International Journal of Pressure Vessels and Piping 166 (2018) 35–47

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp

On the qualitative dynamics of rotating disks: Thermal shocks and structural integrity

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ARTICLE INFO

Keywords:
Transient analysis
Rotating systems
Heat transfer
Load-bearing capacity
Functionally graded material
Thermal shock resistance

ABSTRACT

Within engineering circles, overriding breakthroughs have allowed rotating mechanisms to be safely embedded under severe operational circumstances as well as harsh loads. Meanwhile, a literature survey reflects that the implementation of functionally graded materials (FGMs) has revolutionized the characteristics of rotating disks in industrial segments. One of the most challenging situations for FG rotating disks is exposure to multi-dimensional thermal shocks during heating (ascendant) and cooling (descendant), when even materials with high fracture resistance may become deficient. In this paper, a general picture is drawn of a transient thermoelastic design of FG rotating disks to mitigate failure issues stemming from ascendant/descendant thermal gradients and body forces. Contrary to the majority of reports, thermal and displacement fields of the rotating system are affected in both radial and circumferential paths in the polar system, indicating the need for two-dimensional analysis of transient heat transfer. Material properties of the geometry can be judiciously chosen in the r and θ directions, underpinning a practical recipe in the load-bearing capacity of the model for in-situ applications. Transient numerical simulations of deflections, stresses, and thermal fields of a circular annular disk are graphically elaborated using the Fourier and polynomial differential quadrature approaches. On the basis of awareness of the nature of the applied loads, it is found that an appropriate selection criterion of the variation of the material properties from among all available candidates noticeably ameliorates the impact of temperature shocks on the centrifugal force of the rotary system. With regard to the yielding criteria of the structures, the outcomes of the proposed study extend the boundaries of current traditional designs, demonstrating parallel progress in theories and viable materials.

1. Introduction

As a prominent class of rotating systems, rotating disks have been historically implemented in many engineering applications. In particular, rotating disks are essential components of medical equipment, turbine rotors, air cleaning machines, and rotating machinery [1–5]. Meanwhile, increasing developments in technology have established a fundamental framework for synthesizing material properties and introducing composite materials exhibiting outstanding performance in load-carrying applications. The most commonly used member of the composite family is functionally graded material (FGM). FGMs are multiphase materials with non-uniform but controlled distributions of the constituent phases, in which the material distributions are adjusted according to environmental and functional requirements. These materials are extensively used in high temperature conditions and have a broad range of applications [6–8]. FGMs were first introduced by Japanese scientists in 1984 as temperature resistant materials [9] and since then have attracted much attention [10–19].

Already fabrication of FGMs was restricted to some particular cases. However, the recent technology is capable enough to put material cells together and shape any arbitrary structure. By adjusting the volume fraction, size and shape of material components, different techniques have been presented to fabricate FGMs. Deposition based methods including physical vapour deposition, chemical vapour deposition, electron beam deposition, Ion beam deposition and self-propagating high temperature synthesis can effectively be used in order to deposit thin films on a base material and produce thin FGMs [20,21]. In process of bulk type of FGMs, powder metallurgy is the most prominent approach classified into four steps encompassing powder preparation, powder processing, forming operations, and finally sintering [22]. Centrifugal method which uses the force of gravity through spinning of mould is another technique in producing of bulk FGMs [23]. For high precision and fast fabrication process of FGMs, solid freeform fabrication method, known as three-dimensional printing, can be utilized to make materials

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https://doi.org/10.1016/j.ijpvp.2018.08.001
Received 6 June 2018; Received in revised form 1 August 2018; Accepted 5 August 2018
0308-0161/

Nomenclature

a	Inner radius of rotating disk
$A^{(i)}$	Weighting coefficients of *ith* order of spatial domain in *PDQ*
b	Outer radius of rotating disk
$B^{(i)}$	Weighting coefficients of *ith* order of spatial domain in *FDQ*
c	Specific heat
$C^{(i)}$	Weighting coefficients of *ith* order of time domain in *PDQ*
E	Young's modulus
K	Thermal conductivity
M	Number of grid points in circumferential coordinate
N	Number of grid points in radial coordinate
P	Number of grid points in time domain
t	Time
T	Temperature field
u	Radial component of displacement field
v	Circumferential component of displacement field
z	Axial coordinate

Greek symbols

α	Coefficient of thermal expansion
β	Grading index of material properties
ε_{ij} $(i, j=r, \theta)$	Strain field
θ	Circumferential coordinate
υ	Poisson's ratio
ρ	Density
σ_{ij} $(i, j=r, \theta, vm)$	Stress field
ω	Angular velocity

by joining material cells [24,25]. This advanced method can arbitrarily produce FG structures with the help of three-dimensional compositional gradients.

