Tribology International 95 (2016) 279–289

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

A method for predicting hydrostatic guide error averaging effects based on three-dimensional profile error

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ARTICLE INFO

Article history:
Received 7 June 2015
Received in revised form
22 October 2015
Accepted 22 November 2015
Available online 2 December 2015

Keywords:
Error averaging effect
Analytical method
Hydrostatic guide
Straightness error

ABSTRACT

A method for evaluating the error averaging effect of hydrostatic guides is proposed, which considers three-dimensional profile error of guides. Error averaging models for hydrostatic guides with single pad and double opposed pads are deduced, respectively. Results show that the error averaging effect is influenced by the profile error in both the width and length directions of hydrostatic guides. Additionally, the oil film stiffness plays an essential part in the error averaging effect when a hydrostatic guide is composed of opposed pads. Experimental results show the method is effective for predicting linear motion error caused by components profile error.

1. Introduction

Hydrostatic guides, characterized with high motion accuracy, high stiffness, high damping and almost no wear, have been widely applied to ultra-precision machine tools and equipment [1,2]. They are capable of obtaining higher accuracy in components with relatively lower machining accuracy because of the so called error averaging effect of the supporting oil films [3–5]. It has been found empirically that the accuracy of a hydrostatic guide is about 4 to 10 times smaller than its components' accuracy or even better depending on skilled operators who perform the finish lapping of guide components.

The error averaging effect enables mechanical engineers to build precision machines with accuracies higher than their relatively low component accuracy. There has been dozens of monographs and papers, e.g. by Rowe [6], Hamrock et al. [7], Cheng et al. [8], Mekid [9] and so on, to guide the design and performance analysis of hydrostatic/aerostatic guide. To design and obtain hydrostatic guides of higher accuracy, currently, researchers have investigated error averaging effects to identify parameters influencing its effect quantitatively compared to different mathematical models. Park et al. [10] proposed a transfer function method to analyze the error averaging effect of an oil film quantitatively, and validated the transfer function method by an experiment successfully [11]. Shamoto et al. [12] derived the relationship between the film reaction force and guide rail profile errors of a hydrostatic guide with single pad by a finite element method (FEM), and proposed a new rail surface lapping method to improve the motion accuracy of hydrostatic guides. Xue et al. [13] investigated the mechanism and affecting factors of the error averaging effect in detail, and proposed a new method to quantitatively analyze the motion errors of a typical closed hydrostatic guide with four pads. Wang et al. [14] established a new model to analyze the influence of hydrostatic carriage speeds on the motion errors of a closed hydrostatic guide with four pads. Ekinci et al. [15] simplified the fluid film into spring elements to establish an analytical accuracy model of aerostatic guides based on static equilibrium and verified the model experimentally.

All of these studies have proved a basic fact that the film thickness will fluctuate due to the profile error of the guide rail, which results in the pressure fluctuation in the oil pocket when the hydrostatic guide carriage moves. However, the previous studies take only the rail profile error in the guide length direction into account, with the machining tolerance in the guide width direction neglected. Obviously, the machining error in the guide width direction also induces the oil film clearance variation of a hydrostatic guide, leading to the motion error of a hydrostatic guide. Therefore, it is necessary to establish a new model to reveal the mechanism of the error averaging effect of hydrostatic guides in both the guide length and width directions.

In this paper, we first established an analytical model that considered machining tolerances in both guide width and length directions. Based on the model, the influence of profile errors in

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http://dx.doi.org/10.1016/j.triboint.2015.11.032
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Nomenclature

