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ORIGINAL ARTICLE

Internal torsion resistance in deflected shafts

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Abstract Most of the shaft theories have based their analysis on bending moment, twisting moment or combined between them. Nevertheless, the dynamic behavior of flexural-torsional coupled vibrations in the rotating shafts is affected by the internal resistance forces due to torsion. It is expected that the deflected shafts shall be exposed to this resistance, where these forces were not considered in the analysis before.

The objective of the present work was to estimate the effect of internal torsional resistance in shafts which is caused by deflection, for the reason that it has the upper hand on misalignment problem. With the aim of fulfilling this objective, an experimental rig has been constructed to verify the existence of the torsional resistance in deflected shafts and its variation with the rotation angle.

1. Introduction

Internal resistance is defined as the resistance between the molecules of the subject concerned with the study by the means of an external factor that is producing it. In the present work, the internal torsional resistance of shafts is figured out experimentally under an external force which is the deflection.

In different Mechanical applications shafts are subjected to flexure deflections for example shafts that are carrying belt drives and gears. Flexural-torsional coupled vibration of rotating shafts can occur in many engineering applications such as helicopter, rotors, slewing robot arms, turbomachinery blades, spinning spacecraft and aircraft propellers. The natural frequencies of shafts are important for the design of shafts subjected to excitations. In order to design these mechanisms, the dynamic characteristic, specifically close to resonance cases, must be well studied to guarantee a not dangerous working machine and decrease the downtime maintenance times. Determining the natural frequencies and mode shapes has the priority in importance classifications in various fields for instance, in studying the forced vibration analysis, and aeroelasticity.

So far, all the studies are applied to plane shafts since shafts are usually subjected to deflections. Consequently, it is significant to find the effect of deflection on shaft properties. What is more, at the resonance conditions, dampers are the devices which are used to dissipate energy from the system in order to reduce the vibrations and set the amplitude to minimum as possible. Accordingly, most of the classic designs be dependent on natural frequencies to evade any anticipated large amplitudes. For illustration, bent shafts caused by assembly stack-

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up stresses which come from wheels, gears, etc. are usually not just corrected by simply straightening the shaft itself again. But also, the system must be considered as a one-piece unit, and improved, this is for the reason of sometimes, a change in the fits and tolerances between the shaft and its mating components is essential to get the straightness needed done.

The shafts that are subjected to deflections are expected to suffer more resistance due to additional torsional resistance. The aim of this work was to give an experimental approach for the effect of combined torsional and deflection on shaft resistance to torque.

For a long time, most of studies have focused on a single form of vibration in shafting system such as torsional vibration, flexural vibration or longitudinal vibration, seldom concerning with the coupled vibration caused by the co-operation of these vibration forms on some certain reasons. Tondle [1] studied a model of steam turbogenerator, which was established by a mass-less elastic shaft and two unbalanced rotors. Rabkin [2] studied the coupled vibration of flexible multi-rotor shaft excited by impulse of torque and drew a close conclusion with Tondle. Dokumaci [3] offered a full investigation for the coupled bending and torsional vibration characteristics of uniform beams having single cross-sectional symmetry. In this investigation, the mathematical model for the analysis of coupled bending and torsion vibrations is taken out by combining the Euler-Bernoulli theory for bending and St. Venant theory for torsion. Bishop, Cannon and Miao [4] began from Dokumaci's theory that the Euler-Bernoulli theory of beam flexure might be united with the Saint-Venant theory of torsion in order to define the coupled antisymmetric free vibration of uniform beams having a plane of symmetry. This theory was extended to permit warping calculations of the beam cross section. Bercin and Tanaka [5] started from Bishop's technique [2] taking into consideration the warping stiffness using Timoshenko beams for coupled flexural-torsional vibrations. They demonstrated the effect of proportionality of warping on the natural frequencies. As the warping increases, the natural frequency increases. However, Timoshenko effects in decreasing the natural frequencies. Besides that, a method in numerical results was established.

