University of Technology, Sydney

Centre for Intelligent Mechatronic Systems
Faculty of Engineering and Information Technology

Investigation into Dynamics of a Rolling Body-Bearing-Support System in a Cold Rolling Stand

by

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A thesis submitted for fulfilment of requirements for the degree of

Doctor of Philosophy

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Certificate of Authorship/Originality

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Nomenclature

ABBREVIATIONS USED IN THIS THESIS

AGC	—	Automatic Gauge Control
Assay's	—	Assembly
CRM	—	Cold Rolling Mill
BF	—	Bland and Ford
MBF	—	Modified Bland and Ford
BH	—	Bearing Housing Chock
BR	—	Backup Roll
WR	—	Work Roll
ODE	—	Ordinary Differential Equation
DDE	—	Delay Differential Equation
DOF	—	Degree Of Freedom
STC	—	Stability Threshold Curve
COP	—	Critical Operating Point
SSC	—	Steady State Condition
LQ	—	Linear Quadrant
ESO	—	Extended State Observer

CHAPTER 2 NOTATION

m_{BH}	—	Lumped mass of the bearing housing chock
m_{BR}	—	Lumped mass of the backup roll
m_{WR}	—	Lumped mass of the work roll
C_{yy}^{WR}	—	Equivalent damping component in the vertical direction
K_{yy}^{WR}	—	Equivalent stiffness component in the vertical direction
$F_{dyn,y}^{WR}$	—	Dynamic rolling force component in the vertical direction
y_{WR}, $\dot{y}_{WR}$, $\ddot{y}_{WR}$	—	Displacement, velocity and acceleration of the work roll, respectively
h_c	—	Roll gap spacing at the center plane of the roll gap
K_2, K_3	—	Elastic constant depending on the elastic contact between the backup roll and work roll, respectively
K_1, K_4	—	Elastic constant depending on the elastic deformation of the bearing housing chock and backup roll, respectively

K_0, K_5	—	Elastic constant depending on the elastic contact between the mill housing and mill foundation, respectively
K_6	—	Spring constant depending on the contact between the work roll and strip
K_{var}	—	Elastic deformation resistance in the roll gap
$C_0 - C_5$	—	Viscous damping coefficients
z_1, z_2	—	Displacements of the top and bottom surfaces of the strip, , respectively
$t_{e,\text{var},i}$, $t_{x,\text{var},i}$	—	Variation of tension at entry and exit side, respectively
$v_{e,\text{var},i}$, $v_{x,\text{var},i}$	—	Variation of rolling speed at entry and exit side, respectively
E	—	Young's modulus
D_i	—	Inter-stand distance at (i)th stand
s	—	Laplacian operator
Δ_i	—	Time delay at (i)th stand
f_y	—	Rolling force per unit width
I	—	Identity matrix
A	—	System matrix
x_{BH}, x_{BR}, x_{WR} y_{BH}, y_{BR}, y_{WR}	—	Coordinates of a rolling stand in cold rolling

Subscripts

BH	—	Bearing Housing Chock
BR	—	Backup Roll
WR	—	Work Roll
dyn	—	Dynamic component
var	—	Variable component
i	—	(i)th stand
e	—	Entry side
x	—	Exit side

CHAPTER 3 NOTATION

§ Any previously used terminology is not listed here.

v	—	Strip velocity at any arbitrary point in the roll gap
v_e, v_x	—	Strip velocity at entry and exit sides, respectively
v_R *or* v_n	—	Work roll velocity (Peripheral rolling speed)
$\overline{v}_R$	—	Average rolling speed
h	—	Strip thickness at any arbitrary point in the roll gap
h_e, h_x	—	Strip thickness at entry and exit sides, respectively
h_n	—	Strip thickness at the neutral point

