Petri Sallinen

MODELING DYNAMIC BEHAVIOR IN TILTING PAD GAS JOURNAL BEARINGS

Thesis for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium of the Student Union House at Lappeenranta University of Technology, Lappeenranta, Finland on the 3rd of December, 2004, at noon.
# TABLE OF CONTENTS

## NOMENCLATURE

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
</tr>
</tbody>
</table>

## 1 INTRODUCTION

1.1 Background information of the study  
1.2 The aim of the study  
1.3 Introduction to tilting pad gas bearings  
1.3.1 Principle of hydrodynamic gas bearings  
1.3.2 Geometry of the tilting pad gas bearing  
1.3.3 Tilting pad journal bearing - supported freely pivoted pad  
1.3.4 Pivot point mounting of the tilting pad  
1.4 Tilting pad journal bearing supported by a rotary spring  
1.4.1 Construction and functional description  
1.4.2 Sixsmith bearing design  
1.4.3 LUT bearing design  
1.5 Stability of the journal bearing  

## 2 MATHEMATICAL MODEL OF THE TILTING PAD JOURNAL BEARING

2.1 Navier-Stokes equation  
2.1.1 Reynolds lubrication equation  
2.2 Review of numerical methods in gas bearing film analysis  
2.2.1 Numerical methods for the lubrication solution  
2.2.2 Analytical methods of the lubrication solution  
2.3 Basic bearing equations  
2.3.1 Differential equation for a stationary lubrication case  
2.3.2 Bearing number $A$  
2.3.3 Loading coefficient $C_i$  
2.3.4 Reynolds number  
2.3.5 Modified Reynolds number  
2.3.6 Taylor number  
2.3.7 Sommerfeld number  
2.3.8 Knudsen number  
2.3.9 Centrifugal expansion of the shaft  
2.3.10 Thermal expansion of the pad and the shaft  
2.3.11 Friction power of the gas bearing, laminar flow  
2.3.12 Friction power of the gas bearing, turbulent flow  
2.4 Model of a tilting pad gas bearing in a non-stationary case  
2.4.1 Film forces and coordinates  
2.4.2 Rotary spring and radial stiffness of the pad support  
2.4.3 Single pad mass and inertia  

## 3 NUMERICAL CALCULATION WITH THE TILTING PAD GAS BEARING MODEL

3.1 Pressure distribution of the tilting pad  
3.2 Model analysis  
3.2.1 Simplifications  
3.2.2 Iteration end criteria  
3.2.3 Numerical stability considerations  
3.3 Forces and moments  

## 4 VERIFICATION OF THE SIMULATION PROGRAM AND PERFORMANCE

4.1 Numerical calculation results compared with reference results  
4.1.1 Static loading  
4.1.2 Dynamic loading  
4.2 Pressure distribution with various bearing number $A$ values  
4.3 Estimation of the stability of the tilting pad gas bearing  
4.3.1 Unbalance of the shaft  
4.3.2 Cylindrical whirl  
4.3.3 Rotating forces due to the electric motor  
4.3.4 Pad misalignment  
4.3.5 Pivot position of the tilting pad, $a/\beta$ -ratio  
4.3.6 Rotary spring constant of the tilting pad support  
4.3.7 Radial stiffness of the pad support  
4.3.8 Bearing body radius to shaft radius ratio, $R_b / R$  
4.3.9 Leading edge initial clearance  
4.3.10 Preload of the bearing  
4.3.11 Viscosity of the gas  
4.3.12 Size of the tilting pad gas bearing
4.3.13 Number of tilting pads 115
4.3.14 Ambient gas pressure 115
4.4 Summary of the gas bearings test systems at LUT 116
  4.4.1 Experiments with 9 mm gas bearings 116
  4.4.2 Experiments with 22 mm gas bearings 117
  4.4.3 Experiments with 38 mm gas bearings 122
  4.4.4 Experiments with 52 and 66 mm gas bearings 127

5 MANUFACTURING OF TILTING PAD GAS BEARING 132
  5.1 Manufacturing the bearing body 132
    5.1.1 Sixsmith design 132
    5.1.2 LUT design 133
  5.2 Grinding the bearing 134
  5.3 Vibration measurement of tilting pads 134
  5.4 Tuning the pad alignment 135

6 EXPERIMENTS WITH 125 mm GAS BEARINGS 136
  6.1 Introduction 136
  6.2 Test facility 136
  6.3 Calculated loading capacity 141
  6.4 Comparison of experimental and numerical results 142
  6.5 Error estimate 148

7 CONCLUSIONS 149

REFERENCES 151