A	area of bearing land, mm^2
A_e	effective area of hydrostatic guide pad
A_o	orifice restriction area, mm^2
B	hydrostatic pad width, mm
C_d	orifice discharge coefficient (0.5–0.7)
C_{i0}	initial oil film damping of hydrostatic pad numbered i ($i=1,2$), N s/m
C_{ie}	equivalent oil film damping of hydrostatic pad numbered i ($i=1,2$), N s/m
C_{ir}	oil film damping of hydrostatic pad numbered i ($i=1,2$) in work, N s/m
D_{mn}	coupling profile error amplitude, mm^2
E_x	profile error amplitude in the guide rail length direction, μm
E_{xm}	m-th order profile error amplitude in the x direction ($m=1,2\ldots$), μm
E_y	profile error amplitude in the guide rail width direction, μm
E_{yn}	n-th order profile error amplitude in the x direction ($n=1,2\ldots$), μm
L_s	guide rail length, mm
P_a	ambient pressure, MPa
P_r	downstream supply pressure of orifice, MPa
P_s	upstream supply pressure of orifice, MPa
S	hydrostatic guide stroke, mm
$V_{p\text{-}p}$	straightness, μm
W	load capacity of a hydrostatic guide, N
W_p	payload, N
b	bearing land width in the guide width direction, mm
d	orifice diameter, mm
d_p	recess depth, mm
h_0	initial oil film clearance, μm
h_e	equivalent oil film clearance, μm
h_{er}	profile error of a guide rail, μm
h_{i0}	initial oil film thickness of hydrostatic pad numbered i ($i=1,2$), μm
h_{ie}	equivalent oil film thickness of hydrostatic pad numbered i ($i=1,2$), μm
h_{ir}	oil film thickness of hydrostatic pad numbered i ($i=1,2$) in work, μm
k_{i0}	initial oil film stiffness of hydrostatic pad numbered i ($i=1,2$), N/μm
k_{ie}	equivalent oil film stiffness of pad numbered i ($i=1,2$), N/μm
k_{ir}	oil film stiffness of hydrostatic pad numbered i ($i=1,2$) in work, N/μm
l	bearing land width in the guide length direction, mm
λ_x	profile error wavelength in the guide rail length direction, mm
λ_y	profile error wavelength in the guide rail width direction, mm
μ	dynamic viscosity of lubricant, Pa s
ρ	fluid density, kg/mm^3
φ_x	initial phase angle of guide rail profile error in the x direction
φ_y	initial phase angle of guide rail profile error in the y direction
φ_{xm}	phase angle for the m-th order component of guide rail profile error in the x direction
φ_{yn}	phase angle for the n-th order component of guide rail profile error in the y direction
θ_{mn}	phase angle for the coupling profile error non-dimensional parameters
ζ	error averaging factor
ξ_x	L/λ_x
ξ_y	B/λ_y

both guide length and width directions on the error averaging effect was analyzed quantitatively. After that, error averaging effects of hydrostatic guides with different structures were investigated by this model, respectively. In addition, the influence of oil film stiffness was studied and discussed. Based on the results obtained, some additional guide lines for ultra/high precision hydrostatic guide design were summarized. At last, an experiment was given to verify the method we proposed.

2. Methodology

2.1. Mechanical structure and model

A hydrostatic guide of single pad, composed of a guide rail, a pad, an oil recess, bearing lands, an orifice restrictor, and oil film between the pad and the guide rail, is shown in Fig. 1. Theoretically, all these parameters should be identical to the values

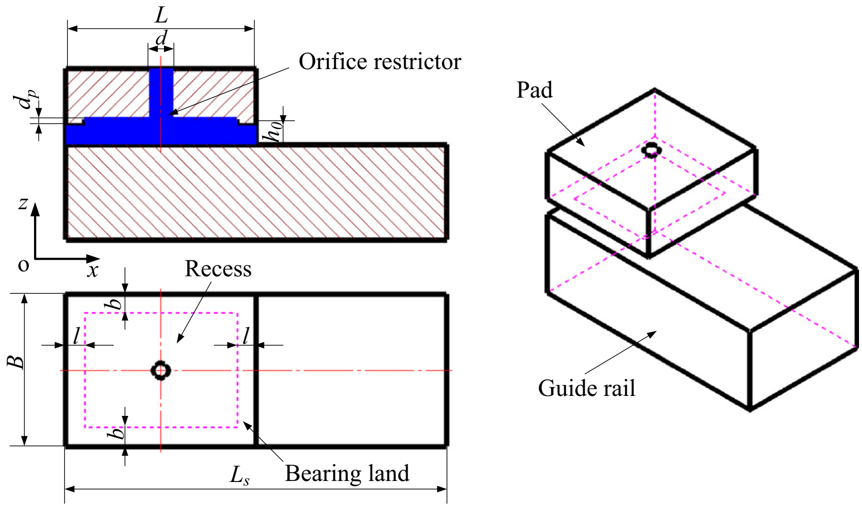

Fig. 1. Schematic of a single pad hydrostatic guide.