h_c	—	Roll gap spacing
Δh	—	Reduction of the strip thickness
W	—	Strip width
R_{WR}	—	Undeformed roll radius
R_d	—	Deformed roll radius
L	—	Roll bite length
ϕ	—	Roll contact angle at any arbitrary point in the roll gap
v	—	Poisson's ratio
F_{sp}	—	Specific rolling force per unit width
c	—	Hitchcock constant
τ_s	—	Friction stress
μ	—	Coefficient of friction
p	—	Normal pressure
m	—	Friction factor
k	—	Material shear strength
α	—	Ratio of the real contact area to the apparent contact area
x	—	Location of the arbitrary point in the horizontal plane
x_n	—	Location of the neutral point in the horizontal plane
ω	—	Operating frequency in unit of *rad/s*
Q	—	Torque characteristics of the driving motor
G	—	Variation of the roll torque
$v_{R,\mathrm{var}}$ or Δv_R	—	Variation of the rolling speed
S_f	—	Forward slip
S_b	—	Backward slip
l_0	—	Parallel line distance in the roll surface
l_1	—	Distance between two imprints by slip
σ_0	—	Base yield strength
σ_Y	—	Yield strength or flow stress of the work-piece
ε	—	Strain in the roll gap
$\dot{\varepsilon}$	—	Strain-rate
$\dot{\varepsilon}_{ref}$	—	Strain-rate reference
$\dot{\varepsilon}_{gap}$	—	Strain-rate in the roll gap
B	—	Material-dependent coefficients
T	—	Temperature
N	—	Peripheral rolling speed of the work roll in unit of *rev/s*
θ	—	Angle subtended by the actual work roll axis
$\dot{\theta}$	—	Angular velocity
X	—	Amplitude of the work roll
t	—	Time

ΔD_i	—	Variable amount of elongation at (*i*)th stand
t_e, t_x	—	Tension stress at entry and exit sides, respectively
t_{avg}	—	Average tension stress
A	—	Cross-sectional area of the roll gap

Superscripts

γ_1	—	Strain exponent (dimensionless)
γ_2	—	Strain-rate sensitivity exponent (dimensionless)

Subscripts

ref	—	Reference
gap	—	Roll Gap
avg	—	Average
Y	—	Yield
b	—	Backward
f	—	Forward

CHAPTER 4 NOTATION

§ Any previously used terminology is not listed here.

f	—	Horizontal rolling force
s	—	Normal pressure
s^-, s^+	—	Normal pressure at entry and exit sides, respectively
c	—	Constant determined by Bland and Ford model
H, H_e, H_n	—	Constant at any arbitrary, entry and neutral planes, respectively
p, q	—	Horizontal and vertical pressures, respectively
σ	—	Yield stress in uniaxial compression
σ_e, σ_x	—	Yield (Flow) stress at entry and exit sides, respectively
ϕ_n	—	Neutral point/angle
$\dot{\varepsilon}^*$	—	Dimensionless strain-rate
F_R	—	Resultant rolling force
F_H, F_V	—	Horizontal and vertical rolling forces, respectively
R_{BR}	—	Backup roll radius
r	—	Reduction rate
μ_{s0}	—	Friction coefficient at the steady-state rolling condition
μ_{sl}	—	Sliding friction coefficient
$\dot{h}_c$	—	Reduction rate with respect to time or rate of change in strip thickness

$F_{dyn,R}^{WR}$	—	Resultant component of dynamic rolling force
$F_{dyn,x}^{WR}$	—	Horizontal component of the dynamic rolling force
$F_{dyn,y}^{WR}$	—	Vertical component of the dynamic rolling force
K_{ij}^{var}	—	Stiffness coefficient components in the dynamic roll gap
C_{ij}^{var}	—	Damping coefficient components in the dynamic roll gap
α_s	—	Friction gradient (s/m)
v_{WR}	—	Work roll velocity
v_S	—	Strip velocity at the exit side
$C_{\text{var}0}$	—	Variation of rolling force to the change in friction coefficient
Q	—	Rolling force variation due to the change in exit strip thickness based on the strip plastic deformation
ΔS_0	—	Variation of the dynamic roll displacement
ΔM_m	—	Elastic mill modulus
Δv_H	—	Variation of the horizontal rolling speed
Δh_c	—	Variation of reduction rate (roll gap spacing)
$\Delta \dot{h}_c$	—	Variation of reduction rate with respect to time
$\dot{R}$	—	Time derivative of roll radius
$\dot{x}_n$	—	Time derivative of neutral position
$\dot{\phi}_n$	—	Time derivative of neutral point
$K_{\text{var}1}$	—	Stiffness component of the dynamic rolling force due to the variation of the vertical displacements
$C_{\text{var}1}$	—	Damping component of the dynamic rolling force due to the variation of the horizontal velocity
$C_{\text{var}2}$	—	Damping component of the dynamic rolling force due to the variation of the dynamic roll gap
$K_{ij}^{\text{var}1}$	—	Stiffness components in the dynamic roll gap due to the variation of the vertical displacements
$C_{ij}^{\text{var}1}$	—	Damping components in the dynamic roll gap due to the relative motion between the work roll and strip
$C_{ij}^{\text{var}2}$	—	Damping components in the dynamic roll gap due to the variation of the horizontal velocity
$C_{ij}^{\text{var}3}$	—	Damping components in the dynamic roll gap due to the variation of the reduction rate (with respect to time)
β	—	Tilted angle caused by offset
μ_c	—	Friction coefficient in metal-to-metal (between BR and WR)
F_{fc}	—	Friction force between the backup roll and work roll
F_{fw}	—	Friction force between the work roll and strip

