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Anna-Lisa Zimmermann

Experimental Investigation of the Characteristics of Aerostatic Thrust Bearings and their Response to Bearing Face Imperfections

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Kurzfassung

Der zunehmende Anteil erneuerbarer Energien auf dem weltweiten Strommarkt führt zu neuen Anforderungen an konventionelle Kraftwerkparks. Sie müssen flexibler betrieben werden, um auf Lastschwankungen im Netz reagieren zu können. Ein derart flexibler Betrieb erfordert modifzierte Turbinen und grundlegend neue Technologien. Eine Antwort auf diesen Trend ist die Entwicklung und Optimierung neuartiger Dichtungstechnologien, welche einen flexibleren Einsatz von Gasturbinen ermöglichen, aber trotzdem zu einer weiteren Verbesserung der Gasturbineneffizienz führen. Selbstadaptierende Gleitringdichtungen erscheinen dabei vielversprechend. Minimale Spalte können über einen breiten Betriebsbereich eingehalten werden und eine gefederte Ausführung ermöglicht es, dass die Dichtung axialen Bewegungen des Rotors folgen kann. Druckluft wird in den Spalt zwischen den relativ zueinander bewegten Gleitflächen gespeist und bildet einen nur wenige Zehntel Millimeter dünnen und zugleich steifen Schmierfilm. Mit ihm entsteht ein Luftpolster, welches den berührungsfreien Betrieb der Dichtung gewährleistet. Vor allem die Druckverteilung im Luftpolster ist von fundamentalem Interesse, da sie die Tragkraft und Steifigkeit des Films bestimmt. Beide Eigenschaften sollten im Idealfall maximal sein und keinerlei Schwankungen unterliegen. Daraus folgen zwei Prämissen. Zum einen muss die Abhängigkeit der Druckverteilung zu konstruktiven Gestaltungsaspekten und jeweiligen Betriebsbedingungen verstanden werden. Zum anderen müssen die realen Leistungsdaten der Dichtung bedacht werden. Fertigungsfehler auf einer der Gleitflächen zum Beispiel bergen das Risiko einer gegenüber der Entwurfsabsicht veränderten Druckverteilung, was wiederum zu einer Veränderung des sich einstellenden Luftspalts führen kann. Die Konsequenzen können signifikant sein und unter Umständen zu Kontakt zwischen den Dichtflächen führen.

Die vorliegende Dissertationsschrift ist das Resultat der Tätigkeit als wissenschaftliche Mitarbeiterin am Institut für Turbomaschinen und Flugantriebe an der Technischen Universität München. Die Arbeit befasst sich mit den aerostatischen Eigenschaften einer adaptiven Gleitringdichtung für den Einsatz in Gasturbinen. Ein Hauptaugenmerk liegt auf dem in der Dichtung integrierten aerostatischen Luftlager, welches im Rahmen einer experimentellen Studie untersucht wird. Im Fokus stehen der Luftverbrauch, sowie die Druckverteilung und Steifigkeit des im Luftlager aufgebauten Luftfilms. Alle drei Eigenschaften werden stets unter variierenden, repräsentativen Betriebsbedingungen untersucht und bewertet. In einem zweiten Teil der Arbeit wird zudem der Einfluss potenzieller Fertigungsfehler definiert und hinsichtlich der Auswirkung auf die zuvor untersuchten statischen Eigenschaften der selbstadaptierenden Gleitringrichtung untersucht. Alle Ergebnisse werden diskutiert und hinsichtlich ihrer Signifikanz bewertet.

Abstract

During the past years, the share of renewable energies in total electricity consumption has increased significantly. This makes the supply side of the grid less predictable than it used to be in the past. Large fluctuations may occur which are to be compensated by the traditional sources of electricity. Today's gas turbines, however, are designed for high performance operation in a base load regime and their design is not well focused on quickly changing load requirements. Flexible operation cycles result in high temperature gradients coupled with large axial and radial displacements of turbine parts and are currently limited by the tight clearance between the rotor and stator. As a consequence, it is becoming increasingly important to introduce new sealing technologies to allow a balancing of energy demand peaks by providing flexible operation; advanced seal design concepts need to be invented, optimized and tested at engine-like conditions. Self-adaptive gas-lubricated face seals, for instance, have been established and seem to be promising in order to satisfy the latest requirements to turbomachinery. They ensure minimal clearances and can handle a wide range of operating conditions. The seal is spring-mounted allowing it to follow the rotor's axial movements at low gas pressure. Small feed holes are present on the axially facing seal's surface injecting high pressure air in the seal/rotor gap, thereby effectively creating an aerostatic gas bearing between static and rotating components. The characteristic attribute of this bearing is a narrow clearance of typically less than 0.1 mm in a complicated geometry. For design and optimization purposes, accurate and detailed knowledge of the pressure distribution acting in this clearance is of fundamental interest as it determines both the load capacity and film stiffness. The seal/rotor system is thereby subject to highest quality requirements in order to ensure a safe and permanent seal performance. Precision machinery and methods are required and manufacturing errors must be avoided as they may cause the seal to deviate from its predicted performance, potentially causing significant damage.

