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A theoretical investigation on the vibrational characteristics and torsional dynamic response of circumferentially cracked turbo-generator shafts

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Abstract

Turbo-generator shafts are often subjected to complex dynamic torsional loadings, resulting in generation and propagation of circumferential cracks. Mode III fatigue crack growth generally results in a fracture surface consisting of peaks and valleys, resembling a factory roof. The fracture surface roughness depends on the material microstructure, the material yield strength, and the applied cyclic torque amplitude. This crack pattern can severely affect the vibration characteristics of the shafts. The accurate evaluation of the torsional dynamic response of the turbo-generator shafts entails considering the local sources of energy loss in the crack vicinity. The two most common sources of the energy loss are the local energy loss due to the plasticity at the crack tip and frictional energy loss due to interaction of mutual crack surfaces. A theoretical procedure for evaluating the values of the system loss factors corresponding to these sources of energy loss is presented. Furthermore, the local flexibility is obtained by evaluating the resistance of the cracked section of the shaft to the rotational displacement. The shaft material is assumed to be elastic perfectly plastic. The effects of the applied Mode III stress intensity factor and the crack surface pattern parameters on the energy loss due to the friction and the energy loss due to the plasticity at the crack tip are investigated. The results show that depending on the amplitude of the applied Mode III stress intensity factor, one of these energy losses may dominate the total energy loss in the circumferentially cracked shaft. The results further indicate that the torsional dynamic response of the turbo-generator shaft is significantly affected by considering these two sources of the local energy loss.

Keywords: Turbo-generator shafts; Circumferential crack; Transient torsional loading; Crack surface interaction; Crack tip plasticity; Torsional dynamic response; Local energy loss

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Nomenclature

a	radius of uncracked region
a_i	dimensionless parameter
b	crack length
c_t	torsional damping constant
h	asperity height
k_t	torsional spring constant
r_P	plastic zone radius for Mode III cyclic loading
r^*	distance from the crack tip in a specified direction
x_1	extent of the crack surface interaction
u_1	axial crack opening displacement at the point x_1
$u_3(x)$	shear displacement
u_{3T}	shear displacement at the crack mouth
$\overline{u_P}$	energy loss density at each point in the plastic zone
α	asperity angle
$\bar{\varepsilon}$	effective strain
$\bar{\sigma}$	effective stress
σ_0	normal stress at the crack tip, Case A
σ_Y	material yield stress
μ	columb friction coefficient
λ	asperity wavelength
ξ	dimensionless parameter
η	loss factor of the spring-damper model
η_P	loss factor of the model due to plasticity at the crack tip
η_f	loss factor of the model due to friction of the mating crack surfaces
ω	frequency of harmonic torque
Φ	response amplitude for the spring-damper model
Γ	effective frictional coefficient
E	material elastic modulus
G	material shear modulus
K_{eff}	effective stress intensity factor
K_{III}	applied stress intensity factor
K_{fric}	frictional stress intensity factor
L	shaft length
$M(\gamma)$	dimensionless parameter
$N_1(\gamma)$	dimensionless parameter
$N_2(\gamma)$	dimensionless parameter
R	shaft radius
R^*	extent of the plastic zone in a specified direction
T	applied torque
U_P	energy loss due to the plastic deformation at the crack tip in one cycle
U_f	energy loss due to friction between the mating fracture surfaces in one cycle
U	total energy loss in one cycle
ΔW	energy loss in one cycle for the spring-damper model