Explicit dynamics finite element modelling of defective rolling element bearings

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A thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy in Mechanical Engineering

on 16 July 2014. Qualified on 11 November 2014.

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Doctoral thesis

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Abstract

Rolling element bearings are widely used in rotating machinery across various industries and their failure is a dominant factor that contributes to machinery breakdown, consequently causing significant economic losses. Numerous experimental and analytical studies have been conducted in the past to understand the vibration response of non-defective and defective rolling element bearings, which have localised, extended, and distributed defects. Previous models have focused on simulating the defect-related impulses, which are generally observed in practice in measured vibration signals, and they implement envelope analysis to predict the significant defect-related frequency components.

The work presented in this thesis is focused on developing an understanding of the underlying physical mechanism by which defect-related impulses are generated in defective rolling element bearings. A novel explicit dynamics finite element (FE) model of a rolling element bearing having a localised outer raceway defect, line spall, was developed and solved using a commercially available FE software package, LS-DYNA. In addition to simulating the vibration response of the bearing, the dynamic contact interaction between the rolling elements and raceways of the bearing were modelled. An in-depth investigation of the rolling element-to-raceway contact forces was undertaken and variations in the forces, as the rolling elements traverse through the defect, were analysed. The contact force analysis has also led to the development of an understanding of the physics behind the low- and high-frequency characteristic vibration signatures generated by the rolling elements as they enter and exit a defect.

It was found that no impulse-like signals are generated during the gradual de-stressing or unloading of the rolling elements as they enter into a defect, which explains the low-frequency characteristics of the de-stressing event. In contrast, a burst of multiple, short-duration, force impulses is generated as the rolling elements re-stress between the raceways in the vicinity of the end of a defect, which explains the high-frequency impulsive characteristics of the re-stressing event. Based on the results of the FE analysis of the rolling element bearing, a mathematical model was developed to predict the gradual de-stressing of the rolling elements as they enter into a raceway defect.

Experimental testing on a rolling element bearing, commonly used in the railway industry, and having a line spall machined on its outer raceway was undertaken. The numerically modelled vibration response obtained using the FE model of the rolling element bearing was compared with the experimentally measured data, and a favourable agreement between the modelled and measured results was achieved. Numerical rolling element-to-raceway contact forces were compared with corresponding analytical results calculated using a quasi-static load distribution analytical model presented in this thesis.

A parametric study to investigate the effects of varying radial load and rotational speed on the vibration response of the bearing and rolling element-to-raceway contact forces was undertaken. It was found that the magnitude of the defect-related vibration impulses and contact forces generated during the re-stressing of the rolling elements increases with increasing load and speed.

The modelled contact forces were correlated with bearing vibration signals, and it was found that the amplitude of the contact forces and acceleration produced during the re-stressing of the rolling elements is much greater than when the rolling elements strike the defective surface. In other words, although a rolling element can impact the surface of a defect and generate a low amplitude acceleration signal, a much higher acceleration signal is generated when the rolling elements are re-stressed between the raceways as they exit from the defect. These higher acceleration signals, generated during the re-stressing phase, are the ones that are generally observed in practice, and subsequently used for bearing diagnosis.

The work presented in this thesis has provided definitive physical and quantitative explanations for the impulsive acceleration signals measured when a bearing element passes through a defect.

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Statement of Originality

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Acknowledgements

I would like to acknowledge the efforts of all the people who have contributed towards the work in this thesis. I would like to thank my supervisors Dr Carl Howard and Emeritus Professor Dr Colin Hansen, and external supervisors from Track IQ$^{\mathrm{TM}}$, Dr Uwe Köpke and Dr David Rennison, for their guidance and support. I acknowledge the support of Track IQ$^{\mathrm{TM}}$ who provided extensive project facilities and funding. I am especially thankful to Dr David Rennison for providing me with additional funding without which it is unlikely that this thesis would have been possible. I am extremely grateful to Emeritus Professor Dr Colin Hansen and Dr Carl Howard, who also supervised me during my Master's (by research) degree, for proof reading this thesis during their extremely busy times. Thanks to Dr Michael Kidner of Vipac Engineers and Scientists Ltd. for many useful discussions on the subject. Thanks to William Bevan for his help with the test rigs used in the experiments. Thanks also to Billy Constantine for his help with the use of supercomputers for the simulations. I also acknowledge the University of Adelaide for providing an APA scholarship, and Australian Research Council for supporting this project.