Subscripts

ij	—	x- or y-directional components, respectively
$R1$, $R2$, $R3$, $R4$	—	First to fourth variable components in the dynamic roll gap

CHAPTER 5 NOTATION

§ Any previously used terminology is not listed here.

F_{HCH}, F_{HCV}	—	Reaction forces from the mill frame and Screw-down forces on top, respectively
F'_{JBH}, F'_{JBV}, F'_{RBH}, F'_{RBV}	—	Bearing force components resulted from support bearings
F_H, F_V	—	Horizontal and vertical rolling forces in the roll gap, respectively
F'_H, F'_V	—	Surface contact force components between BR and WR
F_R, F'_R	—	Resultant rolling force, respectively
F_{HCf}	—	Frictional force in the sliding surface of the housing chock
k^n_{ij}	—	Stiffness coefficients of the system resulted from the bearing housing, backup roll and work roll
c^n_{ij}	—	Damping coefficient of the system resulted from the bearing housing, backup roll and work roll
$[K_{BR}]$	—	Stiffness matrix for the backup roll
$[C_{BR}]$	—	Damping matrix for the backup roll
$[K_{WR}]$	—	Stiffness matrix for the work roll
F_{tot}	—	Frictional and dynamic rolling force components
R_{bb}	—	Journal bearing radius
L_{bb}	—	Journal bearing length
η	—	Dynamic viscosity in the journal bearing
C_{bb}	—	Journal bearing clearance
ε_{bb}	—	Eccentricity
ω_{bb}	—	Rotation speed (*RPM*)
R_{wb}	—	Tapered roller bearing radius
L_{wb}	—	Tapered roller bearing length
Z	—	Number of rolling element
C_{wb}	—	Tapered roller bearing clearance
n	—	Roller bearing exponent
K_n	—	Load deflection constant
α_0	—	Rolling element angle
ω_{wb}	—	Rotational speed (*RPM*)
δ_{im}	—	Mean displacement
δ_{Rm}	—	Resultant elastic deformation
ψ_j	—	Angular position of (j)th rolling element
Δ_{ij}	—	Relative displacement along the axis of loading of two points
f_{ij}	—	Compressive load per unit length
D_{BR}	—	Backup roll diameter
D_{WR}	—	Work roll diameter

F_{ij}	—	Rolling force component
k_{ij}^{C}	—	Stiffness component between two rolls
φ	—	Rotational angle
U_1, U_2, U_3	—	Transformation matrix

Superscripts

n	—	Refer to BH, BR and WR
ij	—	x- or y-directional components, respectively

Subscripts

HCH, HCV	—	Refer to the bearing housing chock in the horizontal and vertical directions, respectively
JBH, JBV	—	Refer to the journal bearing in the horizontal and vertical directions, respectively
RBH, RBV	—	Refer to the tapered roller bearing in the horizontal and vertical directions, respectively
H, V	—	Refer to the horizontal and vertical directions, respectively
R	—	Refer to the resultant component
HCf	—	Frictional component of the bearing housing chock
tot	—	Total
bb	—	Backup roll bearing (Journal bearing)
wb	—	Work roll bearing (Tapered roller bearing)

CHAPTER 6 NOTATION

§ Any previously used terminology is not listed here.

