The Effect of Stacking Sequence Parameters on the Vibration Behavior of Rotating Hybrid Composite Shaft

M. M. Nazari, A. Rahi*, R. Sarfaraz

Department of Mechanical and Energy Engineering, Shahid Beheshti University, Tehran, Iran

ABSTRACT: A rotating composite shaft can be used with power transmission applications in the rotating machinery industry. A composite power transmission shaft usually has higher natural frequencies and critical speeds than a conventional metal power transmission shaft. Accurate determination of the natural frequency of the shaft is of great importance in its design, especially in the case of composite shafts due to the anisotropy of composite materials. In this paper, first in a rotating state, finite element results of a composite shaft of eight layers of carbon/epoxy in the case of two steel discs in the middle are symmetric with different diameters are compared with the results of previous research and the accuracy of the results is verified. A hollow composite shaft of eight layers of carbon/epoxy and glass/epoxy is modeled with two steel discs on the elastic supports. Applying the Lagrange equations, the equations of motion of the hybrid composite shaft are obtained using the modified equivalent modulus beam theory. By writing code in MATLAB software and numerical solution, the amplitude diagram in terms of frequency in the rotating state is obtained and compared with the results of the composite shaft simulation in Ansys software, and validation is performed. Finally, the effect of stacking sequence parameters such as fiber angle, arrangement of use carbon/epoxy, and glass/epoxy on natural frequencies is investigated.

1- Introduction

Nowadays, the composite shaft has wide applications in various industries, including aerospace and automobile industries, due to its lightness and proper strength. Investigating the composite shaft in terms of vibration is very important for the proper operation and stability of the rotating system with high rotation speed. Still, due to the non-isotropic property of composite materials, its dynamic analysis is almost difficult. Qi et al. [1] studied the vibration characteristics of composite shafts using the finite element analysis method, pulse vibration stimulation method, and numerical solution. Bavi et al. [2] investigated the combined effects of shaft asymmetry and geometric nonlinearity and stability of composite shafts. They derived the equations of motion by considering Euler angles and anisotropic properties of the composite material and using Hamilton's extended principle. They also considered the effects of tension, such as gyroscopic torque, rotational inertia, and nonlinear couplings. Barbosa et al. [3] examined the vibrations of a hollow carbon/epoxy composite shaft using the experimental test in rotating mode and finite element analysis by applying the simplified homogenized beam theory and considering the internal damping in the form of the Kelvin-Voigt model.
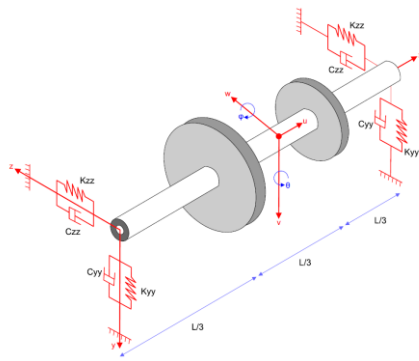
Kafi and Hosseini [4] studied the nonlinear vibrations of a rotating composite shaft. In their research, they considered the gyroscopic effect, rotational inertia, and coupling created due to the non-isotropy of the composite material. They considered the nonlinear geometric effect and the shear deformation to be negligible. Mendonça et al. [5] examined the rotor dynamics of the composite shaft. They investigated the effect of the composite shaft layers' arrangement on the rotor's dynamic behavior. They used the simulation results to present the effect of layering in Campbell diagrams, critical speed, instability threshold, and frequency response functions. Shaban Ali Nezhad et al. [6] investigated the combined resonances of a rotating composite shaft by considering the nonlinear geometry and by applying the harmonic balance solution method.

Gurban and Gupta [7] studied the effect of lamination angle and coupling mechanisms on the natural frequencies of composite shafts. Ghoneam et al. [8] examined the effect of fiber layering and coupling mechanisms on the natural frequencies of glass/epoxy composite shafts. Ravishankar et al. [9] considered hybrid composites with automotive applications in a review paper. They stated that considering that composites have become the preferred and practical material to reduce weight in automobiles, hybrid composite materials are used in many engineering applications due to their diverse properties, including lightweight, high strength-to-weight ratio, low cost, and ease of use. By examining the

*Corresponding author's email: a_rahi@sbu.ac.ir

Fig. 1. Composite shaft with two discs and elastic bearings at both ends

Fig. 2. Phase velocity dispersion curves for a steel pipe with outer diameter of 220 mm and $[45/-45/45/-45]_S$ wall thickness of 4.8 mm

previous research, it can be seen that so far, no specific and comprehensive work has been presented regarding the effect of layering parameters, such as the stacking sequence angle and the arrangement of layers in terms of the order of using carbon/epoxy and glass/epoxy on the dynamic behavior of a hybrid composite shaft.

2- Methodology

First, a non-hybrid hollow composite shaft with eight layers of carbon/epoxy is modeled as a symmetric stacking sequence $[45/-45/45/-45]_S$ to validate its results and then is generalized the modeling to investigate the dynamic behavior of the hybrid composite shaft. In Fig. 1, a hollow composite shaft is shown in the form of two steel discs resting on elastic supports at both ends. The theory of the modified equivalent modulus beam can be used to obtain the motion equations of the composite shaft. The equivalent modulus beam theory is developed by adding transverse shear deformation, rotational inertia, and gyroscopic effects to the Berse-Timoshenko beam theory. In the modified equivalent modulus beam theory, bending-torsional, vertical shear, and bending-tensile couplings are also considered.

Next, a hybrid composite shaft with eight layers of glass/epoxy and carbon/epoxy is modeled. Considering that the cost of carbon/epoxy is about ten times that of glass/epoxy; as a result, two layers of carbon/epoxy and six layers of glass/epoxy are used.