I would like to thank my parents S. Jagmehar Singh and S. Pawinder Kaur for their support to get me where I am today. Thanks also to my siblings, Arvinder and Gurwinder, for their support.

Most of all, I would like to thank my wife, Lovleen, and our three-year old daughter, Ujjalman, for their endless support and encouragement during the pursuit of my studies. I do sometimes regret spending very less time with my family, especially with my daughter, during my studies, and I hope to make up for the elapsed time! Special thanks to Lovleen and my parents for taking care of me when I accidentally squashed my right-hand thumb in the test rig during the experimentation work. Working with one hand for three months was tough!

Finally, thanks to the staff at Track IQ$^{\text{TM}}$ and Vipac for sharing many laughs: Greg Huxtable, Jason Hollis, Robert Hudd, Andrew Meyer, Steve Lewis, Alan Wood, Alex Cowley, and Michael Foo.

Contents

List of Figures

List of Tables

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Nomenclature

Roman Symbols

a_y	acceleration of a node within the FE model of the rolling element bearing in the global cartesian y-direction
b	half-contact width at the interface of two contacting isotropic elastic solid bodies
$b^{'}$, $b^{''}$	extremeties of contact width $2b$ at the rolling element-to-raceway contact interfaces within a rolling element bearing
b_x, b_y	half-contact width at the rolling element-to-outer raceway contact interfaces within a rolling element bearing in the global cartesian x- and y-directions, respectively
B	bending stiffness of a plate / the outer ring of the FE model of the rolling element bearing
c	local material sound speed
c_b	velocity of bending waves
D_c	outer diameter of the cage within the FE model of the rolling element bearing
D_i	diameter of the inner raceway of a rolling element bearing
D_o	diameter of the outer raceway of a rolling element bearing
D_p	bearing pitch diameter
D_r	diameter of the rolling elements within a rolling element bearing
$E^{'}$	equivalent modulus of elasticity of two contacting isotropic elastic solid bodies
E_1, E_2	modulus of elasticity of isotropic elastic solid bodies '1' and '2'
F	Hertzian contact force at the interface of two isotropic elastic solid bodies
f_{bpi}	inner raceway defect frequency or ball pass frequency inner raceway

f_{bpo}	outer raceway defect frequency or ball pass frequency outer raceway
f_c	cage (rotational) frequency
$F_{dj(\text{grad})}$	gradual variation in the contact forces at the rolling element-to-raceway contact interfaces within a defective rolling element bearing
F_{dj}	contact force at a jth rolling element-to-raceway contact interface within a defective rolling element bearing
F_{dx}	horizontal rolling element-to-raceway contact force for a defective rolling element bearing in the global cartesian x-direction
F_{dy}	vertical rolling element-to-raceway contact force for a defective rolling element bearing in the global cartesian y-direction
f^{i}_{noise}	rolling element-to-inner raceway rolling contact noise frequency
f^{i-o}_{noise}	beating noise frequency
F_j	contact force at a jth rolling element-to-raceway contact interface within a non-defective rolling element bearing
$F_{\max}$	maximum force at a rolling element-to-raceway contact interface within a rolling element bearing along the load line (y-axis)
f^{o}_{noise}	rolling element-to-outer raceway rolling contact noise frequency
f_{rc}	ring frequency of a cylindrical shell
f_s	shaft rotational (run speed) frequency
F_x	horizontal rolling element-to-raceway contact force for a non-defective rolling element bearing in the global cartesian x-direction
F_y	vertical rolling element-to-raceway contact force for a non-defective rolling element bearing in the global cartesian y-direction
H_a	height of the adapter within the FE model of the rolling element bearing
h_c	thickness of the cage within the FE model of the rolling element bearing
H_d	depth (height) of the outer raceway defect within a rolling element bearing
h_i	thickness of the inner ring within the FE model of the rolling element bearing
h_o	thickness of the outer ring within the FE model of the rolling element bearing
I	impulsive force

