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Dynamic interaction of heat transfer, air flow and disc vibration of disc drives — Theoretical development and numerical analysis

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ABSTRACT

Steady state air flow, heat transfer and thermoelastic dynamics in the multi-field coupling system of a rotating flexible disc in an enclosure filled with air are investigated within a large speed range. The system represents rotating discs in hard disc drives and optical disc drives. With Navier–Stokes and continuity equations and an improved penalty finite element method, air velocities and pressure induced by disc rotation in the enclosure are obtained. Temperature distribution of the rotating disc, driving shaft, enclosure and air flow is determined under the external heat sources from the shaft-driving motor and the circuit board inside the enclosure, the internal heat source from aerodynamic heating due to viscous dissipation of fluid, the heat convection in air flow, and the free convection heat loss at the enclosure's outside surfaces. Natural frequencies of the rotating disc are solved under the stresses induced by the disc temperature distribution and centrifugal force. Effects of heat convection and aerodynamic heating induced by disc rotation on system heat balance and dynamic characteristics of the rotating disc are investigated. The method presented is helpful to design of hard/optical disc drives and many other applications that involve rotating discs in fluids and with heat transfer.

1. Introduction

Discs are a widely used component in engineering, and they can rotate at high speed in the surrounding environment with fluid and heat transfer. The fluid flow and heat transfer induced by disc rotation and their influences on the dynamics of rotating discs are the fundamental and crucial issues concerning the performance of rotating discs, and they are subjects of great interest in academic research and industrial design [1]. Examples include turbo machineries, computer hard disc drives and optical disc drives. They can operate in harsh environments and involve multi-physical processes.

Firstly, considerable vibration and even flutter instability of a rotating disc can be caused by the fluid flow induced by disc rotation at supercritical speeds. In view of acoustic and structural interactions, Jana and Raman [2] and Kang and Raman [3,4] took the air flow to be initially quiescent, irrotational and infinitesimal, and they solved the wave equation governing the propagation of infinitesimal disturbances of air flow to analyse the vibration and stability of a rotating flexible disc. They found that coalescence between the acoustic and structural modes could lead to flutter instability at supercritical speeds. Some researchers [5–9] treated the coupling dynamics of the fluid flow and rotating disc as fluid and structure interaction problems. With the Reynolds equation of lubrication for thin film flows, Naganathan et al. [5] and Bajaj et al. [6] studied flutter instability and the forced harmonic response of a flexible disc rotating near a rigid wall in the presence of air, and found that the rotating disc could undergo flutter instability when the speed of rotation was above a critical speed, as discovered by a number of researchers in the recent past. Using Navier–Stokes and continuity equations, Gad and Rhim [7] investigated dynamics of a flexible disc coupled to thin air film and rotating close to a rigid rotating wall, and it was shown that the stability of the rotating flexible disc could be improved by a counter-rotating flat stabiliser. With the Navier–Stokes equations for an incompressible air flow of constant viscosity, Yuan et al. [8] studied the self-excited vibration induced by fluid forces of a rotating, umbrella-shaped disc in an open shroud, and Cheng et al. [9] designed several enclosure covers of an optical disc drive to improve the flow-induced vibration of rotating discs.

Secondly, heat transfer in the surrounding environment of rotating discs is affected considerably by the fluid flow induced by disc rotation in many applications [1]. Inamuro et al. [10] investigated the axisymmetric incompressible flow and heat transfer in a rotating cylindrical container with a counter-rotating disc, and discussed effects of disc rotation and of Prandtl numbers on them.

