INVESTIGATION OF THE DYNAMICS OF RAILWAY BOGIES SUBJECTED TO TRACTION / BRAKING TORQUE

Yunendar Aryo Handoko

A Thesis Submitted in Partial Fulfilment for the Award
of the Degree of Doctor of Philosophy (PhD)

Centre for Railway Engineering
Central Queensland University
Australia

September 2006

ABSTRACT

The limitations of current simulation packages in addressing the true longitudinal behaviour of railway bogie dynamics during braking/traction has prompted the development of a Rail Bogie Dynamics (RBD) program in this thesis. The RBD program offers novel features for the calculation of the speed profile as a function of the brake torque as well as explicitly determining wheelset angular velocity. With such capability, the speed profile is no longer treated as an input calculated as a priori as required by most of the current simulation systems. The RBD program has been developed using a formulation that includes the wheelset pitch degree of freedom explicitly with a coordinate reference system that is fixed in space and time. The formulation has made the simulation of the bogie dynamics during braking/traction possible in a natural way using the brake/traction torque as the input and the resulting speed profile as the output without any need for working out the speed profile as a priori. Consequently, severe dynamics during braking such as the wheelset skid and the onset of wheel climb derailment can be modelled and critical parameters investigated using the RBD program.

The RBD program has been validated, where possible, through a series of simulations using a commercial software package (VAMPIRE). For cases which cannot be simulated by VAMPIRE such as the wheelset skid, a novel experimental program has been designed and commissioned in the Heavy Testing Laboratory of the Central Queensland University as reported in this thesis. One of the possible applications of the RBD program in examining the effect of asymmetric brake shoe force in bogies equipped with one-side push brake shoe arrangement is illustrated in this thesis. It is believed that the model and RBD program will have significant benefit in understanding the true longitudinal behaviour of wagons in suburban passenger trains that operate under braking/ traction torques for most of their travel. Similar studies will also be useful to freight train wagon dynamics during entry and exit of speed restriction zones and tight curves.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

Scalar Symbols

a_e	Longitudinal semi axis of the contact ellipse
b_e	Lateral semi axis of the contact ellipse
a_a	Acceleration (magnitude)
a_b	Deceleration (magnitude)
b_a	Half of the distance between accelerometers in the left and the right axle boxes
C	Proportionality constant of Polach's formulation
c_{11}, c_{22}, c_{23}	Kalker's coefficient
c	Damping constant
c_r	Rotational damping constant
dv_{sensor}	Resolution tolerance of the sensor measuring longitudinal movement
$d\Omega_{sensor}$	Resolution tolerance of the sensor measuring the wheelset rotation
D	Effective diameter of brake piston
F_B	Brake shoe force (magnitude)
F_{Beff}	Effective brake shoe force (magnitude)
F_{CR}	The creep forces resultant (magnitude)
F_{CT}	Brake cylinder piston thrust (magnitude)
F_R	Magnitude of counter force exerted by slack adjuster
F_s	Magnitude of spring-damper force
F_T	Brake shoe tangential force (magnitude)
F_x	Magnitude of longitudinal force at contact point
F_Z	Magnitude of vertical force at contact point

g	Constant of gravitation
i_t	Total brake rigging ratio
i_b	Bogie brake rigging ratio
J_y	Polar moment of inertia
k_s	Spring constant
k_r	Rotational spring constant
k_{ir}	Parameter of track irregularities
k_{y_rail}	Rail lateral stiffness
L_H	Klingel hunting wavelength
l	Current spring length
l_o	Undeformed length of the spring
m	Body mass
N_w	Wheel load
n	Number of system coordinates
n_c	Number of constraint equations
p_c	Air pressure in the brake cylinder
Q	Normal load
R	Radius of curve
r_w	Nominal wheel radius
s_1^w, s_2^w	Surface parameters of the wheel
s_1^r, s_2^r	Surface parameters of the rail
s_a	Longitudinal distance travelled during acceleration
s_b	Longitudinal distance travelled during braking
T_B	Brake Torque (magnitude)
T^{ij}	Magnitude of the torque exerted by rotation spring element between body i and body j
V^i	Volume of the rigid body i

v	Longitudinal velocity
v_C	Circumferential velocity
y_f	Flange clearance
y_w	Wheelset lateral displacement
Δ_{ir}	Amplitude of track irregularities
$\xi_{analytical}$	Analytical value of longitudinal creepage
ξ_x	Longitudinal creepage
$\xi_{\exp}$	Longitudinal creepage measured during experiment
ξ_y	Lateral creepage
ξ_{yc}	Lateral creepage after incorporation of spin
ξ_{sp}	Spin creepage
ξ_t	Total creepage (resultant of lateral and longitudinal creepages)
ω	Angular velocity (magnitude)
λ_w	Wheel conicity
η	Brake rigging efficiency
ρ	mass density
μ_b	Brake shoe friction coefficient
μ_r	Wheel-rail friction coefficient
θ^{ij}	Magnitude of relative rotation between body i and body j
$\theta_0^i, \theta_1^i, \theta_2^i, \theta_3^i$	Euler parameters
ψ	Yaw rotation
ϕ	Roll rotation
τ	Tangential stress
σ	Normal stress
φ	Gradient of tangential stress curve in the area of adhesion