i	imaginary unit ($= \sqrt{-1}$)
j	rolling element
K	contact stiffness at the interface of two isotropic elastic solid bodies
k_{zm}	modal wavenumbers
k_{cs}	contact or spring stiffness at the interface of two contacting segments in an FE model
K_{dj}	stiffness at a jth rolling element-to-raceway contact interface within a defective rolling element bearing
l	length of two contacting isotropic elastic solid bodies
L_{10}	life of a rolling element bearing
L_d	length of a localised raceway defect
L_e	length of an extended defect
l_{fe}	smallest characteristic dimension of an element within an FE model
l_r	length of the rolling elements within a bearing
m	axial mode numbers
m_1, m_2	masses of two segments in contact within an FE model
n	circumferential mode numbers
N_r	number of rolling elements within a bearing
n_s	rotational speed of a rolling element bearing
N_w	window length
$o^{'}$	initial point of contact between two non-conformal isotropic elastic solid bodies
$P_{\max}$	maximum pressure at the interface of two contacting isotropic elastic solid bodies
Q	quality factor of a second-order notch filter
r_c	mean radius of a cylindrical shell
$R_d^{'}$	curvature difference of two contacting isotropic elastic solid bodies
$R^{'}$	curvature sum of two contacting isotropic elastic solid bodies

R_x	equivalent radius of curvature of two contacting isotropic elastic solid bodies in the global cartesian x-direction
R_z	equivalent radius of curvature of two contacting isotropic elastic solid bodies in the global cartesian z-direction
S_d	profile of the outer raceway defect within a rolling element bearing
T	time period of defect-related impulses
t	time vector
u_y	displacement of a node within the FE model of the rolling element bearing in the global cartesian y-direction
V	stressed volume of the bearing material
v_y	velocity of a node within the FE model of the rolling element bearing in the global cartesian y-direction
W	radial (vertical) load in the global cartesian y-direction
w_a	width of the adapter within the FE model of the rolling element bearing
$x(t)$	time-varying signal
$\hat{x}(t)$	analytic signal
Z	number of cycles of repeated (stress) loading within a rolling element bearing
z_0	depth at which maximum stress at the rolling element-to-raceway contact interfaces occurs

Greek Symbols

α	contact angle within a rolling element bearing
β_j	a factor for introducing gradual changes at the entry and exit edges of a defect within a rolling element bearing
δ_1, δ_2	deformation of isotropic solid elastic bodies '1' and '2'
δ	total deformation at the contact interface of two isotropic elastic solid bodies
δ_{dj}	total contact deformation at a jth rolling element-to-raceway contact interface within a defective rolling element bearing
δ_i	displacement of the inner ring of a rolling element bearing
δ_j	displacement at a jth rolling element-to-raceway contact interface within a rolling element bearing

