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Research paper

A nonlinear six degrees of freedom dynamic model of planetary roller screw mechanism

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ABSTRACT

A nonlinear six degrees of freedom (DOFs) dynamic model to determine the motion and internal forces acting on the moving parts of the planetary roller screw mechanism (PRSM) is proposed in this paper. A load distribution coefficient is assumed and introduced to describe the load distribution among threads of the screw, roller and nut. The friction forces at the screw-roller, nut-roller and ring gear-carrier interfaces are calculated by using the Coulomb friction, rolling contact and Couette flow principles, respectively. Because the friction and contact forces acting on the screw, roller, nut and carrier constitute a spatial force system, the equations of motion for the PRSM, which are derived by using Newton's second law, relate the forces to the six DOFs of those parts. The transient and steady-state behaviors of the PRSM under a heavy or light external load and the sinusoid motion of the mechanism are simulated and discussed. The results show that the load conditions have great influence on the motion and internal forces of the PRSM.

1. Introduction

A planetary roller screw mechanism (PRSM) is a mechanical device that is mainly applied in electromechanical actuator (EMA) to convert rotational into linear motions. It has a symmetrical structure that splits the external load amongst each nut-roller-screw path and offsets radial forces. Also, there are a large number of contact points at the screw-roller and nut-roller interfaces. Thus, the PRSM has the advantages of high power-to-weight ratio, high speed capability and high reliability.

As the high performance and wide application of the PRSM [1,2], many aspects of it have been studied such as contact position and clearance [3–7], load distribution among threads [8–13], load sharing among rollers [14], slip tendency [15], kinematic analysis [16–19], transmission accuracy [20–21], lubrication and wear behavior [22–24], friction heat [25], dynamic load test [26], working capacity criteria [27], manufacturing [28] and the measurement of thread profile [29]. Even though dynamic analysis is essential to determine the motion and forces acting on the screw, roller, nut and carrier in the PRSM when the screw rotates, very few researchers have proposed relevant dynamic models. The limited number of studies found in the open literature is summarized next.

Using Lagrange's Method, Jones et al. [30] derived the dynamic equations of motion for the PRSM. They introduced a viscous friction coefficient to calculate the friction force at the screw-roller interface and simulated the transient and steady-state behaviors of the PRSM. The results of the simulation showed that the steady-state carrier rotational velocity obtained