Vector-Matrix Symbols

$\mathbf{A}^i$	Transformation matrix of the rigid body i
$\mathbf{A}^j$	Transformation matrix of the rigid body j
$\mathbf{C}$	Contact constraint (set of equations)
$\mathbf{C}_\mathbf{q}$	Sub-Jacobian matrix of constraint equation associated with generalised coordinates
$\mathbf{C}_\mathbf{s}$	Sub-Jacobian matrix of constraint equation associated with surface parameters
$\mathbf{F}_1^i, \mathbf{F}_2^i, \dots \mathbf{F}_{n_f}^i$	Set of forces acting on the rigid body i
$\mathbf{G}^i$	Matrix that relates the angular velocity vector of body i and time derivatives of Euler parameters of the body
$\mathbf{G}^j$	Matrix that relates the angular velocity vector of body j and time derivatives of Euler parameters of the body
$\bar{\mathbf{I}}_{\theta\theta}^i$	Inertia tensor of the rigid body i
$\mathbf{M}^i$	Mass matrix of the rigid body i
$\mathbf{M}_1^i, \mathbf{M}_2^i, \dots \mathbf{M}_{n_m}^i$	Set of moments acting on the rigid body i
$\mathbf{m}_{RR}^i$	Inertia matrix of body i associated with the translation of the body reference
$\mathbf{m}_{\theta\theta}^i$	Inertia matrix of body i associated with the rotation of the body reference
$\mathbf{m}_{\theta\theta}^i$	Inertia coupling between the translation and rotation of the body i reference
$\bar{\mathbf{n}}^{ik}$	Normal vectors to the surface of body i at contact point k
$\bar{\mathbf{n}}^{jk}$	Normal vectors to the surface of body j at contact point k
$\mathbf{Q}$	Sum of the vectors of generalized applied forces and quadratic velocity vector

$\mathbf{Q_d}$	Vector that absorbs the quadratic term in the first order time-derivatives of the generalised coordinates
$\mathbf{Q}_e$	Vector of generalized applied force
$\mathbf{Q}_R^i$	Vector of generalised forces associated with translational coordinates of body i
$\mathbf{Q}_\theta^i$	Vector of generalised forces associated with rotational coordinates of body i
$\mathbf{Q}_v$	Quadratic velocity vector
$\mathbf{q}$	Vector of generalised coordinates
$\mathbf{q}_d$	Vector of dependent generalised coordinates
$\mathbf{q}_i$	Vector of independent generalised coordinates
$\mathbf{R}^i$	Global position vector of the origin of the body i reference frame
$\mathbf{R}^j$	Global position vector of the origin of the body j reference frame
$\mathbf{r}_p^{ij}$	Vector position of point P^i at body i with respect to point P^j at body j
$\mathbf{s}$	Vector of surface parameters
$\mathbf{s}_d$	Vector of dependent surface parameters
$\mathbf{s}_i$	Vector of independent surface parameters
$\overline{\mathbf{t}}_l^{ik}$	Tangent vectors to the surface of body i at contact point k, ($l=1,2$)
$\overline{\mathbf{t}}_l^{jk}$	Tangent vectors to the surface of body j at contact point k, ($l=1,2$)
$\overline{\mathbf{u}}_p^i$	Position vector of the point P^i with reference to the body i coordinate system
$\overline{\mathbf{u}}^{ik}$	Position vector of the contact point k with reference to the rigid body i coordinate system

$\bar{\mathbf{u}}^{jk}$ Position vector of the contact point k with reference to the rigid body j coordinate system

$\boldsymbol{\lambda}$ Vector of Lagrange multiplier

$\boldsymbol{\omega}^{i}$ Angular velocity vector of the rigid body i

$\boldsymbol{\omega}^{j}$ Angular velocity vector of the rigid body j

LIST OF ABREVIATIONS

AAR	Association of American Rail Roads
ABS	Anti-lock Braking System
BR	British Railway
BS	British Standard
CQU	Central Queensland University
CRE	Centre for Railway Engineering
DAQ	Data Acquisition
HTL	Heavy Testing Laboratory
INKA	Industri Kereta Api (Indonesian Railway Industry)
IRF	Inertial Reference Frame
RBD	Rail Bogie Dynamic
SHE	Shen-Hedrick-Elkins (theory of wheel-rail rolling contact)
TRF	Track-following Reference Frame
TTL Signal	Transistor - Transistor Logic Signal
UIC	Union Internationale des Chemins de fer (International Union of Railways)
3D-WTSD	Three Dimensional Wagon Track System Dynamic (a 3D model of wagon-track interaction by Sun & Dhanasekar (2001))

ACKNOWLEDGEMENT

It is my pleasure to acknowledge those who have encouraged and supported me in many ways during my PhD research studies.

