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Dynamics analysis of planar rigid-flexible coupling deployable solar array system with multiple revolute clearance joints

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ABSTRACT

This paper numerically analyzes action of journal at clearance joint and interaction of journal between multiple clearance joints to reveal the dynamic behavior of planar rigid-flexible coupling solar array system considering joint clearance in depth. A typical solar array model used is composed of a rigid main-body described by Nodal Coordinate Formulation (NCF) and two flexible panels described by Absolute Nodal Coordinate Formulation (ANCF). The system consists of two torque springs, one closed cable loop (CCL) configuration, two latch mechanisms and two clearance joints. The normal contact force effect and tangential friction effect at clearance joint are considered by using nonlinear contact force model and amendatory Coulomb friction model, respectively. Action and interaction of clearance joints are studied to indicate motion property of journal in initial phase, deployment phase and post-lock phase, which provide foundations for effect analysis of overall dynamic behavior. Then comparison results reveal the effects of joint clearance, panel flexibility and their coupling on dynamics of solar array system at these three phases. Coupled with clearance at collision phase, elastic vibration property of flexible panels dominates to cause system shock; while coupled with clearance at contact phase, suspension damping property of flexible panels dominates to steady the system. Finally, rational distribution of clearance size may provide a way to balance wear degree between joints. Decrease joint clearance with more intense collision could reduce the wear depth and balances wear degree between clearance joints.

1. Introduction

Joint clearance is inevitable in articulated multi-body mechanisms due to the design, manufacture and assembly processes. Follows, a wear performance will intensify the clearance effect. Generally, vibration, noise, and large instantaneous impact forces at joints are the characteristics of the multi-body system with clearance joints. These joint clearance effects may reduce system's accuracy, reliability and stability, lead to failure of the mechanism's kinematic and dynamic outputs, or even destroy the mechanism.

Over the last few decades, many researchers have studied effects of clearance on dynamic responses of planar and spatial multi-body mechanisms using theoretical and experimental approaches. Flores et al. [1–6] compared the kinematic and dynamic responses of rigid planar and spatial multi-body systems considering dry and lubricated friction, and studied the effects of clearance size and the operating conditions on predicting the dynamic responses of multibody systems. Erkaya

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Nomenclature

T	torque of mechanism ($N \cdot m$)
K	stiffness ($N \cdot m/rad$)
l	distance between two wheels (m)
φ	relative rotation angle of two wheels (m)
ϕ	angle between the center line of two wheels and the belt (m)
θ	angle (rad)
$\mathbf{A}$	rotation matrix
$\mathbf{r}$	position vector in global coordinate
$\bar{\mathbf{r}}$	position vector in local coordinate
$\mathbf{C}_P$	coordinate transformation matrix
$\mathbf{S}$	shape function
$\mathbf{f}_p$	concentrated force
$\mathbf{M}$	mass matrix (kg)
$\mathbf{M}$	torque ($N \cdot m$)
$\mathbf{q}_e$	generalized coordinates of element
$\mathbf{q}$	generalized coordinates of system
ρ	density (kg/m^3)
$\mathbf{Q}_{ex}$	generalized external force matrix
$\mathbf{Q}$	generalized elastic force matrix
k	curvature (m^{-1})
ε	strain
$\mathbf{v}_t$	relative tangent velocity (m/s)
$\mathbf{d}$	eccentricity vector (m)
$\mathbf{n}$	normal direction
$\mathbf{t}$	tangential direction
δ	penetration depth (m)
R_b	radius of the bearing (m)
R_j	radius of the journal (m)
C_e	restitution coefficient
$\mathbf{F}_n$	normal contact force (N)
E	Young's modulus
u	Poisson's ratio
$\dot{\delta}^{(-)}$	initial impact velocity
$\mathbf{F}_t$	tangential friction force (N)
c_f	friction coefficient
c_d	dynamic correction coefficient
$\Phi_{\mathbf{q}}$	Jacobi matrix of constraint equation
λ	Lagrange multiplier column matrix
$\mathbf{C}$	damping matrix
$\mathbf{F}_c$	generalized contact force matrix
K_W	dimensionless wear coefficient
H	hardness of materials
s	relative slippage distance of contact surface
p	normal contact pressure
h	wear depth

et al. [7–10] revealed that a flexible small-length flexural pivot plays suspension effects to decrease the undesired responses of the system with clearance joints by comparing the mechanism having rigid and flexible links. Tian Q et al. [11–15] used Absolute Coordinate Based method to establish flexible multibody systems with dry and ElastoHydroDynamic lubricated clearance joints. Marques et al. [16] presented a new formulation to model spatial revolute joints with radial and axial clearances. Zheng E et al. [17,18] used ADAMS software to model flexible multibody mechanism for ultra-precision presses and a closed high-speed press system. Salahshoor et al. [19] used multiple scales method to conduct a vibration analysis of a mechanical system with multiple clearance joints. And some researchers investigated kinematics and dynamics of 3-RRR and 4-RRR parallel mechanisms with clearance joints [20,21]. Marques et al. [25] used a spatial four-bar mechanism with a spherical joint as an application example to examine and quantify the effects of various friction force models, clearance sizes, and the friction coefficients. On the other hand for some biological applications, Askari et al. [22,23] developed a spatial multibody dynamic hip model using a friction-velocity constitutive law combined with a Hertzian contact model and