$\delta_{\max}$	maximum displacement at the rolling element-to-raceway contact interface within a rolling element bearing along the load line (y-axis)
δ_o	displacement of the outer ring of a rolling element bearing
δ_x, δ_y	deformation at the rolling element-to-outer raceway contact interfaces within a rolling element bearing in the global cartesian x- and y-directions, respectively
ϵ	load distribution factor for a rolling element bearing
γ_j	a factor that zeros the load distribution outside the load zone within a rolling element bearing
κ	Weibull slope for the experimental life of a rolling element bearing
λ_b	bending wavelength
μ	coefficient of friction between mating bearing components in the FE model of the bearing
ω_{mn}	natural frequencies of the outer ring of the FE model of the rolling element bearing
ν_1, ν_2	Poisson's ratio of isotropic elastic solid bodies '1' and '2'
$\Delta\Omega$	band width of a second-order notch filter
ω_c	angular velocity of the cage or rolling elements within a bearing
Ω_o	notch frequency of a second-order notch filter
ω_s	angular velocity of the shaft on which a rolling element bearing is installed
ψ_0	initial angular position of the cage within a rolling element bearing
ψ_c	angular position of the cage within a rolling element bearing
$\Delta\psi_{\mathrm{cw}}$	angular extent of contact width $2b$ at the rolling element-to-raceway contact interfaces within a rolling element bearing
$\Delta\psi_d$	angular extent of the outer raceway defect within a rolling element bearing
ψ_d	centre of the outer raceway defect within a rolling element bearing
ψ_j	angular position of a jth rolling element
ψ_l'	half-angular extent of the bearing load zone centred at ψ_{lc}
ψ_{lc}	centre of the bearing load zone

ρ	material density
$\Delta t_{\text{critical}}$	critical time step for the explicit time integration scheme used in LS-DYNA
Δt_{event}	time difference between the consecutive de-stressing or re-stressing events
Δt_{stable}	stable time step used in LS-DYNA
θ_r	angular spacing between the rolling elements within a bearing
Υ	probability of survival of a rolling element bearing
ε_0	maximum orthogonal shear stress in the rolling element-to-raceway contact interfaces
ς	diametral clearance within a rolling element bearing
ζ	damping ratio

Miscellaneous Symbols

$\mathscr{D}$	Dirac delta function
$\mathscr{F}$	Fourier transform
$\mathscr{H}$	Hilbert transform
$\mathscr{K}$	spectral kurtosis
$\mathscr{S}$	short-time Fourier transform

Superscripts

i	inner raceway
$i-o$	inner-to-outer raceway
n	exponent — $n = 3/2$ for point, circular and elliptical contacts, and $n = 10/9$ for line and rectangular contacts
o	outer raceway

Subscripts

1, 2	isotropic elastic solid bodies ‘1’ and ‘2’
b	bending waves
bpi	ball pass inner raceway
bpo	ball pass outer raceway
c	cage for retaining the rolling elements within a bearing

cw	contact width
d	defective rolling element bearing
e	extended defect
fe	finite element
i	inner raceway
j	rolling element
lc	centre of the load zone
max	maximum
o	outer raceway
p	bearing pitch
rc	cylindrical shell
s	shaft
x	global cartesian x-direction
y	global cartesian y-direction
z	global cartesian z-direction

Abbreviations

2-D	two-dimensional
3-D	three-dimensional
AAR	Association of American Railroads
ABMA	American Bearing Manufacturers Association, Inc.
ADINA	Automatic Dynamic Incremental Nonlinear Analysis
ADORE	Advanced Dynamics of Rolling Elements
ANSI	American National Standards Institute, Inc.
BEAST	Bearing Simulation Tool
BEAT	BEAring Toolbox
BPFI	ball pass frequency inner raceway
BPFO	ball pass frequency outer raceway

COBRA	Computer Optimized Ball and Roller Bearing Analysis software
CW	clockwise
CWRU	Case Western Reserve University
DOF	degree-of-freedom
EHL	elasto-hydrodynamic lubrication
EPW	elements-per-wavelength
FE	finite element
FFT	Fast Fourier Transform
IBDAS	Integrated Bearing Dynamic Analysis System
ISO	International Organization for Standardization
PSD	Power Spectral Density
RailBAM®	Railway Bearing Acoustic Monitor
RMS	root mean square
RPM	revolutions per minute
SFM	scale factor on default master penalty stiffness
SFS	scale factor on default slave penalty stiffness
SK	spectral kurtosis
SLSFAC	scale factor for sliding interface penalties
STFT	short-time Fourier transform
TADS®	Trackside Acoustic Detection System
Track IQ™	Trackside Intelligence Pty. Ltd.
TTCI®	Transportation Technology Center, Inc.