Firstly I would like to express my earnest gratitude to my supervisor Dr. Manicka Dhanasekar, Associate Professor and Director, Centre for Railway Engineering (CRE), Central Queensland University (CQU) for his valuable discussion and guidance throughout the three and half years for enabling me to write this thesis. He has supported me both in the technical and personal matters during my stay with the CRE.

I should thank Ir. Roos Diatmoko, Director of Indonesian Railway Industry (PT INKA), for his support and continuous encouragement since I started working there in 1996. I also thank the management board and my colleagues in PT INKA for their support.

I also record my special thanks to Florian Sumpf, an exchange student from The University of Aachen, Germany who actively participated in the designing of the bogie braking experiment. The technical assistance related to experimental work in the Heavy Testing Laboratory was thankfully received from a range of technical staff of CQU, Bernard Jansen, Gary Hoare, Ian Major, Grant Caynes, Trevor Ashman, Ken Morrison and Dr. Marcel Frank.

The support from Queensland Railway (QR) that enabled me to carry out the full scale bogie brake experiment is thankfully acknowledged. Special thanks are due to QR Engineers Andrew Nelmes and Bruce Brymer, and a range of other QR staff who installed the track, and also measured various parameters both of the track and bogie components. Without QR support this experiment would not have been possible.

I also thank Dr. Fuji Xia, Dr. Yan Quan Sun, Dr. Colin Cole, Dr. Jian Jun Han, Mitch McClanachan and Scott Simson for valuable technical discussions provided on many occasions. Special thanks to Tim McSweeney and Scott Simson for spending their valuable time for providing very useful suggestions for improvement of my PhD thesis.

Finally, I should thank my family, especially my parents and my wife, Sari Wulandari, for their encouragement, patience and support; and also to my children, Dhila, Hanif and Syifa, as they are my inspiration.

I acknowledge the financial support offered by the CRE, and PT INKA.

DECLARATION

The work contained in this thesis is a direct result of the original work carried out by me and has not been submitted for the award of a degree or diploma at any other tertiary institution in Australia or overseas.

Signed:__________________________ Date____________________

Yunendar Aryo Handoko

Author

PUBLISHED WORK

As a direct result of the research reported in this thesis the following papers have either been published or are under review:

1. Yunendar Handoko and Manicka Dhanasekar (2006), An Inertial Reference Frame Method for the Simulation of the Effect of Longitudinal Force to the Dynamics of Railway Wheelsets, (Accepted to be published in *International Journal of Non Linear Dynamics*).

2. Yunendar Handoko and Manicka Dhanasekar (2006), Simulation of Railway Bogie Skid, (*Journal of Rail and Rapid Transit, Proceedings of Institution of Mechanical Engineer, Part F*, under review)

3. Yunendar Handoko and Manicka Dhanasekar (2006), Simulation of Bogie Dynamics under Heavy Braking, (Accepted to be published and presented in the *Proceedings of the Conference on Railway Engineering* in Melbourne)

During the completion of the research higher degree program at Central Queensland University the author has also co-authored the following papers:

1. Y. Handoko, F. Xia, and M. Dhanasekar, Effect of Asymmetric Brake Shoe Force Application on Wagon Curving Performance, *Vehicle System Dynamic Supplement 41, Proceeding of IAVSD Conference* in Japan, 2004, p113-122.

2. M. McClanachan, Y. Handoko, M. Dhanasekar, D. Skerman, and J. Davey, Modelling Freight Wagon Dynamics, *Vehicle System Dynamic Supplement 41, Proceeding of IAVSD Conference* in Japan, 2004, p438-447.

1. INTRODUCTION

Suburban passenger trains operate under braking / traction condition during most of their travel. Most heavy haul and long haul trains are also operated under similar condition when they enter and exit speed restriction zones and/or tight curves. Although braking/ traction torques modify the operating speed in a complex manner, which could only be realistically evaluated using rigorous calculations, current simulations are routinely carried out for constant speed conditions with the speed profile input as a priori.

