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Author Name

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Author Name

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Prof. Guide 1 Name

and

Prof. Guide 2 Name

Department of Mechanical Engineering
Indian Institute of Technology Kharagpur
Kharagpur - 721 302, India

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Dedicated to my parents

INDIAN INSTITUTE OF TECHNOLOGY KHARAGPUR

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DSC1 Name
Designation
Mechanical Engineering
Department
IIT Kharagpur
(Member, DSC)

DSC2 Name
Designation
Mechanical Engineering
Department
IIT Kharagpur
(Member, DSC)

DSC3 Name
Designation
DSC3 Department Name
(Non-ME Department)
IIT Kharagpur
(Member, DSC)

Guide 1 Name
Designation
Mechanical Engineering
Department
IIT Kharagpur
(Supervisor)

Guide 2 Name
Designation
Mechanical Engineering
Department
IIT Kharagpur
(Joint Supervisor)

External Examiner Name
Designation
External Examiner Department
External Examiner Institute
Name
(External Examiner)

DSC Chairman Name
Designation
Mechanical Engineering
Department
IIT Kharagpur
(Chairman, DSC)

भारतीय प्रौद्योगिकी संस्थान खड़गपुर
खड़गपुर : ७२१ ३०२ , भारत
Indian Institute of Technology Kharagpur
Kharagpur – 721 302, India
Department of Mechanical Engineering

CERTIFICATE

Date: / / 2022

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Prof. Guide 1 Name
Designation
Mechanical Engineering Department
Indian Institute of Technology Kharagpur
Kharagpur - 721 302, India

Prof. Guide 2 Name
Designation
Mechanical Engineering Department
Indian Institute of Technology Kharagpur
Kharagpur - 721 302, India

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Author Name

Abstract

Modern electric locomotives collect power from the catenary, an overhead power supply line consisting of messenger and contact wires connected by droppers, using a roof-mounted power collecting apparatus known as the pantograph. As the train travels, the sliding motion of pantograph generates mechanical waves in the wires of the catenary, which eventually affect the current collecting efficiency of the pantograph.

Keywords: Pantograph-catenary system, Coupled dynamics, Mutual interaction, Wave propagation, Mathematical modelling

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Nomenclature

$\Im(\cdot)$	Imaginary part of a complex variable
$\Re(\cdot)$	Real part of a complex variable
μ/μ_j	Linear mass density of string $/ j = 1$ and 2 for contact and messenger wires, respectively (average dropper mass included)
ω	Circular frequency
$\mathbf{I}_n$	Identity matrix of dimension $n \times n$
c_j	Phase velocity of string $/ j = 1$ and 2 for contact and messenger wires, respectively (calculated using μ_j)
w/w_j	Transverse displacement of a continuum $/ j = 1$ and 2 for contact and messenger wires, respectively
x	Spatial coordinate

Chapter 1

Introduction

In the era of the industrial revolution, the advancement in steam engine technology had changed the concept of land transportation with the introduction of railway locomotives which led to the rapid growth of commercial railways. In modern days, rail transportations are not only more effective than flights for mid-range or intercity travel (150 - 900 km) due to a great increase in speed but also completely environment-friendly owing to their very high passenger carrying capacity and the use of electricity for generating necessary driving power with a very low carbon footprint.

The pantograph-catenary system is the most reliable and widely used current collecting equipment throughout the world for better efficiency compared to a third rail system. In an ideal situation, carbon contact strips placed on the bow-shaped panhead of the pantograph should be in continuous contact with the current-carrying wire of the catenary by exerting a specific and constant contact force. In reality, however, keeping steady contact with no fluctuation in contact force is the biggest challenge. One could think of a simple solution of applying a high static preload using the pantograph to ensure continuous contact with the catenary, but it would actually cause severe wear and damage both to the carbon contact strips and the contact wire during operation. It is, thus, always preferable to keep the static preload value as low as possible. The low value, on the other hand, may increase the chance of contact loss. Loss of contact produces arcing between the panhead and the overhead contact wire, which results in significant damage to the whole system. The problem of contact loss amplifies with the increase in train speed as the dynamic interaction between the overhead wire and the pantograph increases causing high fluctuation in contact force. As a result, the train fails to attain the desired speed due to insufficient and lack of continuous power supply to the wheelsets. Sometimes, the use of multiple pantographs in a train becomes necessary. Electric multiple units (EMUs) are generally equipped with more than one pantograph for a better and continuous supply of power to the wheelsets and other electrical equipment. It also reduces high current density on the panheads of individual pantographs. Better power distribution and reduced current density result in less wear in the contact wire of the catenary and achieving higher speed. In cold countries, extra pantographs are often used to knock off the ice from the contact wire. However, increasing the number of pantographs may lead to problems like higher contact force on the trailing pantographs, increased chances of contact loss and subsequent arcing due to mutual interaction through the overhead wire.