The thermoelastic responses of rotating disks made of FGM have been numerically and analytically presented in a number of references. The creep behavior of the FG rotating disks has been the main object in some studies [26–32] [33]. used layer-wise theory and investigated axisymmetric displacements and stresses in FG disks. The non-linear analysis of FG with the help of the dynamic relaxation and finite difference discretization techniques were presented by Ref. [34] [35]. Employed the higher-order shear deformation theory combined with multi-layer method to calculate thermal stresses of FG rotating thick cylindrical vessels [36]. Assumed a radial variation for material properties and numerically and analytically studied elastic-plastic behavior of FG disks [37]. Employed a shooting method and the Runge-Kutta strategy to investigate the stress response of an FG rotating disk [38]. used homotopy perturbation and Adomian's decomposition methods to calculate the distributions of stresses and displacements in rotating annular elastic disks, considering cases of both uniform and variable thickness and density [39]. Developed a semi-analytical solution for FG rotating disks. They developed a plane stress solution for both hollow and solid disks [40]. Developed an analytical method for investigating thermal stresses in an FG rotating disk rotating at a constant angular velocity about its central axis [41]. Presented an accurate elastic solution for rotating sandwich solid disks with faces made of different isotropic materials and the core made of FG material [42]. Employed the finite difference method and obtained the stress field in FG rotating disks.

In summary, considering the progressive demands of rotating machinery in many branches of industry, it is highly significant to explore structural integrity assessment and the management of material properties. Indeed, rotating disks frequently experience huge thermal gradients, putting at risk the safety of the whole structure. A quick review of the work carried out in the past decade revealed that little attention has been paid to multi-dimensional transient analysis of FG rotary systems under the domination of thermo-mechanical interactions. Inspired by the foregoing review and with the help of quadrature formulation, a numerical investigation is conducted to address the urgent need for redesign of rotating mechanisms undergoing r, θ-oriented transient thermal shocks, in order to boost performance industrially and extend operational life. It is highlighted that the transient deformations of FG rotating disks are markedly perturbed by grading parameters, temperature shocks, and body forces.

2. Description of the problem

A thin circular annular disk made of an FG, isotropic material with the inner radius of a and the outer radius of b is considered. In Fig. 1, a schematic view is provided of the geometry of the disk and the corresponding coordinate system, i.e. the r, θ, and z coordinates.

One of the most important applications of a thin rotating disk lies at turbine rotating components. As a core part of an aero-engine or gas turbine, the turbine disks operate subjected to severe and complex conditions of body forces and transient thermal loadings. Hence, a progressive structural deterioration is plausible as a result of the accumulation of creep and fatigue damages. The presented case study is a representative of the experimental-numerical analysis of turbine disks reported in some references [3,4,43–47].

The disk is assumed to be rotating at a constant angular velocity (ω) and subjected to thermal shocks as a function of the radial and circumferential coordinate, $T=T(r, \theta)$. As the disk rotates, the r-directional body force acts throughout the volume of the FG disk. In this work, the body force purely results from the angular velocity. Also, thermo-elastic analysis of the problem is conducted while the material properties are assumed to be temperature-independent. Material properties of the disk, namely the thermal conductivity (K), the Young's modulus (E), the coefficient of thermal expansion (α), and the density (ρ), are assumed to be functions of the radial and circumferential coordinates according to the following general formula:

$$Y = Y(r, \theta) \tag{1}$$

where $Y(r, \theta)$ represents the corresponding material property of the disk. Since the Poisson's ratio slightly varies in the range of 0.25–0.35 for most of the engineering materials, it is considered to be constant throughout the structure [40].

Typically, a radial-based function is assumed for the material

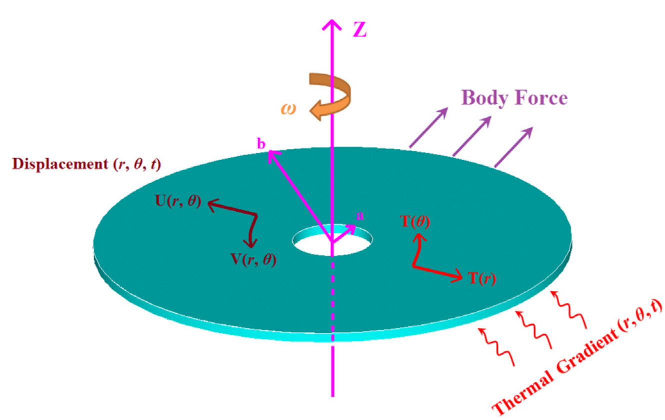

Fig. 1. Graphic view of the geometry of a rotating disk exposed to transient thermal gradients and body force.