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Research on two methods for improving the axial static and dynamic characteristics of hydrostatic lead screws

Yongtao Zhang[a,b], Changhou Lu[a,b,*], Jinkui Ma[a,b]

[a] School of Mechanical Engineering, Shandong University, Jinan 250061, PR China

[b] Key Laboratory of High-efficiency and Clean Mechanical Manufacture (Shandong University), Ministry of Education, Jinan 250061, PR China

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ABSTRACT

This paper researches two methods for improving the axial static and dynamic characteristics of hydrostatic lead screws, i.e. (a) using membrane restrictor instead of capillary restrictor and (b) utilizing the intentional periodic pitch errors in the nut to generate hydrodynamic effect of the lubricating film. The Reynolds' equation, which is applicable to the lubricating film in hydrostatic lead screws, is deduced based on the equivalent plane of the flank surface of threads. The perturbation technique and the finite difference method are used to obtain the static and dynamic characteristics. The JFO boundary condition is used for capturing the cavitation. The results show that the axial static and dynamic characteristics can gain a marked improvement by combining the two methods.

1. Introduction

The superior characteristics of hydrostatic lead screws, such as near-frictionless transmission, high load capacity, high stiffness, and high motion accuracy [1], just adapt to the development of machine tools towards the direction of high speed, heavy load, and high accuracy. Furthermore, hydrostatic lead screws overcome the disadvantages of ball screws, such as contact wear, high speed collision, and heavy load pitting [2]. Recently, hydrostatic lead screws get more attention and application [3].

In a feed system, external radial forces and overturning moments are mainly supported by guideways, and external axial forces are mainly supported by hydrostatic lead screws. The main concern for a feed system is the axial characteristics of hydrostatic lead screws. The lubricating film has both hydrostatic effect and hydrodynamic effect when hydrostatic equipment operates in a hybrid mode, which enlightens us that the axial static and dynamic characteristics of hydrostatic lead screws can be improved in the following two aspects: (a) from the view point of enhancing hydrostatic effect: adjusting the method of compensation, and (b) from the view point of enhancing hydrodynamic effect: creating fluctuant film clearance for generating hydrodynamic effect.

El-Sayed and Khatan [4] proposed an equivalent sectorial plane of the flank surface of threads, which included the influence of the bending of helicoid due to the helix and thread angles and was used to exactly calculate the static characteristics of hydrostatic lead screws. Actually, the equivalent sectorial plane is an approximately unfolded drawing of the flank surface of threads. Then El-Sayed and Khatan [1] optimized the dimension parameters of threads in hydrostatic lead screws according to two criteria, i.e. maximum load per unit power and maximum stiffness per unit power. And they [5] put forward two possible methods for eliminating the inherent overturning moments applied on the hydrostatic nut, caused by the radial component of the film force. Bassani proposed a flow self-regulating hydrostatic lead screw with trapezoidal threads [6] and rectangular threads [7], in which the total flow from the pump was automatically separated into two half flows in the two helical recesses. The literature [8] compared the performance of the flow self-regulating hydrostatic lead screw with that of the ordinary hydrostatic lead screw supplied by two pumps, or by one pump but through two flow regulators. Zhang et al. [9] researched the averaging effect of the lubricating film on pitch errors in hydrostatic lead screws with continuous helical recesses, by transforming the hydrostatic lead screw into a specific hydrostatic guideway and based on the static equilibrium of the hydrostatic nut. Then Zhang et al. [10] investigated the transient motion of hydrostatic lead screws under high speeds and variable external loads, which reflected the motion accuracy, the running stability, and the ability to resist variable external loads.

The performance of hydrostatic equipment is greatly affected by the type of restrictors, i.e. fixed-flow restrictor (capillary, orifice and constant flow valve) and variable-flow restrictor (membrane type and spool-type restrictor). Morsi [11] comparatively studied the static

* Corresponding author.
E-mail address: luchh@sdu.edu.cn (C. Lu).

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Nomenclature

A_m	effective area of membrane, mm^2
C_a	axial damping coefficient, N s/mm
D	effective diameter, mm
d_c	diameter of capillary restrictor, mm
E	amplitude of intentional periodic pitch errors, mm
$f_k(\theta)$	intentional periodic pitch errors in nut, mm
g	switch function
h_{a0}	designed axial clearance, mm
h_{ak}	axial film thicknesses, mm
h_k	normal film thicknesses, mm
h_{m0}	designed gap-height in membrane restrictor, mm
h'	normal film thickness on unfolded sectorial plane, mm
K_m	stiffness of membrane, N/mm
l_c	length of capillary restrictor, mm
n	number of nut threads with helical recesses
o-xyz	rectangular coordinates located on nut
o-$r\theta$	polar coordinates located on nut
o'-$r'\theta'$	polar coordinates located on unfolded sectorial plane
P	lead, mm
p_c	cavitation pressure, Pa
p'	pressure, Pa
p'_r	recess pressure, Pa
p_s	supply pressure, Pa
Q	total flow of lubricant, mm^3/s
Q_c	flow of lubricant through capillary restrictor, mm^3/s
Q_m	flow of lubricant through membrane restrictor, mm^3/s
r_i	inner radius of nut, mm
r_o	outer radius of lead screw, mm
r'_i	inner radius of unfolded sectorial plane, mm
r'_o	outer radius of unfolded sectorial plane, mm
r_{m1}	inner radius of sill in membrane restrictor, mm
r_{m2}	outer radius of sill in membrane restrictor, mm
r_1	inner radius of recess, mm
r_2	outer radius of recess, mm
r_c	curvature radius, mm
S_a	axial stiffness coefficient, N/mm
T	period of intentional periodic pitch errors
W_a	axial load capacity, N
α	half of thread angle
γ	designed pressure ratio
Δh	displacement of nut, mm
Δz	axial displacement disturbances, mm
$\Delta\dot{z}$	axial velocity disturbances, mm/s
η	dynamic viscosity of lubricant, Pa s
ρ	density of lubricant, kg/m^3
ρ_c	density of lubricant at cavitation pressure, kg/m^3
θ_r	wrap angle of helical recess in the θ direction
β	bulk modulus of lubricant, Pa
λ_r	helix angle
φ_1, φ_2	phase of intentional periodic pitch errors
ϕ	film content
ω	rotational speed of lead screw, r/s

