

MATHEMATICAL SIMULATION FOR LATERAL DYNAMICS OF CONVENTIONAL AND UNCONVENTIONAL RAILWAY TRUCKS

by

P MANNAR JAWAHAR

*A THESIS SUBMITTED
IN FULFILMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE OF
DOCTOR OF PHILOSOPHY*



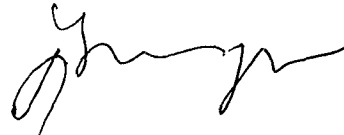
**Department of Mechanical Engineering
INDIAN INSTITUTE OF TECHNOLOGY, DELHI
1989**

DEDICATED
TO MY BELOVED PARENTS

Thiru R.PONNUSWAMY
and
Thirumathi M.KAMALAM

CERTIFICATE

The thesis entitled **MATHEMATICAL SIMULATION FOR LATERAL DYNAMICS OF CONVENTIONAL AND UNCONVENTIONAL RAILWAY TRUCKS** being submitted by **Mr. P. MANNAR JAWAHAR** to the Indian Institute of Technology, Delhi, for the award of the degree of Doctor of Philosophy, is a record of bonafide research work carried out by him. He has worked under my guidance and supervision, and has fulfilled the requirements for the submission of this thesis which has attained the standard required for the Ph.D. degree of the Institute. The results presented in this thesis have not been submitted elsewhere for the award of any degree or diploma.



(Dr. K. N. GUPTA)

Professor, Mechanical Engineering Department
Indian Institute of Technology,
New Delhi

ACKNOWLEDGEMENTS

I wish to express my deepest sense of gratitude to Dr.Ing.K.N.GUPTA, Professor of Mechanical Engineering, IIT, Delhi for introducing the problem area, motivating and inspiring to take up the present study and for his valuable guidance and supervision. I am extremely indebted to him for his constant encouragement, immense help, sincere and timely advice, and for keeping the spirits high throughout the study to enable its successful completion. Working with him has been a highly rewarding experience. I take this opportunity to offer my most sincere thanks to him.

I take this opportunity to express my gratitude towards Dr.V.C.Kulandaichamy, the Vice Chancellor of Anna University and Dr.S.Sathikh, the Director of MIT, Madras for sponsoring me to IIT, Delhi for doctoral research programme under QIP scheme of the Ministry of Education, Govt. of India. I am highly grateful to all my colleagues in the Department of Automobile Engineering of MIT, for readily agreeing to share the workload during my sponsorship period of 3 years.

I am highly grateful to Prof.J.Kisilowsky and Dr.W.Choromanski for inviting me to Warsaw University of Technology, Poland and giving me three months research training in the area of Railway Vehicle Dynamics. My sincere thanks are due to them.

I convey my gratitude to Mr.D.L.Nagpal, Mr.Shyamlal and Mr.Umesh Chandra of Research Designs and Standards Organisation, Ministry of Railways, Govt. of India, Lucknow for providing the informations required for this thesis and for arranging all facilities during my visits at RDSO, Lucknow.

I am thankful to all the faculty members of this Department for their suggestions and encouragement during the course of this work. Thanks are also due to the staff members of the Personal Computer Lab of Mechanical Engineering Department and the Institute Mainframe Computer Centre for the facilities provided for this work.

I am very much grateful and a special word of thanks to my friends Mr.A.Noorul Haq and Mr.R.Muthukumar who have helped me with interest and care during the preparation of my thesis. During the tenure of this research work, out of sheer love and compassion many friends, whose names do not figure here, have helped me in this endeavour. To all of them I am highly indebted.

Special appreciation to my wife Jewelcy and sons Nishant and Nitin for patiently enduring certain difficulties and for their understanding, co-operation and encouragement that made it possible for me to complete my doctoral work in time.

Appreciation is expressed to Mr. Akhilesh Chippli, for typing the manuscript with great patience and care at a short notice.

A handwritten signature in black ink, appearing to read 'P. Mannar Jawahar', with a stylized, cursive script.