This dissertation thesis is the result of research activities that have been conducted at the Chair of Turbomachinery and Flight Propulsion at the Technical University of Munich. The thesis seeks to strengthen the knowledge on the field of film-lubricated and large-diameter face seals that employ aerostatic thrust bearings. The motivation is to gain confidence about their applicability to new and demanding operating conditions. Eventually, a new type of seal is studied experimentally. The results of investigation are presented, focusing on three main characteristics of the seal. These are the air consumption, as well as the pressure distribution and stiffness developed in the air film. All three characteristics are studies under engine-like conditions. Furthermore, in a second part of the thesis, the impact of potential manufacturing defects on the static characteristics are investigated. All results are discussed in terms of their significance for manufacturing accuracy and quality.

Acknowledgments

The research in this thesis was performed at the Chair of Turbomachinery and Flight Propulsion in fulfillment of the requirements for the doctoral degree of engineering sciences (Dr.-Ing.) at the Technical University of Munich. Undertaking this three-year journey has been an enriching experience. Many people accompanied me on my way and I am very grateful for all the support and guidance I have received.

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List of Symbols

The symbols from the first column are explained in the second column. The third column, if present, shows the dimension. The basic parameters are length (L), mass (M), time (T), temperature (Θ) and amount of substance (N).

Symbol	Description	Dimension
A	Flow passage	L^2
C_d	Discharge coefficient	1
c	Constant	1
D	Diameter	L
d	Diameter	L
d	Depth	L
F	Force	$\mathrm{M\ L\ T}^{-2}$
H_0	Bearing face height	L
h	Axial clearance	L
h_e	Form error	L
h_0	Local bearing clearance	L
j_eq	Equivalent gap width	L
k	Air film stiffness	$\mathrm{M\ T}^{-2}$
k	Number of feed holes	1
k	Exponent	1
L	Length	L
L	Leakage flow path	L
L_0	Length of one bearing face segment	L

m	Mass	M
m	Exponent	1
$\dot{m}$	Mass flow rate	M T^{-1}
Ma	Mach number	1
P	Static pressure	M L^{-1} T^{-2}
p	Static pressure	M L^{-1} T^{-2}
R	Gas constant	M L^{2} T^{-2} Θ^{-1}
R	Radius	L
r	Radius	L
r, θ	Cylindrical coordinates	L
T	Temperature	Θ
t	Time	T
V	Volume	L^{3}
W	Load	M L T^{-2}
x, y, z	Cartesian coordinates	L
α, β	Angle	1
γ	Isentropic exponent for ideal gas	1
δ	Delta	1
ΔP	Differential pressure across the seal	M L^{-1} T^{-2}
ε	Form error sensitivity h_{e}/h_0	1
η	Scaled pressure	1
κ	Permeability coefficient	L^{2}
Π	Pressure ratio	1
π	Mathematical constant	1
ρ	Density	M L^{-3}
σ	Standard deviation on flatness	L
Ψ	Flow function	$\Theta^{0.5}$ T L^{-1}

*	Dimensionless quantity
$\bar{\ }$	Average

Indices	**Description**
a	annular
amb	ambient
approx	approximate
bf	bearing face
c	circular
des	design
eq	equivalent
fh	feed hole
I	Configuration I
II	Configuration II
id	ideal
in	inlet
leak	leakage
lt	labyrinth tooth
max	maximum
min	minimum
opt	optimum
out	outlet
p	pocket
r	recess
ref	reference
s	supply
tot	total

vent	vent cavity
vh	vent hole

Acronym	**Description**
C	Concavity
CFD	Computational Fluid Dynamics
CMM	Coordinate Measuring Machine
FS	Full scale
KIT	Karlsruhe Institute of Technology
LES	Large Eddy Simulation
LT	Longitudinal Tilt
LTF	Chair of Turbomachinery and Flight Propulsion
PTT	Partial Transversal Tilt
RANS	Reynolds-averaged Navier–Stokes equations
RMS	Root Mean Square
TT	Transversal Tilt
TRL	Technology Readiness Level
TUM	Technical University of Munich