slightly, as expected. The first three natural frequencies increase by just over 10%, from 202 Hz at 0 rpm to 225 Hz at 6000 rpm.

The mode shapes at the highest considered rotational speed, 6000 rpm, are shown in Figure 4. Each row of the figure represents a group of modes with an almost identical frequency. The mode shapes are driven by the motion of the blades. The natural frequencies are not exactly identical because,

although the blades are the same, the grooves in the central propeller hole that are used to attach the propeller to the engine shaft are slightly non-axisymmetric, leading to slight differences in natural frequencies.

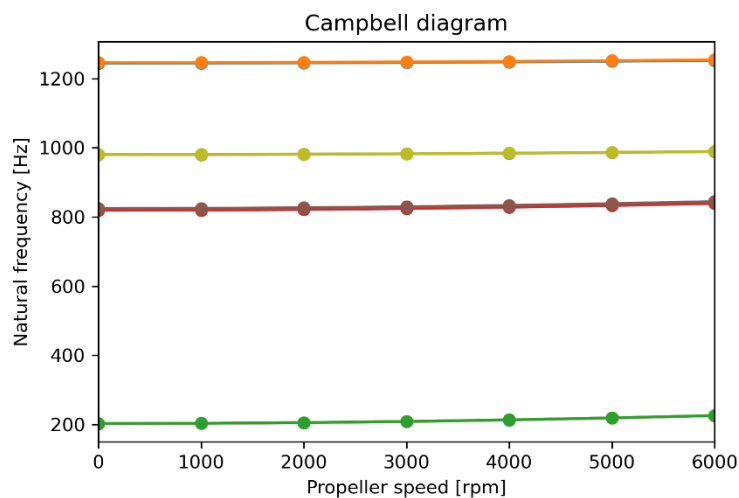


Figure 2: Campbell's diagram of the rotating boat propeller

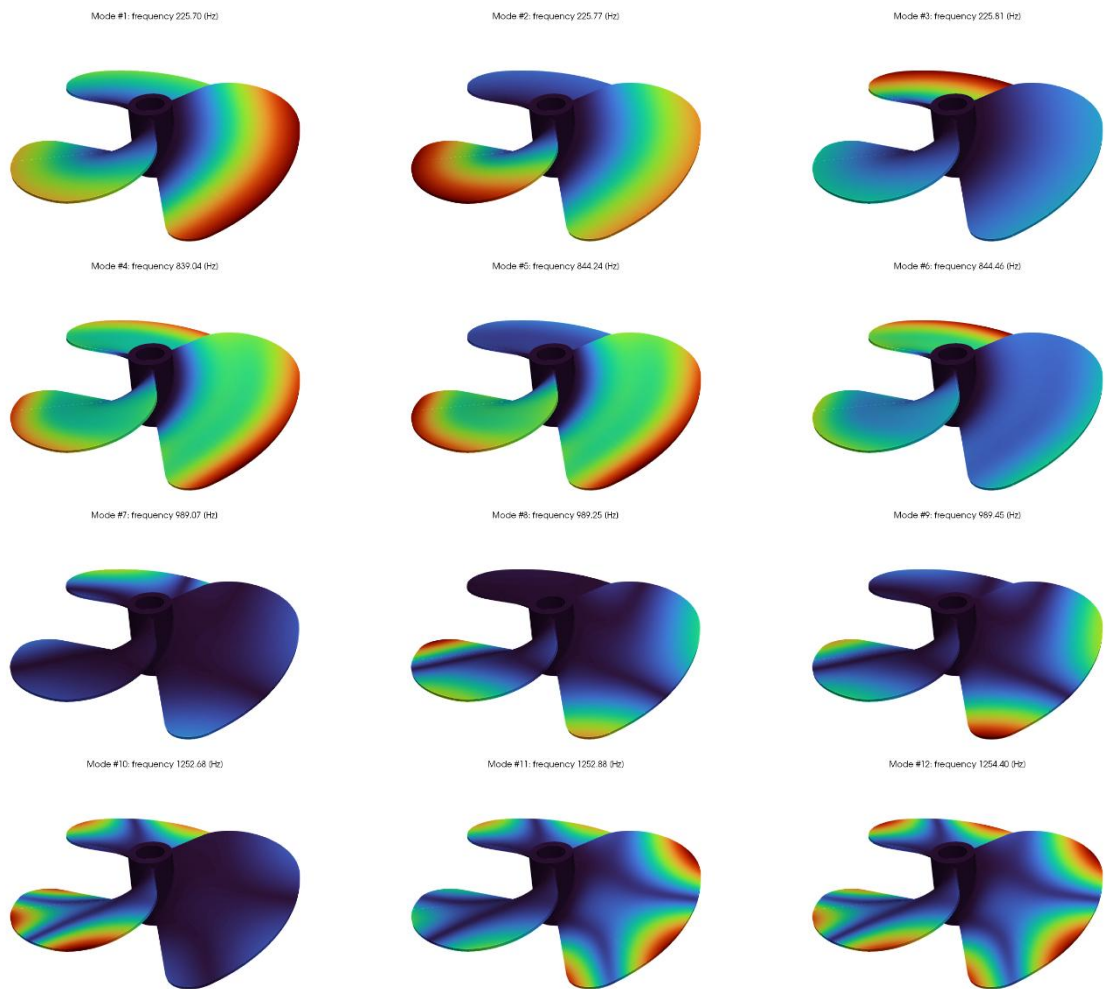


Figure 4: Mode shapes of the boat propeller at maximum rotational speed. Each row represents one set of mode shapes with almost identical natural frequency.