The conservative Finite Element Method or the FEM has less advantages than the dynamic stiffness matrix method in vibration analysis of beams or frameworks. Mainly if much better results are required, accuracy is a crucial parameter, and/or when at higher frequencies the system is operating at. The reason behind the less dependency on the FEM is that each individual element properties is derived from the assumed shape function. Thus, it has not much accuracy as the dynamic stiffness matrix method. On the contrary, in latter method, the properties of each individual element matrix are based mainly on the closed form analytical solution of the differential equation of the element and hence are reasonably to be called 'exact'. Hallauer and Liu, [6] along with Friberg [7] formulated the dynamic stiffness matrix of a bending-torsion coupled beam based on a method which relies on successive matrix operations. Their work was trailed by Banerjee and Fisher [8] where he studied the coupled bending-torsional vibration in the method of dynamic stiffness matrix in an axially loaded condition in the method of dynamic stiffness matrix (1D).

Khanlo et al. [9] studied the bending-torsion coupling effects on the dynamic behavior of rotating continuous flexible shaft–disk systems with rub–impact. They investigated how the chaotic vibration behavior of a system can be affected by torsional coupling. Their model was solved using numerical methods.

The natural frequency of an axially loaded shaft had as well an abundant share from the researchers since it is of a great importance for the designers; thus, many efforts have been made to figure it out. Behzad and Bastami [10] studied the effect of shaft rotation on its natural frequency. They assumed that the axial force comes from the centrifugal force and the Poisson effect combined neglecting the gyroscopic effect. Their model was solved using D'Alembert principle for shaft in cylindrical co-ordinate system. And the rotation of a cylindrical shaft is found out that affects its lateral natural frequency except gyroscopic momentum. Hosseini et al. [11] investigated the effect of shaft which is axially loaded on the lateral natural frequencies of a flexible rotating shaft with a cubic nonlinearity. Starting from Euler-Bernoulli theory, they derived a nonlinear partial differential equation of motion taking into consideration the equilibrium equations for an element of the shaft.

Adam [12] investigated coupled bending and torsional vibrations of beams under forced vibration. He had solved the governing coupled set of partial differential equations by separating the dynamic response in a quasistatic and in a complementary dynamic response and getting the generalized decoupled single-degree-of-freedom (DOF) oscillators by means of Duhamel's convolution integral. Zhao et al. [13] a Jeffcott rotor model with imbalance -crack- was held he investigated the coupling of lateral and longitudinal vibration by using D'Alembert Principle. His model was approximated to four DOF. To solve his model, he used the stiffness matrix method. Moreover, the breathing behavior of the crack under axial excitation is studied in terms of several eccentricity phases and rotation speeds.

The finite element method (FEM) and the transfer matrices (TM) also are used. Papadopoulos and Dimarogous [14] did a comprehensive investigation on many kinds of the coupled vibration in the cracked shaft system by FEM. Wu and Yang [15] deduced a computer technique for forced coupled torsional-flexural vibration of shafting system with damping, where the eccentricity of the locus of the mass centers had been taken into consideration. In their study, a discrete model with multi-degrees of freedom (MDOF) is applied. Qing and Cheng established the finite element model of coupled torsional-flexural vibration of shaft system, and the properties of coupled vibration were studied by combining FEM, TM and impedance method by Qin and Mao [16,17] established. El-Saeidy [18,19] showed a formulation in FEM for the dynamic analysis of a rotating shaft with or without nonlinear characteristics under the action of a moving load.

Katz [20] studied the dynamic response of a rotating shaft subject to moving and rotating loads. In addition, he presented an analytical expression for this response. Huang and Yang [21] continued [20] work and simulated a lathe machine as a rotating Rayleigh beam and showed that the presence of the axial moving force can yield one major instability region for each vibration mode. Although Katz, Huang, and Yang work is much related to the present work, they didn't give a good estimation for the internal torsional resistance and just studied the dynamic response as presented here.