P. MANNAR JAWAHAR

ABSTRACT

This thesis aims at developing a methodology for modelling and analysis of Lateral Stability and Dynamic Response of a Railway Vehicle System. Since higher operating speeds and greater axle loads are due to be implemented in Indian Railways, it is absolutely essential to obtain a better understanding of the rail-vehicle system under this situation.

The lateral dynamics of rail vehicle system is strongly influenced by the interaction forces between the wheel and the rail. When a wheelset is disturbed from the central position on a tangent track, large horizontal forces called creepforces are generated at the wheel rail interface. These horizontal forces are responsible for truck hunting.

Here a linear and non-linear mathematical model has been constructed by deriving the equations of motion of a railway vehicle truck using Newton's law. For linear modelling, Kalker's creep theory is applied to evaluate the contact tangential forces acting between wheel and rail. For non-linear modelling, the non-linear formula is used to evaluate the wheel rail contact forces. The non-linear profile of wheel and rail are taken into account. Also the lateral stiffness of the track is taken into consideration.

In both linear and non-linear modelling, the equations of motion are derived for (a) truck with conventional wheelset (b) truck with unconventional wheelset (independently rotating wheels). For lateral vibration, 7 degrees of freedom are considered. The degrees of freedom represent lateral and yaw movements of both the wheelsets and lateral, yaw and roll movements of the truck.

Linear modelling is used to analyse lateral stability. Here the equations of motion are transformed into a standard eigen value problem. Eigen values are determined using similarity transformations and double QR Algorithm with shift strategy. By noting the sign change in the real part of the eigen values obtained by changing various input parameters, particularly speed, the threshold of stability is determined.

Non-linear modelling is used to analyse lateral dynamic response. Here the equations of motion are transferred into a form suitable for numerical integration by Adam's method.

To carryout all these mathematical operations, two computer softwares are developed, one for linear modelling and the other for non-linear modelling. In the interest of computing economy, certain approximations have been introduced for calculating creep forces.

Sample results are given for a model of a typical railway vehicle used by Indian Railways. The lateral stability and lateral dynamic response of the railway vehicle for both conventional and unconventional wheelset has been analysed.

Finally at the end, based on comprehensive synthesis of research reported in different chapters, it has been attempted to highlight contributions and limitations of the research pursued, and scope of further research in related areas. The thesis concludes with a detailed list of references and an appendix.

CONTENTS

	PAGE NO.
ABSTRACT	i
LIST OF FIGURES	iv
LIST OF TABLES	vii
NOMENCLATURE	viii
CHAPTER-1 INTRODUCTION	
1.1 RAIL-VEHICLE SYSTEMS AND ASSOCIATED PROBLEMS	2
1.2 STATE-OF-ART	6
1.2.1 Computer Modelling	7
1.2.2 Simulation	8
1.3 R & D ACTIVITIES IN RAILWAY ENGINEERING	8
1.4 SCOPE OF PRESENT WORK	10
CHAPTER-2 LITERATURE REVIEW	
2.1 INTRODUCTION	13
2.2 BASIS OF THE PRESENT REVIEW	13
2.3 THE PICTORIAL SCHEME FOR THE REVIEW	15
2.4 RAILWAY VEHICLE WHEELSET	18
2.4.1 Wheelset Contact Force	19
2.4.2 Wheelset Contact Geometry	22
2.4.3 Wheelset Stability	23
2.5 RAILWAY VEHICLE TRUCK	24
2.5.1 Truck Stability	25

2.6	RAILWAY VEHICLE	26
2.6.1	Vehicle Stability	26
2.6.2	Vehicle Response	27
2.7	RAILWAY TRACK	28
2.8	UNCONVENTIONAL WHEELSET	29
2.9	MATHEMATICAL MODELLING	29
2.10	GENERAL-MISCELLANEOUS TOPICS	30
2.10.1	Curving	30
2.10.2	Steering	31
2.10.3	Stability	32
2.11	THE CURRENT STATE OF THE RESEARCH	32
2.12	NEED FOR FURTHER RESEARCH AND AREAS OF STUDY	33
2.13	CONCLUSIONS	34
CHAPTER-3	MATHEMATICAL MODELLING	
3.1	INTRODUCTION	36
3.2	SYSTEMS AND ASSUMPTIONS	40
3.2.1	General Assumptions	40
3.2.2	Additional Assumptions in Linear Modelling	41
3.2.3	Additional Assumptions in Non-linear Modelling	42
3.3	CONVENTIONAL WHEELSET (LINEAR MODELLING)	42
3.3.1	Wheel-Rail Contact Forces	42
3.3.2	Suspension Forces	50
3.3.3	Gyroscopic Forces	52
3.3.4	Equations of Motion	52