With a view to providing a simulation platform which truly accounts for traction/braking torque induced dynamics of wagons, this thesis formulates a model that explicitly accounts for the wheelset pitch degree of freedom. The formulation is provided with reference to a coordinate system that is fixed in space and time. The formulation enables the simulation to be performed in a natural way using the brake/traction torque as the input and the resulting speed profile as the output without any need for working out the speed profile as a priori. A MATLAB computer program titled Rail Bogie Dynamics (RBD) program which uses the formulation is developed and reported in this thesis.

1.1. AIM AND OBJECTIVES

The aim of the thesis is to formulate a model with the potential for simulating true longitudinal dynamics of bogies under braking/traction torque. This aim is achieved through the enabling objectives listed below:

1. Review the dynamics of rail bogies including the effect of braking/traction through literature study.
2. Review the theory of wheel-rail rolling contact available in the literature to incorporate suitable criteria in the model developed.
3. Formulate the system dynamic equations and their solution technique capable of truly modelling the longitudinal dynamics of bogies subjected to braking/traction torque.
4. Develop the Rail Bogie Dynamics (RBD) program based on the formulation and solution technique as per objective 3.
5. Validate the RBD program against VAMPIRE where possible
6. Validate the other and most severe cases using a full-scale laboratory test.
7. Apply the RBD program to evaluate the severe dynamics of bogies induced due to asymmetric brake shoe forces.

1.2. SCOPE AND LIMITATION

The scope of this thesis is to investigate the dynamics of railway bogies subjected to traction/braking torque. The severe bogie dynamics involving wheelset skid will be investigated through simulation and experiments. The effect of the asymmetric braking due to error in the distribution of the brake shoe normal force within a single wheelset in bogies equipped with one-side push brake shoe will also be examined.

The limitations are:

i. Only tangent track will be considered.
ii. Only simple and most common bogies will be considered.
iii. Whole wagon dynamics will not be considered.

1.3. OUTLINE OF THE THESIS

This thesis contains 10 chapters that cover the formulation, validation, and application of the RBD program.

Chapter 1 outlines the aim, objectives, scope and limitation of the thesis.

In Chapter 2, the basic terminologies used in wagon and bogie dynamics are reviewed. The mechanics of wheel-rail contact, which is fundamental to the bogie and wagon dynamics, is discussed. The wagon braking and traction systems and their principle of working are reviewed briefly for completeness. In the last part of this chapter, a review of the current railway wagon simulation software systems and their limitations to perform true longitudinal dynamics of wagon simulation is presented.

Chapter 3 describes in detail the formulation of the RBD program. The coordinates of reference and the formulation of multibody system equations are presented in detail. The law of contact between rigid bodies contact and its mathematical formulation applied to the wheel-rail contact patch are described. The calculation of creep forces using the Polach formulation is presented. The technique for solving the system equations that involves the differential equilibrium equations and algebraic constraint equations in the augmented form is exhibited. Finally, the algorithm for the railway bogie dynamic analysis is presented in a flow chart.

Validation of the RBD program against VAMPIRE, where possible, is contained in Chapters 4 and 5. The simulations in Chapter 4 deals with the dynamics of the wheelset within a bogie frame whilst Chapter 5 deals with the dynamics of simplified two axle bogies. A series of simulations with or without the application of braking/traction torque with various track irregularities are presented.

Chapter 6 describes the design of an experimental program to validate the novel features of the RBD program for the calculation of the speed profile as a function of the brake torque as well as explicitly determining wheelset angular velocity. The concept of the measurement system and the specification of measurement devices used in the experiments are presented. The modifications of the bogie used in the experiment to suit the mounting of the measurement devices and the construction of the test track are also explained.

Chapter 7 presents the results of the experimental program described in Chapter 6. For convenience, the data obtained from the experiments is categorised into two parts. The first part presents the primary data which is gathered directly from the measurement devices and the second part presents the derived data which is manipulated from the primary data. Three brake cylinder pressure cases have been examined from the experimental data; they are 130 kPa, 150 kPa, and 180 kPa. These cases represent the condition below the skid limit, at the skid limit, and above the skid limit respectively.

The comparison of the experimental results with the results obtained through the simulation using the RBD program is exhibited in Chapter 8. The input for the simulation is the measured experimental brake torque and the output is the longitudinal acceleration / deceleration, speed profile, angular velocity and slip.

Chapter 9 presents the application of the RBD program to simulate the severe bogie dynamics due to application of asymmetric brake normal forces within a single wheelset in bogies equipped with a one-side push brake shoe arrangement. The effect of various levels of asymmetric brake shoe forces and application time is examined and reported in this chapter.

Chapter 10 provides the summary of the thesis and lists the conclusions that have emerged from this research. Some recommendations for further research are also offered in this chapter.