The University Of Sheffield.
Department Of Mechanical Engineering.

EFFECT OF COMPRESSION, IMPACT AND SLIPPING ON ROLLING CONTACT FATIGUE AND SUBSURFACE MICROSTRUCTURAL DAMAGE

A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

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February 2020

ABSTRACT

Rolling Contact Fatigue (RCF) manifests itself in different engineering applications such as bearings, gears, railway tracks, and cams. In Wind Turbine Gearboxes (WTGs), which are designed to be in service for 20 to 25 years, the service life of their bearings is often below their design life despite depending on advanced technologies and standards in the gearbox design. This premature bearing failure occurs by flaking, mainly in the bearing inner races. Furthermore, bearing service life cannot be precisely predicted despite many life prediction models and using advanced analyses for the gearbox design. This premature bearing failure increases the wind energy cost due to unplanned maintenance and early replacement. In addition to that the main causes and mechanisms of this premature failure have not been completely understood. This has motivated an increasing investigation in this field due to the scientific and economic impacts.

There are a considerable number of factors affecting premature bearing failure. Three parameters which are widely reported as the main causes were investigated in this study which are contact pressure, slipping and impact loading. Two failed planetary bearings from a multi-megawatt wind turbine gearbox were investigated first to evaluate their surface and subsurface damage features and to estimate the parameter testing levels. A new test rig that can apply impact loading in combination with compression and slipping was designed. Two contact discs made from bearing material (AISI 52100 steel) were used in this test rig. Sixteen tests are designed using Minitab software for design of experiments using a line contact with flat test discs with stress concentration at the contact edges because stress concentration cannot be avoided in roller bearings, which is the type usually used in the turbine gearboxes. The effect of the key parameters on the test disc life in terms of the number of cycles to failure and subsurface damage features distribution at the microscale level were analyzed. These distributions were correlated with the subsurface stress distribution within the contact region of the bearings and the test discs to predict which stress type was responsible for each damage type. Further tests were also designed and conducted to avoid the stress concentration using fully crowned disc profiles to investigate the effect of the key parameters on disc life. The investigation led to the suggestion of a new simple damage estimation model depending on the contact stress levels and the number of cycles under each level.

The results of the qualitative and quantitative investigation confirm the considerable role of contact stress followed by slipping and then impact loading. Despite impact-loading affecting damage as contact pressure, it reveals two different effects on the subsurface damage features. The first was observed in shallow regions as internally cracked inclusions within the disc material while, the second by introducing damaged inclusions in deeper regions. The individual and interactive effects of impact loading with the other two parameters were found to be different from the compression loading effects. The correlation of damage distribution with the subsurface stress distributions confirms the postulation of Von-Mises and maximum shear stresses as being the main contributors to damage initiation and propagation. The suggested life prediction model was tested by using the test results and real wind turbine operating data of SCADA for two years in addition to using the average annual wind speed distribution. The results of this model were very close to the reported wind turbine gearbox bearing life. More testing is still required to confirm the reliability of this simple and applicable model. The metallographic investigations confirmed that the subsurface microcracks were often not associated with non-metallic inclusions, but may be started from the voids associated with the material carbides is a significant damage initiation source in addition to that of non-metallic inclusions which have been widely reported in the previous studies. Furthermore, Slipping Ratio (SR) is found to have more effect under low contact loading levels. A considerable role of impact loading in the butterfly wing damage feature is postulated. Moreover, the Intrusion/Extrusion and dislocation damage mechanism theories may be more suitable for describing overloading fatigue damage.

The novelty of this study is that it is the first study of the rolling contact fatigue life and the behaviour of the bearing steel under impact-loading in combination with compression and sliding to investigate the individual and interactive effects of these parameters on the trend of fatigue life variation by developing a new test rig. A new bearing life prediction methodology is proposed, and the results showed a lower percentage of errors in the turbine bearing predicted life compared with the standards currently use. More tests and metallographic investigations are recommended to investigate the effect of lower and higher contact stress levels and impact loading to understand the effect of these parameters on the initiation and propagation of the subsurface damage features.