3- Results and Discussion

To validate the finite element analysis, the simulation results of the eight layers composite shaft are compared with the numerical results of Mendonsa's research [5]. Fig. 2 shows the Campbell diagram of a rotating hollow composite shaft with eight layers of carbon/epoxy with $[45/-45/45/-45]_S$ a symmetrical stacking sequence in the state of two steel discs with different external radial that is placed on elastic bearings at both ends, using the finite element method, which is compared Campbell diagram of research [5] and validation
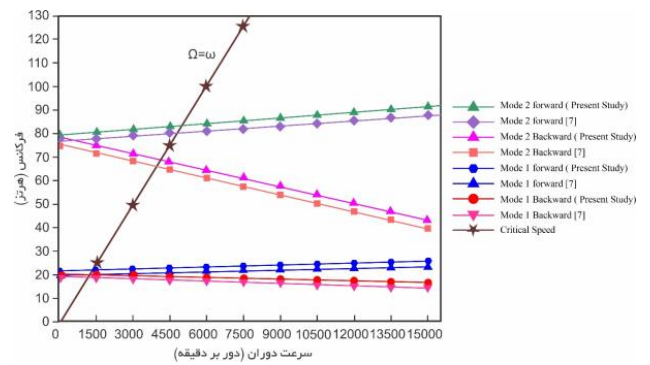
of the results is confirmed. The forward and backward frequencies in the first and second modes are observed only due to gyroscopic effects. The accuracy of the results in the first and second forward and backward modes is acceptable, and the error is less than 9% in all rotation speeds.

4- Conclusions

This research investigated the dynamic behavior of a hybrid composite shaft with elastic bearings. First, a composite shaft with carbon/epoxy eight layers was modeled in the state of two steel discs with different diameters in the middle symmetrically placed on elastic supports. The results of the finite element were compared with the results of research [5], and the validity of the results was confirmed. In the following, the composite shaft was developed in the hybrid mode, and the governing equations of the hybrid composite shaft were derived in matrix form using Lagrange's equations. Then, by coding in MATLAB software and numerical solution, forward and backward frequencies in the first and second modes at different rotational speeds were obtained through the amplitude versus frequency diagram and compared with the finite element results, and validation of the results was done. In the end, the effect of stacking sequence parameters on forward and backward frequencies was investigated. The results showed that the cumulative sequence parameters have a significant effect on the vibration behavior of the hybrid composite shaft, which was summarized as follows:

1) The higher the stacking sequence angle, the higher the natural frequency of the hybrid composite shaft.

2) If the carbon/epoxy layer is the outer layer or is closer to the outer layers, the natural frequency of the hybrid composite shaft will also increase.

3) A higher stacking sequence angle of carbon/epoxy will have a greater effect in the hybrid composite shaft than the placement arrangement of the carbon/epoxy layer in the outer layers.

4) For the eight layers hybrid composite shaft, we will have the highest natural frequency in the case where the two

outer layers of the shaft are carbon/epoxy with a 90-degree angle, the two inner layers are glass/epoxy with a zero-angle, and the middle four layers are also glass/epoxy with The angles are 45 and -45 degrees.

5) To save money, it is possible to increase the number of natural frequencies and critical speeds by hybridizing the composite shaft and using less carbon/epoxy using layering and placing the appropriate carbon/epoxy and glass/epoxy. The results can be approached to the carbon/epoxy non-hybrid composite shaft.

References

[1] L. Qi, C. Li, X. Yu, W. Min, H. Shi, L. Tao, H. Wang, M. Yu, L. Ni, Z. Sun, Effect of reinforced fibers on the vibration characteristics of fibers reinforced composite shaft tubes with metal flanges, Composite Structures, 275 (2021) 114460.

[2] R. Bavi, A. Hajnayeb, H.M. Sedighi, M. Shishesaz, Simultaneous resonance and stability analysis of unbalanced asymmetric thin-walled composite shafts, International Journal of Mechanical Sciences, 217 (2022) 107047.

[3] P.C. Barbosa, V.T. Del Claro, M.S. Sousa Jr, A.A. Cavalini Jr, V. Steffen Jr, Experimental analysis of the SHBT approach for the dynamic modeling of a composite hollow shaft, Composite Structures, 236 (2020) 111892.

[4] H. Kafi, S. Hosseini, Dynamic analysis of nonlinear rotating composite shafts excited by non-ideal energy source, ZAMM-Journal of Applied Mathematics and Mechanics/Zeitschrift für Angewandte Mathematik und Mechanik, 99(5) (2019) e201800279.

[5] W.R.D.P. Mendonça, E.C. De Medeiros, A.L.R. Pereira, M.H. Mathias, The dynamic analysis of rotors mounted on composite shafts with internal damping, Composite Structures, 167 (2017) 50-62.

[6] H. Shaban Ali Nezhad, S. Hosseini, M. Moradi Tiaki, Combination resonances of spinning composite shafts considering geometric nonlinearity, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 41(11) (2019) 1-21.

[7] H. Gubran, K. Gupta, The effect of stacking sequence and coupling mechanisms on the natural frequencies of composite shafts, Journal of sound and vibration, 282(1-2) (2005) 231-248.

[8] S. Ghoneam, A. Hamada, M. EL-Elamy, The Effect of Stacking Sequence and Coupling Mechanisms on Eigen-Nature of Composite Shafts, in: International Conference on Aerospace Sciences and Aviation Technology, The Military Technical College, 2013, pp. 1-21.

[9] B. Ravishankar, S.K. Nayak, M.A. Kader, Hybrid composites for automotive applications–A review, Journal of Reinforced Plastics and Composites, 38(18) (2019) 835-845.