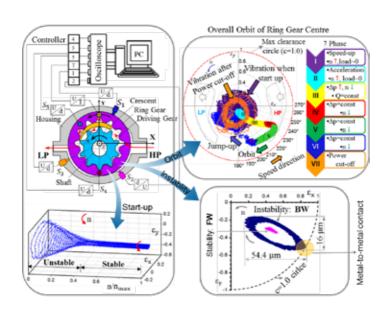




Reihe Fluidmechatronische Systeme

Trong Hoa Pham

Analysis of the Ring Gear Orbit, Misalignment, and Stability Phenomenon for Internal Gear Motors and Pumps



Analysis of the Ring Gear Orbit, Misalignment, and Stability Phenomenon for Internal Gear Motors and Pumps

Von der Fakultät Maschinenwesen der Technische Universität Dresden

zur

Erlangung des akademischen Grades
Doktoringenieur (Dr.-Ing.)
angenommene Dissertation

M.Sc. Trong Hoa Pham

Born on August 20, 1982 in Bac Giang, Vietnam

Tag der Einreichung: November 21, 2017

Tag der Verteidigung: March 09, 2018

Gutachter: Prof. Dr.-Ing. J. Weber

Prof. Dr.-Ing. B. Schlecht

Vorsitzender der Prüfungskommission: Prof. Dr.-Ing. Habil. U. Füssel

Fluidmechatronische Systeme

Trong Hoa Pham

Analysis of the Ring Gear Orbit, Misalignment, and Stability Phenomenon for Internal Gear Motors and Pumps

Shaker Verlag Aachen 2018

Bibliographic information published by the Deutsche Nationalbibliothek The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Dresden, Techn. Univ., Diss., 2018

Copyright Shaker Verlag 2018
All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-5932-8 ISSN 2196-2340

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

Internet: www.shaker.de • e-mail: info@shaker.de

Acknowledgments

The author wishes to express my sincere gratitude to my advisor Professor. Dr.-Ing. Jürgen

Weber- director of the Institute Fluid Power (IFD) at Technical University of Dresden (TUD)

for his motivation and immense knowledge. His guidance helped me in all time. Special

thanks to Professor Berthold Schlecht - director of Institute of Machine Elements and

Machine Design for taking the time to review my study and give me valuable comments on

this thesis.

I would specially like to thank Dr.-Ing. Lutz Müller, the leader of the component group for

his patience and immense knowledge. Thanks are also expressed to all my colleagues in IFD $\,$

for your encouragement, collaboration and friendship during my study. I thank all the

technical staff of the laboratory of the Institute Fluid Power for their help and cooperation.

Gratitude is expressed to Vietnam for providing the 911 Scholarship Program Award and

University of Transport and Communication (UTC) to support the finance during this study.

Special appreciation is expressed to my wife, Thi Thuy Duong Vu, my son Trong Hung

Pham, and my family for their moral support and continuous encouragement.

Thank you so much, everyone!

Pham, Trong Hoa

Dresden, December 2017

Contents

Conte	ents Page
1	Introduction1
2	State of Research and Technology
2.1	Internal gear motor/pump
2.2	Survey of studies about internal gear motors/pumps4
2.3	Sommerfeld theory9
2.3.1	Reynold's equation9
2.3.2	Sommerfeld theory9
2.3.3	Sommerfeld theory applied to the internal gear motor/pump
2.3.4	Calculation of the radial force acting on the ring gear
2.4	Hydrodynamic/hydrostatic pressure distribution in the oil film14
2.4.1	Pressure distribution in hydrodynamic lubrication
2.4.2	FDM for the calculation of the film pressure distribution
2.4.3	Resistance model for the calculation of hydrostatic pressure16
2.5	Theoretical analysis of the orbit and the film thickness of rotors/shafts/bearings 17
2.5.1	Linear model
2.5.2	Non-linear model
2.6	Analytical mobility method for the journal bearing subjected dynamic load20
2.7	Thermal analysis
2.8	Experimental study of the orbit and the film thickness of rotors/shafts/bearings .23 $$
2.9	Misalignment effects on the performance of rotors/shafts/bearings26
2.10	Forward and backward whirling motion of rotors/shafts/bearings29
2.11	Metal-to-metal contact between the rotor and the stator31
3	Objectives and Method of the Study32
4	Governing the Mathematical Models
4.1	Mathematical model without considering the misalignment
4.1.1	Three gap sensors based on the circle equation
4.1.2	Using two gap sensors based on the circle equation
4.1.3	Using 4 radial sensors based on the diametric relation
4.1.4	Using two gap sensors based on radial film thickness
4.2	Governing of the mathematical model in consideration of the $$ misalignment40 $$
4.2.1	Governing of the film thickness equation
4.2.2	Two radial and two axial sensors based on the ROFT and the AOFT equations $\!45$
4.2.3	Three radial sensors and two axial sensors based on the ROFT and the AOFT $\dots 47$