PUBLICATIONS AND PRESENTATIONS

Publications

- Jasim H Al-Bedhany and Hui Long, “Microscopic investigation of subsurface initiated damage of wind turbine gearbox bearings,” J. Phys.: Conf. Ser. 1106 012029, 2018.
- Tahseen Ali Mankhi, Stanisław Legutko, Jasim H AL-Bedhany and Abdulmuttalib A Muhsen, “Selecting the Most Efficient Bearing of Wind Turbine Gearbox Using (Analytical Hierarchy Process) Method “AHP”, International Conference on Sustainable Engineering Techniques, Iraq, March 2019.

Presentations

- “Investigation of premature failure of wind turbine gearbox bearings,” Energy 2050, Energy Research Symposium (ERS), Grantham Centre, the University of Sheffield, UK, 2017.
- “Microscopic investigation of subsurface initiated damage of wind turbine gearbox bearings”, MPSVA conference, Clare College, University of Cambridge, Cambridge, UK, 2018.

Poster presentations

- “BEARING WHITE ETCHING CRACK DAMAGE AND LIFE PREDICTION METHOD,” a poster presented in the Ph.D. poster Event at the University of Sheffield 2017.

DEDICATION

To my homeland (IRAQ) the dearest than all. To every drop of blood spilled by the Iraqi martyrs and any others injured during the battle against ISIS (Terrorism State). To my university (Misan), its Engineering college and everybody who supported me during the study.

To the spirit of my father, to my mother and my brother Ahmed.

To my wife and my children Hasan, Aya, Retaj, Zahraa, and Ahmed.

To my friends who care about me and hope me to succeed.

I hope I will be as you expect, and I promise you that, I shall continue doing my best to serve humanity.

Jasim H. AL-Bedhany

ACKNOWLEDGMENTS

The author sincerely thanks the Iraqi Ministry of Higher Education and Scientific Research (MOHESR), The Iraqi Cultural Attaché in London, UK, Misan University and Engineering College for sponsoring my Ph.D. scholarship. Special thanks to my supervisor Professor R. Lewis for his support, guidance, and monitoring of this study and for Professor Bill Nimmo and the head of the department Professor Neil Sims. Thanks to Vestas Wind System A/S for supplying the two failed planetary bearings.

A special thanks to many others have provided a fruitful input to this project, including:

* Terry Hattersley, Harthill© Development Ltd. company for his support and help in the manufacturing of the test rig.
* Phillip C. Pickstock, the Departmental Technical Manager, for his support in installing the electrical controls of the test rig.
* Jamie Booth, the department research technician, for his support in manufacturing some components for the test rig.
* Karl Rotchell, the electrical workshop team leader for his support in completing urgent mechanical works required.
* Ashley KW Ng, MEng student for working together on MATLAB software to analyze the bearing contact stresses.
* Dr. Alistair John, The University of Sheffield for his support and fruitful recommendations.

Jasim Hasan AL-Bedhany

NOMENCLATURES

Unless otherwise stated, all units used through this thesis are SI.

σ	Stress (Pa)
P_o	Maximum contact pressure (Pa)
a and b	Half of the contact width (m)
τ , τ_{xy}, τ_{max}	Shear, orthogonal and unidirectional shear stresses (Pa)
σ_1, σ_2, σ_3	Principal stresses (Pa)
σ_y	Yield stress (Pa)
z	Depth beneath the contact surface (m)
Z_{rol}	Number of bearing roller
L_{10}	Rated bearing life with 90% reliability in million cycles (Cycle)
c	Dynamic load capacity (N)
p_{eq}	Equivalent radial load (Pa)
n	Number of cycles
N, N_f	Number of cycles to failure
e	Life estimation empirical exponent
D	Damage
x_k	Variable depends on loading level
r	Cyclic ratio (number of rotating cycles to number of cycles to failure)
A and B	Constants
w	Exponent depend on fatigue stress amplitude
α	The fraction for crack initiation
β	The fraction of crack propagation
N_I, N_{II}	Number of cycles for crack initiation and propagation respectively
m and n	Contact parameters