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Nomenclature

a	disc's outer radius
b	disc's inner radius
c_a	specific heat of air
e	the e-th ring element
e_{max}	maximum element length
e_{min}	minimum element length
E	Young's modulus
g_r	the second r-component of thermal membrane stress in the r direction
g_θ	the second r-component of thermal membrane stress in the θ direction
h	disc's thickness
h_a	convective heat transfer coefficient of air
J_m	thermal membrane stress resultant
k_a	thermal conductivity of air
k_r	the first r-component of thermal membrane stress in the r direction
k_s	thermal conductivity of shaft, disc and enclosure
k_θ	the first r-component of thermal membrane stress in the θ direction
l_r^m	the third r-component of thermal membrane stress in the r direction
l_θ^m	the third r-component of thermal membrane stress in the θ direction
L_b	enclosure's base thickness
L_g	enclosure's gap width
L_r	element size in the r direction
L_t	enclosure's cover thickness
L_w	enclosure's wall thickness
L_z	element size in the z direction
L_1	enclosure's upper cavity height
L_2	enclosure's lower cavity height
m	number of nodal circles of a disc mode
n	number of nodal diameters of a disc mode
p	relative air pressure
$\underline{p}$	averaged relative air pressure
P	steady state pressure difference across disc thickness
P_A	total heat generation power of aerodynamic heating
P_B	heat generation power of enclosure base
P_S	heat generation power of shaft base
q	aerodynamic heating flux
$\underline{q}$	averaged aerodynamic heating flux
q_B	heat flux to the enclosure's base
q_S	heat flux to the driving shaft
r	radial coordinate
r_0	radial coordinate at centre of a ring element
R	enclosure's inside radius
Re	Reynolds number
t	time
T	temperature
T_a	atmospheric temperature
u_r	radial air velocity component
u_z	transversal air velocity component
u_θ	circumferential air velocity component
$\underline{u}_r$	averaged radial air velocity component
$\underline{u}_z$	averaged transversal air velocity component
$\underline{u}_\theta$	averaged circumferential air velocity component
V_a	solution domain of air media
V_s	solution domain of solid media
w	disc's transverse deflection
$w_{m,n}$	modal coordinate of disc's transverse deflection corresponding to disc mode (m, n)
z	transverse coordinate
z_0	transversal coordinate at centre of a ring element
α_T	coefficient of linear thermal expansion
$\gamma_{m,0}$	self-adjoint eigenvalue
Γ	temperature increment
$\underline{\Gamma}$	averaged temperature increment
Γ_{Air}	temperature increment due to internal heat generation
$\underline{\Gamma}_{Air}$	averaged temperature increment due to internal heat generation
Γ_{Base}	mean temperature increment due to internal heat generation
$\underline{\Gamma}_{Base}$	averaged temperature increment due to external heat generations
ε	penalty parameter
η_r	dimensionless radial coordinate
η_z	dimensionless transversal coordinate
θ	circumferential coordinate
Θ_M	mean temperature increment
Θ_M^{Air}	mean temperature increment due to internal heat generation
Θ_M^{Base}	mean temperature increment due to external heat generation
Θ_Q	'moment' of the temperature increment
λ	eigenvalue
μ_a	coefficient of air viscosity
ν	Poisson's ratio
ξ_r	radial thermal membrane stress resultant
ξ_θ	circumferential thermal membrane stress resultant
ρ	disc's density
ρ_a	air density
σ_r	radial membrane stress resultant due to centrifugal force
σ_θ	circumferential membrane stress resultant due to centrifugal force
$\varphi_{m,n}$	mode shape of disc mode (m, n)
Φ	potential function of viscous dissipation
Ψ	thermal stress function
Ψ_H	homogenous part of thermal stress function
Ψ_N	non-homogenous part of thermal stress function
$\omega_{m,n}$	natural frequency of disc mode (m, n)
Ω	disc's rotating speed
Ω_{cr}	lowest disc's critical speed
Ω_M	maximum disc speed
$\mathrm{I}_n(r)$	modified Bessel function of the first kind
$\mathrm{J}_n(r)$	Bessel function of the first kind
$\mathrm{K}_n(r)$	modified Bessel function of the second kind
$\mathrm{Y}_a(r)$	Bessel function of the second kind
Superscript $^{-1}$	matrix inverse
Superscript ^{T}	matrix transpose
Superscript $'$	derivative with respect to radial coordinate r, i.e. d/dr
Superscript $\sim$	conversion matrix or vector at heat flux boundaries
Superscript ^	($\boldsymbol{I}_P$ or $\boldsymbol{J}_P$ rows, $\boldsymbol{I}_P$ or $\boldsymbol{J}_P$ columns) elements in a matrix; ($\boldsymbol{I}_P$ or $\boldsymbol{J}_P$ rows) elements in a vector
Superscript $^-$	($\boldsymbol{I}_P$ or $\boldsymbol{J}_P$ rows, $\boldsymbol{i}_B$ or $\boldsymbol{j}_B$ columns) elements in a matrix; ($\boldsymbol{i}_B$ or $\boldsymbol{j}_B$ rows) elements in a vector
Constant	normal upright 'A'
Matrix	bold upright '**A**'
Variable	normal italic '*A*'
Vector	bold italic '***A***'