3.4	UNCONVENTIONAL WHEELSET (LINEAR MODELLING)	55
3.5	TRUCK WITH CONVENTIONAL WHEELSET (LINEAR MODELLING)	56
3.5.1	Wheel-Rail Contact Forces	58
3.5.2	Suspension Forces	58
3.5.3	Gyroscopic Forces	61
3.5.4	Equations of Motion	62
3.6	TRUCK WITH UNCONVENTIONAL WHEELSET (LINEAR MODELLING)	67
3.7	CONVENTIONAL WHEELSET (NON-LINEAR MODELLING)	70
3.7.1	Wheel-Rail Contact Forces	70
3.7.2	Suspension Forces	72
3.7.3	Gyroscopic Forces	72
3.7.4	Track Forces	73
3.7.5	Geometrical Terms	75
3.7.6	Equations of Motion	76
3.8	UNCONVENTIONAL WHEELSET (NON-LINEAR MODELLING)	77
3.9	TRUCK WITH CONVENTIONAL WHEELSET (NON-LINEAR MODELLING)	78
3.9.1	Wheel-Rail Contact Forces	79
3.9.2	Suspension Forces	82
3.9.3	Gyroscopic Forces	83
3.9.4	Track Forces	83
3.9.5	Geometrical Terms	84
3.10	TRUCK WITH UNCONVENTIONAL WHEELSET (NON-LINEAR MODELLING)	85

CHAPTER-4	COMPUTER MODELLING	
4.1	INTRODUCTION	87
4.2	LINEAR MODELLING	89
4.2.1	Stability Analysis	89
4.2.2	Stability Analysis Program (SAP)	93
4.3	NON-LINEAR MODELLING	107
4.3.1	Dynamic Response Analysis	107
4.3.2	Dynamic Response Analysis Program (DRAP)	111
4.4	CONCLUSION	122
CHAPTER-5	SIMULATION RESULTS AND DISCUSSION	
5.1	INTRODUCTION	123
5.2	MODEL PARAMETER DETAILS	123
5.3	SIMULATION OF LINEAR COMPUTER MODELLING	125
5.3.1	Effect of Nominal Wheel Radius	128
5.3.2	Effect of Axle Load	134
5.3.3	Effect of Rail Gauge	134
5.3.4	Effect of Primary Suspension Stiffness	135
5.3.5	Effect of Primary Suspension Damping	135
5.4	SIMULATION OF NON-LINEAR COMPUTER MODELLING	136
5.4.1	Wheelset Lateral Response	173
5.4.2	Lateral Response of Truck (Bogie)	173

5.4.3	Wheelset Yaw Response	174
5.4.4	Yaw Response of the Truck (Bogie)	174
5.4.5	Rotation of the Truck About Longitudinal Axis	175
5.4.6	Creep Forces at the Point of Contact of Wheel and Rail	175
5.4.7	Variation of Wheel Radius	177
5.4.8	Variation of Conicity Angle	178
5.5	GENERAL CONCLUSION	179
CHAPTER-6 CONCLUSIONS		
6.1	INTRODUCTION	181
6.2	SUMMARY OF THE RESEARCH CARRIED OUT	181
6.3	MAJOR FINDINGS AND SIGNIFICANT RESEARCH CONTRIBUTIONS MADE	182
6.4	LIMITATIONS OF THE PRESENT RESEARCH	183
6.5	SCOPE FOR FUTURE EXTENSIONS	184
6.6	CONCLUDING REMARKS	185
	REFERENCES	186
	APPENDIX	199
	LIST OF PUBLICATIONS	
	CURRICULUM VITAE	