C_{Tlusty}^{1}	—	Damping component of a variable force component depending on the rolling speed by Tlusty
C_{Kimura}^{1}	—	Damping component of a variable force component depending on the rolling speed by Kimura
k_f	—	Deformation resistance of the material
C_{Tlusty}^{2}	—	Damping component of a variable force component due to negative damping effect by Tlusty
C_{Gap}	—	Positive damping component in the bearing support (resulted from the mill structure) and the roll gap
C_{var}	—	Negative damping component in the dynamic roll gap
K_{Tlusty}	—	Stiffness component of a variable force component presented by Tlusty
K_{Kimura}	—	Stiffness component of a variable force component presented by Kimura
K_{Gap}	—	Positive stiffness component in the bearing support (resulted from the mill structure) and the roll gap

K_{var}	—	Stiffness coefficient in the deformed strip
$[M]$	—	Mass matrix
$[K]$	—	Stiffness matrix
$[C]$	—	Damping matrix
0_6	—	6×6 zero matrix
I_{D6}	—	6×6 identity matrix
ζ	—	Damping ratio
f_i	—	Damped natural frequency (Hz)
X	—	Displacement vector of a rolling stand
$\dot{X}$	—	Velocity vector of a rolling stand
cSt	—	Kinematic viscosity ($1cSt = 1mm^2/s$)
η	—	Dynamic viscosity
η_0	—	Viscosity at ambient pressure and temperature
ρ	—	Fluid density
υ	—	Kinematic viscosity
$P_{\max}$	—	Oil-film pressure at a maximum
α	—	Pressure coefficient of viscosity

Subscripts

i	—	Refer to the first to sixth mode
JBH, JBV	—	Refer to the journal bearing in the horizontal and vertical direction

CHAPTER 8 NOTATION

§ Any previously used terminology is not listed here.

ΔL	—	Variation of length of arc contact in the roll gap)
y_i	—	Dynamic oscillation of the work roll
$t_{e,\text{var}}\big\vert_{Tlusty}$	—	Tension variation at the entry side by Tlusty
$t_{e,\text{var}}\big\vert_{Yun}$	—	Tension variation at the entry side by Yun
$t_{e,\text{var}}\big\vert_{Dyn}$	—	Tension variation at the entry side by the current model
$\phi_{n,\text{var}}$	—	Variation of the neutral point

Subscripts

i	—	Refer to the work roll

Abstract

The objective of this thesis is to gain a good understanding of the chatter phenomenon incorporating the dynamic rolling model and mechanical system model of a rolling stand in cold rolling. Although such systems have received great attention in the academic literature, research to-date has not covered dynamic characteristics of the multiple rolling body-bearing-support system due to its complexity and nonlinearities.

In this thesis, a steady-state rolling process model that includes the work hardening and work roll flattening effect was developed based on the homogeneous deformation theory with the relaxation of conventional assumptions. A dynamic model of the rolling process was then formulated by taking into account multiple nonlinearities such as the change in friction coefficient, rolling speed, roll gap (strip thickness) reduction and reduction rate with respect to time. In linearisation of rolling force variations as stiffness and damping coefficients, negative gradient of friction coefficient was introduced to identify the negative damping effect in the dynamic roll gap. Also, dynamic rolling force components were included in the analysis by the linearisation of variations of the strip thickness and rolling speed at exit side and of variations of reduction rate with respect to time.

In addition, a mechanical system model was derived through the inclusion of the support bearings and surface contact between rolls. For the backup roll, a journal bearing model was introduced to examine oil-film thickness change and a tapered roller bearing model was adopted to model the work roll motion. In order to explain dynamics in the surface contact between the backup roll and work roll, Hertzian contact theory is incorporated into the mode-coupling theory. Finally, by coupling the dynamic rolling process model with a mechanical system model including support bearings and surface contact, a 6DOF mill vibration model for the analysis of vibrations symmetric to the roll gap was developed.

In determination of stability in the derived cold rolling stand chatter model, stability analyses were performed through the change in the friction coefficient and rolling speed at a given friction gradient. Many different aspects of stability threshold curves (STC) have been obtained from the eigenvalues analysis of the system characteristic equation. Influences of 10 rolling parameters such as the friction gradient, strip width, roll radius, exit thickness, strain and strain-rate exponent, roll offset, bearing viscosity, length and clearance on mill stability were thoroughly investigated. With the linearised stiffness and damping coefficients at the given operating conditions, transient studies were executed to prove the validity of the presented model.

Finally, in order to understand the effects of tension variations from the adjacent mill stand, three different tension models were applied into the dynamic roll gap. By so doing, the mill stability has been determined through the inclusion of transient characteristics in the dynamic roll gap. In light of observation from the practical mill configuration, simulation results suggest that chatter arises as the rolling speed increases and friction coefficient decreases under the steady-state rolling conditions. When tension variation applied, instability occurs as the inter-stand distance decreases and a strip feed-in speed variation frequency matches to one of the system natural frequencies.