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Nonlinear centrifugal effects on a prestressed laminated rotor

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ABSTRACT

Electrical rotors are usually used in rotating machinery such as in ship engine pods. Designing such rotors in bending requires careful modeling of a laminated stack prestressed by tie rods. Theoretically, steel sheets, varnish layers and prestressing make it difficult to homogenize the constitutive properties of a stack both at rest and under operating conditions. Moreover, it is noteworthy that tie rods subjected to centrifugal forces bend until reaching annular clearance. Their nonlinear bending tends to increase their stiffening effects and the axial lamination load, therefore it affects the homogenized constitutive properties of a stack modeled with Timoshenko beams. By combining a fixed-point algorithm and penalty method at each speed of rotation, it is possible to plot the Campbell diagram and unbalance responses by considering updated properties and the axial load of the tie rods generated by centrifugal effects. An industrial application is used to show that centrifugal effects have a slight influence on rotor dynamics.

1. Introduction

High speed induction motors (HSM) are mainly used in new rotating machinery technologies. They can run at 20,000 rpm and supply a 2 MW power or even reach 30 MW at 6 000 rpm, leading to a speed close to sound velocity, i.e. 250 $m \cdot s^{-1}$ peripheral speeds in relation to the stack radius. The laminations of the stack are axially prestressed either on a central shaft [1,2], by peripheral tie rods or a combination of both of these technologies [3]. It is well known that a compressive axial load reduces the lateral stiffness of slender structures while it increases that of laminated structures [4,5]. This article focuses on rotors with a laminated core prestressed by tie rods screwed at two shaft-ends, Fig. 1. The short-circuit rods are located at the periphery of the magnetic core, in contact with two short-circuit rings. Predicting the rotordynamics of these composite/laminated structures requires not only a finite element model based on homogenized techniques and taking into account classical gyroscopic effects, but also stress stiffening and centrifugal effects.

Therefore Timoshenko elements were chosen to build a model containing several degrees of freedom (dof); however, homogenized constitutive properties were required, especially in the laminated stack [2,6,7]. As a function of prestressing and geometrical parameters, in [7], the Young and shear moduli of the stack were established on the basis of experimental modal analyses carried out on twenty five laminated rotors. The aim of this article is to describe how the model of the laminated stack was enhanced by focusing on the centrifugal effects on composite/laminated structures. Most papers consider the influence of a centrifugal axial load on lateral behavior [8,9], whereas very few have assessed the influence of centrifugal transverse load on lateral rotor dynamics. In [10], the authors compared the influence of gyroscopic and centrifugal effects on an axially constrained rotor.

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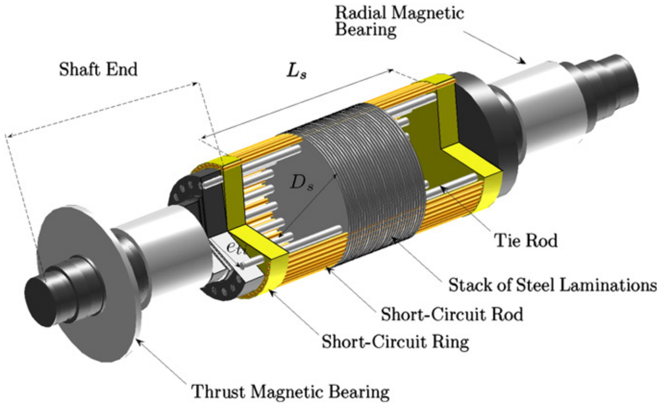

Fig. 1. Sketch of a laminated rotor.

This paper therefore presents a finite element model of a laminated rotor in bending, including a model of the magnetic core with prestressed eccentric tie rods. The homogenized constitutive properties of the stack stem from several identification procedures, all of them performed at rest on different sizes and prestressed laminated rotors. The minimization of a functional based on a hybrid Rayleigh quotient [11] is associated with the Craig and Bampton method [12], in order to combine predicted and measured natural frequencies and mode shapes. By using a multiple linear regression approach [13], the sample of identified data is approximated by a power law, as a function of both geometrical and mechanical parameters such as magnetic core length, diameter and compressive prestressing. The centrifugal effects are taken into account with a distributed nonlinear transverse load acting on the tie rods. Owing to the periodic symmetry of the magnetic core assembly, it is possible to solve this quasi-static problem by considering one tie rod and a part of the laminated stack. At each speed of rotation, a quasi-static nonlinear deflection of a tie rod and an axial compression of the stack are calculated by using an iterative fixed-point algorithm and a penalty method to model the contact [14,15] when the contact occurs between a tie rod and the stack. Finally, Campbell diagrams and unbalance responses are plotted with and without centrifugal effects to assess their influence on critical rotor speeds.

2. Finite element modeling

2.1. Laminated rotor

The rotor model is based on Euler angles ψ (precession), θ (nutation) and ϕ (intrinsic speed) and Timoshenko theory [16]. Note that each calculation is performed with $\dot{\phi} = \omega$ constant. The model consists of N_e two-node elements $\mathscr{K}_e$, i.e. n_δ dof, including two lateral translations u, w along $\overrightarrow{x}$, $\overrightarrow{z}$ respectively, and two rotations θ, ψ around $\overrightarrow{z}$ and $\overrightarrow{x}$. Let Ω be the following union of elements $\mathscr{K}_e$:

$$\Omega = \bigcup_{e=1}^{N_e} \mathscr{K}_e, \tag{1}$$

related to eight dof stored in the displacement vector:

$$^{e}\delta = (w_e, u_e, \psi_e, \theta_e, w_{e+1}, u_{e+1}, \psi_{e+1}, \theta_{e+1})^t. \tag{2}$$

The dynamic behavior of the discretized rotor is governed by the set of n_δ equations in the inertial frame [17]:

$$M\ddot{\delta} + [C_b(\omega) + C_G]\,\dot{\delta} + [K_b(\omega) + K]\delta = F(t), \tag{3}$$

with δ, $F(t)$ the nodal displacement and external force vectors respectively, $(\dot{\cdot})$ stands for time derivative. C_G represents the skew gyroscopic matrix, Eq. (B.1) while K_b and C_b are the non symmetric ω-dependent stiffness and damping matrices of the hydrodynamic bearings, respectively. Mass M and stiffness K matrices are split as in [17,18]:

$$M = M_t + M_r. \tag{4a}$$

$$K = K_f + K_G, \tag{4b}$$