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Nomenclatures

F_{Nz}	External load acting on the nut
$\mathbf{f}^q_{qs,k}$, $\mathbf{f}^q_{qn,k}$	Friction forces acting on the *k*th thread tooth of the roller #*q* at the screw and nut sides
$\mathbf{f}^q_{qp,j}$	Friction force acting on the *j*th pin of the roller #*q*
$\mathbf{f}^P_{Sq,k}$, $\mathbf{f}^P_{Nq,k}$	Friction forces acting on the threads of the screw and nut
$\mathbf{F}^P_{Sq,k}$, $\mathbf{F}^P_{Nq,k}$	Contact forces acting on the threads of the screw and nut
$\mathbf{F}^q_{qs,k}$, $\mathbf{F}^q_{qn,k}$	Contact forces acting on the *k*th thread tooth of the roller #*q* at the screw and nut sides
$\mathbf{F}^q_{qg,\ j}$, $\mathbf{F}^q_{qp,j}$	Contact forces acting on the *j*th spur gear and *j*th pin of the roller #*q*
$\mathbf{F}_{Np,j}$	Contact force between the nut and carrier #*j*
$\mathbf{F}^P_{Nqg,j}$	Contact force between the ring gear and the *j*th spur gear on the roller #*q*
$\mathbf{H}^{Pq}_q$	Rotational matrix relating the coordinate system o_q-$x_qy_qz_q$ to the local coordinate system o_{Pq}-$x_{Pq}y_{Pq}z_{Pq}$
$\mathbf{H}^{Pq}_{Nq}$	Rotational matrix relating the coordinate system o_{Nq}-$x_{Nq}y_{Nq}z_{Nq}$ to the local coordinate system o_{Pq}-$x_{Pq}y_{Pq}z_{Pq}$
$\mathbf{H}^{Nq}_{En}$	Rotational matrix relating the coordinate system o_{En}-$x_{En}y_{En}z_{En}$ to the coordinate system o_{Nq}-$x_{Nq}y_{Nq}z_{Nq}$
I_S, I_q, $I_{P,j}$	Rotational inertia of the screw, roller #*q* and carrier #*j*
j	$j = 1$ or 2
*k*kth	*k*ththread tooth on the roller
m_q, m_N, $m_{P,j}$	Mass of the roller #*q*, nut and carrier #*j*
M_{Sz}	Torque acting on the screw
$M_{fpr,j}$	Drag torque acting on the carrier #*j* caused by lubricant oil/grease
q	Roller #*q*
$\mathbf{M}^q_{fqn,k}$	Friction torque acting on the *k*th thread teeth of the roller #*q* at the nut side
$\mathbf{T}_{Pq}$	Coordinate transformation matrix relating the local coordinate system o_{Pq}-$x_{Pq}y_{Pq}z_{Pq}$ to the global coordinate system *O-XYZ*
μ_{SR}	Friction coefficient between the screw and roller
μ_{NR}	Friction coefficient between the nut and roller
ν_{PG}, ρ_{PG}	Viscosity and density of lubricant oil/grease
ζ_T	Load distribution coefficient
ζ_{PS}	Ratio between th e rotational velocities of the carrier and screw
η	Efficiency
$\dot{\theta}_S$, $\dot{\theta}_P$, $\dot{\theta}^P_q$	Rotational velocities of the screw, carrier and roller #*q*

from the dynamic model [30] was slightly slower than that from the purely kinematic model [17]. They also studied the influence of the lead and flank angle on the magnitude of the steady-state slip velocity between the screw and roller.

The model proposed by Jones et al. [30] is the first work to theoretically analyze the dynamics of the PRSM, and there are some factors needed to be considered for a better understanding of the dynamic characteristics of the mechanism. Firstly, the external load acting on the nut is unequally shared over the threads at the screw-roller and nut-roller interfaces, even though the screw, roller and nut are regarded as rigid bodies [10]. Secondly, to determine the forces acting on the moving parts of the PRSM, the radial force between the carrier and roller, the contact force between the ring gear and roller, and the friction forces at the ring gear-carrier, carrier-roller and nut-roller interfaces should be considered in the equations of motion for the PRSM. Lastly, as the forces acting on the screw, roller, nut and carrier constitute a spatial force system, the forces must be related to the coordinates of those parts in dynamic model.

In view of the gap that exists in the literature, in this study, a nonlinear six degrees of freedom (DOFs) dynamic model of the PRSM is proposed, which is used to determine the motion and internal forces acting on the moving parts of the mechanism without considering the deformations and errors of those moving parts. Referring to the model proposed by Blinov et al. [10], a load distribution coefficient is assumed and introduced to describe the distribution of contact forces between threads at the screw-roller and nut-roller interfaces. Then, the contact force between the roller and carrier and that between the spur gear on the roller and ring gear are analyzed. The friction forces at the screw-roller and carrier-roller interfaces are obtained by using Coulomb's friction model [31]. As there is no slip between the nut and roller [17], the theory of rolling contact [32] is used to calculate the friction force at the nut-roller interface. Besides, the drag torque between the ring gear and carrier caused by lubricant oil/grease are derived. Considering the contact positions of the PRSM given in Ref. [7] and using Newton's second law, the equations of motion for the screw, roller, nut and carrier are derived. The rotational velocity of the carrier obtained from the proposed model is compared with that from Ref. [30], when the friction force at the screw-roller interface is calculated by using the viscous friction coefficient in Ref. [30] and the friction forces at the other interfaces are neglected. At last, the transient and steady-state behaviors and sinusoid motion of the PRSM are simulated.