s	Bearing raceway survival probability (%)
L_f	Fatigue life (Cycle)
a_o *and* a_f	Initial and final crack lengths (m).
E	Modulus of elasticity (GPa)
v	Poisson's ratio
G	The gear ratio of the turbine gearbox
P_{gen}	Power of turbine generator (W)
H	Number of rows in planetary bearings
ω_{gen}	Rotating speed of the turbine generator (rad/s)
η	Overall drivetrain efficiency
R_D	Ring gear diameter in planetary stage (m)
S_D	Sun gear diameter in planetary stage (m)
T	Torque (N.m)
R_a	Arithmetic surface roughness
HV	Vickers hardness
HRC	Rockwell Hardness
U_{ud} , U_{ld}	The linear velocities of the upper and lower test disc respectively (m/s)
SR	Slipping ratio
AR	Aspect ratio
T_1, T_2	Upper and lower test disc thickness respectively (m)
R_1, R_2	Upper and lower test disc radii respectively
ρ	Density (kg/m^3)
φ	Dynamic viscosity (cSt)
h_f	Lubricant film thickness (μm)
$\mathscr{k}$	kinematic viscosity (cP)
ϑ	Pressure-viscosity coefficient
μ	Friction coefficient

V_{cam}	Tip cam velocity (m/s)
N_{cam}	Cam rotational speed (rpm)
R_c	Cam tip radius (m)
ω_{il}	Impact lever rotational speed (rad/s)
V_{imp}	Impact velocity (m/s)
M_{eff}	Effective impact mass (kg)
d_g	The distance between the radius of gyration and impact lever center (m)
I	Angular mass moment of inertia ($kg.m^2$)
L	Length (m)
k_s	Stiffness parameter (N/m)
E_{imp}	Impact energy (J)
F_i	Impact force (N)
p_{oi}	Maximum contact pressure due to impact (Pa)
μ_{mean}	Mean value of the output
β_{input}	Effect of the input factor
ε_{noise}	Error due to noise
SD	Standard deviation
ß	Scale Parameter
א	Shape Parameter
$F_{(pr)}$	probability fraction
t_n	Test number
N_T	Total number of tests
t	Time (s)

ABBREVIATIONS

RCF	Rolling Contact Fatigue
WTGs	Wind Turbine Gearboxes
O&M	Operating and Maintenance
WT	Wind Turbine
WE	Wind Energy
RE	Renewable Energy
LSS	Low-Speed Shaft
PP	Planetary Pin
HSS	High-Speed Shaft
MSS	Medium Speed Shaft
UW	UpWind
DW	Down Wind
WSF	White Structure Flaking
DEAs	Dark Etching Areas
WTGBs	Wind Turbine Gearbox Bearings
WEAs	White Etching Areas
WEBs	White Etching Bands
WECs	White Etching Cracks
SR	Slipping Ratio
R/S	Rolling/Sliding
SCADA	Supervisory Control And Data Acquisition
WTs	Wind Turbines
LRM	Light Reflection Microscope
OD	Over-rolling Direction
WL	White Layer
DZ	Deformed Zone

LEDS	Low Energy Dislocation Structure
FHA	Frictional Heat Accumulation
LEAs	Light Etching Areas
LAB	Low Angle Band
HAB	High Angle Band
FE	Finite Element
EHL	Elastohydrodynamic Lubrication
NREL	National Renewable Energy Laboratory
SRCR	Single-Row Cylindrical Roller bearing
DRCR	Double-Row Cylindrical Roller bearing
SEM	Scanning Electron Microscope
EDX	Energy Dispersive X-ray analysis
WD	Working Distance
HV	Vickers Hardness
AISI	American Iron and Steel Institute
HRC	Rockwell Hardness
SRACBs	Single Row Angular Contact Ball Bearings
DOE	Design Of Experiment
SD	Standard Deviation
PDF	Probability Density Function
EFDA	Energy Fraction of Damage Accumulation
P-M	Palmgren-Miner theory
CTE	Coefficient of Thermal Expansion
DLDR	Double Linear Damage Rule
TF	Transfer Function
LEFM	Linear Elastic Fracture Mechanics
AR	Aspect Ratio

PS	Probability of Survival
COD	Crack Opening Distance

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