3.3 Maximum blade deflection and stress

The maximum blade tip displacement due to the centrifugal forces generated by rotation is shown in Figure 5. As expected, the maximum occurs at the point furthest from the axis of rotation. The maximum displacement at 6000 rpm is just over 0.012 mm, which is less than 0.01% of the blade's 85 mm length. The displacement increases quadratically with rotational speed. This is in line with expectations, since the centrifugal force causing this displacement is quadratically dependent on propeller speed.

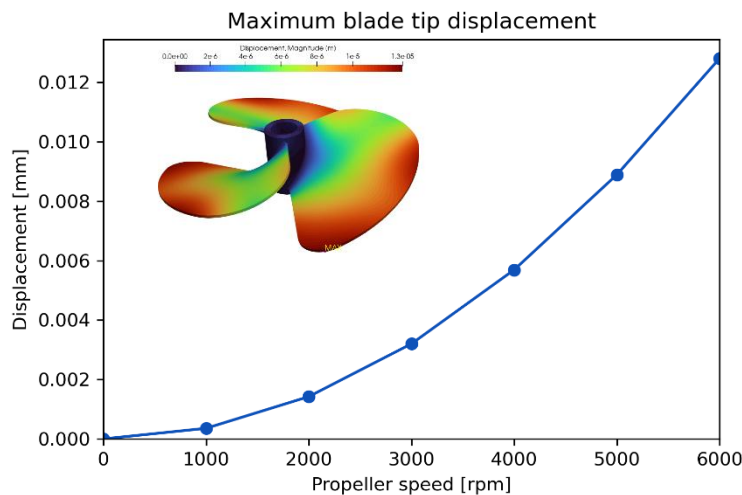


Figure 3: Maximum blade tip displacement due to rotation

Unlike displacement, the maximum stress occurs at the root of the blade. This is expected, as the load generated by the centrifugal force is highest at the location closest to the axis of rotation. The blade root is also a natural stress concentration point where the highest stress is typically observed. The highest von Mises stress at 6000 rpm is just over 80 MPa. This is less than 38% of the yield stress. Therefore, plastic deformation is not expected to occur in this propeller, with a safety margin of over 2.6. Similarly to displacement, the stresses at the blade root increase quadratically with propeller speed.

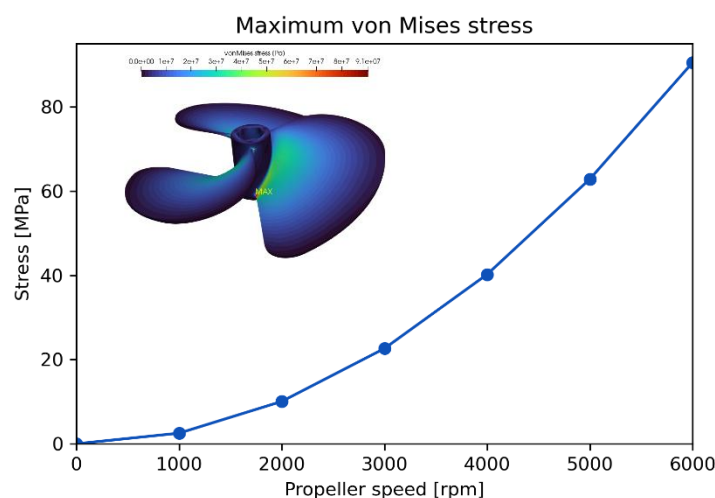


Figure 4: Maximum von Mises stress due to rotation

4 Conclusions

This report predicted the modal properties, displacements, and stresses of a rotating boat propeller using finite element analysis. The main conclusions are:

- There are 12 natural frequencies below 1250 Hz, occurring in triples and corresponding to blade modes. The natural frequencies are not highly sensitive to rotational speed within the propeller's operational speed range. The largest frequency increase is observed for the first three natural frequencies and is approximately 10%.
- The maximum stress of 80 MPa occurs at the blade root at the maximum rotor speed. This stress is well below the yield stress, with a safety factor of 2.68.
- The maximum blade extension at 6000 rpm is 0.012 mm, which is less than 0.01% of its length.

Based on these findings, the propeller is acceptable. No redesign is recommended.