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On dynamic analysis of variable thickness disks and complex rotors subjected to thermal and mechanical prestresses

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ABSTRACT

This paper is focused on the analysis of complex rotating structures subjected to plausible operating conditions. Effects of the temperature gradient and the centrifugal stiffening contribution have been evaluated. In particular, the analyses have been performed considering disks with constant and variable thicknesses, which have been assumed either clamped at the bore or supported by a deformable shaft. The prestress contributions have been obtained through the integration of the three-dimensional stress state, which is generated by centrifugal and thermal loads, multiplied by the non-linear terms of the strain field. The weak form of the governing equations has been solved using the Finite Element method. High-fidelity one-dimensional elements have been developed according to the Carrera Unified Formulation. The comparisons between the current results and those obtained from solid finite element solutions have demonstrated that the proposed methodology can represent a valuable alternative to the three-dimensional modelling technique by ensuring a comparable accuracy with a lower computational effort.

1. Introduction

As one of the advanced engineering systems, turbomachines are widely used in aerospace and power plant industries. In these machines, vibration phenomena are the primary cause of failure of rotating parts such as blades, disks and shafts. Thus the dynamic characteristics must be carefully taken into account in structural analysis and design of such structures.

On the other hand, in real applications such as aero-engines and industrial turbine engines, a rotor assembly is geometrically complex and is usually formed as a combination of individual parts. For instance, several disks with variable thickness, spacers, and air seals with a shaft may be axially tied together by bolts or a special welding method can be used to attach adjacent disks and spacers to each other. In other cases, as well as, a forged integrated drum with rings to carry the blades may be employed as a rotor assembly. However, due to the dynamic interaction effects between the constituent components, dynamic characteristics of each single component may change significantly in the rotor assembly.

Furthermore, in operation, the rotors may be concurrently subjected to external mechanical and thermal loads, in addition to the centrifugal force. Prestresses induced by these loads can considerably affect the dynamic behavior of the rotor. Thermal loads, as well as prestress, can lead to variation of the material properties, and consequently, the dynamic characteristics of the rotor.

The dynamic behavior of rotating structures has been investigated by many researchers since the second half of

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nineteenth century so that a comprehensive history of rotor dynamic has been presented by Rao [1], as well. Moreover, theoretical basis and different methods relating to the rotor dynamic analysis can be easily found in the textbooks [2–5].

In the traditional rotordynamic analysis, simplified mathematical models are used on the basis of one- and two-dimensional assumptions. According to one-dimensional (1D) modeling, the rotor shafts are modeled as beams, while other components such as disks are considered as a series of concentrated masses with specified moments of inertia. Bauer [6], Chen and Liao [7] and Banerjee [8] employed the classical beam theory to study vibration of rotors. It is well known that the classical theory cannot correctly model short and thick beams. Thus, refined theories of beam have been extensively used by researchers to take into account shear deformations for the beams with a low slenderness. For instance, vibrations of a rotating Timoshenko beam was investigated by Zu and Han [9] and Choi et al. [10]. Tai and Chan [11] applied Legendre polynomials to improve Timoshenko beam element. They validated this model in static, dynamic and rotordynamic analyses.

It is recalled that in the 1D rotordynamic, a rotor is reduced to deformable beams with rigid mass points, so that flexibility of disks and other components of the rotor which extend along the radius is not concerned. Disregarding the flexibility may lead to unrealistic solutions, especially when deformation of a disk is considerable. Chivens and Nelson [12] studied analytically the effect of disk flexibility on the dynamic characteristics in a rotating shaft-disk problem. Genta et al. [13,14] developed a finite element (FE) formulation to study the vibration of rotors containing flexible thin disks and bladed disks. They modeled the shaft as a beam while disks and blades were assumed to be annular elements whose displacements were approximated by Fourier series in the circumferential direction. The gyroscopic effects as well as influence of the centrifugal and the thermal prestresses in disks under the plane stress conditions were taken into account in this studies. This approach can only be employed for axisymmetric thin disks. Furthermore, Liu et al. [15] investigated free vibration of rotating annular plates by using a modified axisymmetric FE method. All the components of prestress induced by the centrifugal force were computed and taken into account in their analysis. In addition, the vibration of a mechanical clutch system with rotating disks was studied by Awrejcewicz et al. [16–18]. These authors investigated effects of the wear processes, the flexibility of the disks and the heat transfer between the disks and environment on the dynamic behavior of the system.

Owing to the geometrical intricacies, complicated loads, non-classical boundary conditions, and intrinsic limitations of 1D models, three-dimensional (3D) models have been used in practical applications. Nowadays, the FE Method is the most common numerical technique to study the dynamic behavior of rotating structures. Rao and Sreenivas [19] investigated the interaction of flexible supports and casing on the dynamics behavior of a twin rotor system. They used solid elements to model these structures in ANSYS software. The Stress stiffening and spin softening were taken into account in this study. Hong et al. [20] developed MSC/NASTRAN to study dynamic behavior of rotor assembly and casing in an aero-engine model. They considered effects of prestress due to centrifugal force and gyroscopic moment using 3D solid elements in their analysis. Moore et al. [21] employed several available 3D FE codes such as ANSYS to study the effect of foundation and casing dynamics on dynamic response of the rotor in a typical air compressor. Taplak and Parlak [22] used Dynrot program to evaluate the dynamic characteristics of a gas turbine rotor. Zhuo et al. [23] studied dynamic behavior of a rotor-bearing system subjected prestress effects using 3D FE ANSYS. The prestress distributions caused by centrifugal and steady-state thermal loads were considered in their study.

It is obvious that the 3D FE modeling leads to more accurate results than the traditional models. However, dramatic increase of degrees of freedom (DOF) and, consequently, computational efforts is a notable drawback of the 3D models. Indeed, a 3D rotordynamic model with huge DOF reduces the computational competence especially in an iterative design process of a complex rotor assembly. To lessen the computational costs without loss of accuracy, reduced FE techniques may be used.

A class of refined 1D FE methods with 3D capabilities has been presented by Carrera et al. [24]. In fact, they developed a unified formulation for the FE analysis, the so-called CUF (Carrera Unified Formulations), to overcome the limitations of beam theories. According to CUF, the displacement field over the beam cross-section can be approximated by arbitrary expansions such as polynomials, harmonics, and exponentials. Carrera et al. successfully employed the unified formulation to study the dynamic behavior of a rotor made of isotropic [25] and composite materials [26] including the shaft and the thin constant thickness disk. In these papers, they used Taylor-like polynomial approximations to describe the cross-section deformations. Applying Lagrange-like polynomial expansions, the CUF was then presented for the vibration analysis of thin constant thickness rings and disks; and bladed flexible shafts by Carrera and Filippi in [27]. In this study, effects of the geometrical stiffening due to centrifugal plane stresses on the dynamic behavior were considered. Moreover, the CUF approach has been recently adopted by the authors, Entezari et al. [28,29], to perform thermoelastic analysis of rotors and rotating disks. Therefore, the refined FE method in the context of the CUF may be its ability to handle more complex rotordynamic problems subjected to the combined mechanical and thermal loads.

This paper is aimed, following previous works [28,25–27,29], at extending the CUF approach for dynamic analysis of variable thickness disks and complex rotors considering thermal and mechanical prestress effects.

2. Variational formulation of rotating structures

To obtain the equations of motion of rotating structures in the variational form, Hamilton's principle can be used. This principle, in the absence of non-conservative forces, is written as