Non**-dimensional **Parameters

$\overline{C}_a$	$C_a(h_{a0}^3/\eta r_o^4)$
$\overline{C}_{sr}$	$\pi d_c^4/(128 h_{a0}^3 l_c)$, for capillary restrictor
$\overline{C}_{sr}$	$\frac{\pi}{6\ln(r_{m2}/r_{m1})}\left(\frac{h_{m0}}{h_{a0}}\right)^3$, for membrane restrictor
$\overline{C}_m$	$A_m p_s/(K_m h_{m0})$, membrane compliance
$\overline{h'}$	h'/h_{a0}
$\Delta\overline{h}$	$\Delta h/h_{a0}$
$\overline{p'}$	p'/p_s
$\overline{p'}_r$	p'_r/p_s
$\overline{p'}_{\bar{z}k}$	$\partial\overline{p'}_k/\partial\bar{z}$
$\overline{p'}_{\bar{\dot{z}}k}$	$\partial\overline{p'}_k/\partial\bar{\dot{z}}$
$\overline{Q}$	$Q(\eta/p_s h_{a0}^3)$
$\overline{Q}_c$	$Q_c(\eta/p_s h_{a0}^3)$
$\overline{Q}_m$	$Q_m(\eta/p_s h_{a0}^3)$
$\overline{r}$	r/r_o
$\overline{r'}$	r'/r_o
$\overline{r_c}$	r_c/r_o
$\overline{S}_a$	$S_a(h_{a0}/p_s r_o^2)$
$\overline{W}_a$	$W_a/p_s r_o^2$
$\Delta\bar{z}$	$\Delta z/h_{a0}$
$\Delta\bar{\dot{z}}$	$\eta r_o^2\Delta\dot{z}/(p_s h_{a0}{}^3)$
$\overline{\omega}$	$\eta r_o^2\omega/(p_s h_{a0}{}^2)$
$\overline{\beta}$	β/p_s
τ	$t(p_s h_{a0}{}^2/\eta r_o^2)$
Λ	$12\rho_c r_o^2\omega^2\cos\alpha/p_s$

Subscripts and superscripts

k	1, 2
a	axial
c	capillary or curvature
m	membrane
r	recess
s	steady or supply
0	initial or steady-state
1	on the top side of nut thread
2	on the bottom side of nut thread
$'$	on the unfolded sectorial plane

stiffness and power requirement of a hydrostatic thrust bearing compensated by fixed-flow restrictor and variable-flow restrictor, in which the variable-flow restrictor showed obvious advantage. Wang and Cusano [12] analyzed the dynamic characteristics of a double-pad circular thrust with membrane compensation under static loads or load composed of a static and cyclic component. The results indicated that membrane compensation gave better overall performance than capillary compensation. Jain et al. [13] comparatively studied the static and dynamic characteristics of a multi-recess flexible journal bearing compensated by different restrictors, including capillary, constant flow valve, orifice and membrane restrictors. Singh et al. [14] analyzed the influence of the type of restrictor on the static and dynamic characteristics of a multi-recess flexible journal bearing considering various recess shapes. The literatures [13,14] indicated that the membrane restrictor had obvious advantage in the minimum film thickness, the dynamic stiffness, the damping and the stability threshold speed margin. In a water-lubricated hydrostatic thrust bearing, Gohara et al. [15] used membrane restrictor to achieve higher stiffness and lower power consumption.

Additionally, Liang et al. [16] put forward a concept of dynamic pressure ratio for quantitatively measuring the hydrodynamic effect on the bearing land, and investigated the variation of dynamic pressure ratio with the eccentricity ratio and the rotating speed in a four-recess capillary compensated hydrostatic journal bearing.

The cavitation can exert significant influence on the performance of hydrostatic lead screws and will occur in different locations due to the fluctuant film clearance. In the Reynolds' boundary condition, the film rupture is appropriately treated but the reformation of the film is essentially neglected [17]. The Jakobsson-Floberg-Olsson (JFO) boundary condition can satisfy mass conservation in both the full-film