ii Contents

4.2.4	Two radial sensors and three axial sensors based on the ROFT and the AOFT49
4.2.5	Two RS and four AS based on the ROFT and the diametric relation49
4.2.6	Four RS and four AS based on the diametric relation51
4.3	Experimental setup
4.3.1	Selection of the test motor/pump53
4.3.2	Selection of the type of gap sensor for the experiment
4.3.3	Setup of the radial and the axial sensor on the motor/pump housing56
4.3.4	Setup of the test rig
5	Analysis of the Ring Gear Orbit and the Film Thickness62
5.1	The case of no applied load62
5.2	The position of the ring gear with constant operating pressure and constant rotating speed (steady-state operating points)
5.3	The orbit of the ring gear center as a function of the operating pressure64
5.4	The orbit of the ring gear center as a function of the rotating speed66
5.5	The ROFT as a function of the rotating speed67
5.6	The ring gear orbit with the available rotating speed and operating pressure 68
5.7	Overall orbits of the ring gear center over 7 phases70
5.7.1	The overall orbit when the operating pressure ratio is $\Delta p/\Delta pmax=0.25$ 71
5.7.2	The overall orbit when the operating pressure ratio is $\Delta p/\Delta pmax=0.5$ 73
5.7.3	The overall orbit when the operating pressure ratio is $\Delta p/\Delta pmax=0.75$ 76
5.7.4	The overall orbit when the operating pressure ratio is $\Delta p/\Delta pmax=1.0$ 78
5.8	The effects of the value of the initial eccentricity on the vibration81
5.9	Conclusion on the orbit of the ring gear centre84
5.10	FW and BW whirl phenomenon of the ring gear: direction, shape, and size85
5.11	The BW whirling motion of the ring gear in the case of the instability93
5.12	Theoretical and experimental determination of the stability phenomenon98
5.13	Conclusion on the forward and backward motion
6	Effects of the Misalignment
6.1	The misalignment angle
6.2	The misalignment angle as a function of the rotational speed104
6.3	The misalignment angle as a function of the operating pressure106
6.4	The effects of the misalignment on the frictional moment and minimum film thickness
6.5	The effects of the misalignment on the metal-to-metal contact phenomenon109
6.6	The effects of misalignment on the orbit of the ring gear

Contents iii

ents	J
Inspection of the motor after measurement	113
Conclusion on the effect of misalignment phenomenon	114
Analysis of the pressure distribution in the oil-film	116
Hydrodynamic lubrication	116
Hydrostatic lubrication	123
Hybrid lubrication	125
Modification of the mobility method	126
Background for the modification	127
Additional mobility vector	129
Numerical procedure and computational flow chart	132
Simulation results and comparison to the experimental results	133
Start-up phase (no load)	133
Dynamically loaded case	137
Prediction of the overall ring gear orbit over 7 phases	142
Prediction of the film thickness and the ring gear orbit for 4-Q	145
Definition of the stability for the internal gear motor/pump	150
Investigation the effect of the geometry parameters on the stability	152
Conclusion on prediction of orbit and stability	153
New Configuration for the Oil Support System	154
Summary and Outlook	157
•	
References	161
Appendix	a1
Governing the film thickness equation for the aligned ring gear	a1
Governing the film thickness equation for the misaligned ring gear	a3
Solving the equation system	a4
Definition of the radial force for the 4-Quadrant	a9
	Inspection of the motor after measurement Conclusion on the effect of misalignment phenomenon Theoretical Analysis of the Dynamic Behavior and the Stability Analysis of the pressure distribution in the oil-film Hydrodynamic lubrication Hydrostatic lubrication Hybrid lubrication Modification of the mobility method Background for the modification Additional mobility vector Numerical procedure and computational flow chart Simulation results and comparison to the experimental results Start-up phase (no load) Dynamically loaded case Prediction of the overall ring gear orbit over 7 phases