The coupled dynamics of railway pantograph and catenary, thus, has been attracting many researchers for several decades due to its wide range of technical challenges. Before going into the details of the specific problem of the present work, short descriptions of individual systems are presented along with the major issues associated with the contact loss between them. The possible research gaps are then identified following a thorough survey of the recent research activities carried out in this field.

1.1 The Catenary

1.2 The Pantograph

1.3 The Pantograph-Catenary Interaction

1.4 Literature Review

Researches on the pantograph-catenary system have started in the '60s based on experimental studies and investigations (Sell et al., 1964). In the following decades, a vast amount of research is carried out with the fast advancement of railway technology and the advent of high-speed railways, which addresses a diverse range of technical issues, e.g., the structure of catenary, design of suitable pantograph, interaction dynamics, active control of pantograph, contact modelling, estimation of wear on panhead contact strip and contact cable of catenary, the aerodynamics of pantograph, the effect of track irregularities and environmental perturbation on pantograph's performance, etc. In the following, a brief survey of literature covering some of these aspects is presented.

1.4.1 On the structure of and wave propagation in the catenary

1.5 Scope of Research and Objectives

1.6 Organisation of the Thesis

Chapter 2

Dynamics of a Viscoelastically Supported Infinite String Subjected to a Number of Moving Point Loads

In studying the coupled dynamics of railway pantograph and catenary system, one, first, needs to understand the overall dynamics of the catenary consisting of heavily tensed contact and messenger wires connected by varying lengths of droppers. The disturbance caused by the passing pantographs mediates as mechanical waves through the contact wire of the catenary and is a major reason for contact loss since the waves generated from a leading pantograph affect the operation of the trailing ones. If the transverse oscillation of the messenger or carrying wire is neglected because of wide mismatch between the wave propagation speeds in the two wires, and if the excitation frequency is considered low enough so that it excites large wavelength oscillation in the contact wire, the catenary can be modelled as a single wire supported over a homogeneous viscoelastic layer. The effects of individual droppers get averaged out in the large wavelength allowing the discrete droppers to be replaced by a viscoelastic layer. In this chapter, thus, the wave propagation characteristics of such a simplified mathematical model of catenary subjected to uniformly moving single or multiple point loads have been elaborately discussed. An infinite taut string which has no bending rigidity is used to represent the contact wire since the interest in finding the response of the continuum does not lie in close proximity to the moving load. Therefore, this model is only valid when the excitation frequency of the moving load is low, and the displacement of the wire is measured far enough from the point of application of the load. Further discussions on the acceptability of the viscoelastic layer as distribution of droppers and the credibility of string model in predicting the response in the vicinity of the moving load have been presented in Chapters 3 and 4, respectively.

This chapter is divided into three major sections. In Section 2.1, the mathematical model of the infinite string subjected to constant and harmonic moving point load has been described. A more general formulation in case of a number of moving loads has also been reported at the very last of this section. The displacement field function as well as the displacement of the continuum at the point of application of the load has been calculated using these models and presented in Section 2.2 followed by a brief summary of the chapter in Section 2.3.

2.1 Mathematical Model

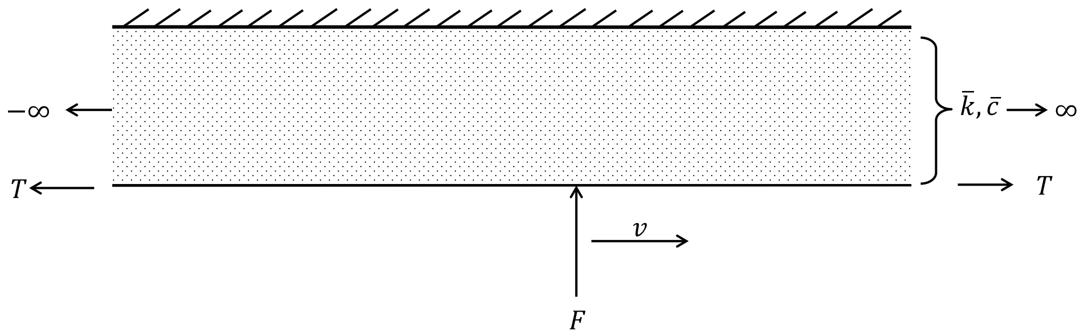

Figure 2.1: Infinite string supported by a homogeneous viscoelastic layer.

2.2 Results and Discussion

2.3 Summary

In this chapter, the contact wire of the overhead equipment or catenary has been modelled as an infinite string by neglecting the bending stiffness of the wire. The string is supported by a viscoelastic layer which represents the dropper distribution. The steady-state responses of the string when subjected to different types of moving loads have been calculated.

- Increase in separation distance decreases the mutual interaction among the loads.

Chapter 3

Response of Railway Overhead Catenary under Moving Harmonic Load

3.1 Results and Discussion

The response of two-string model of railway catenary under different loading conditions is presented in this section. The parameters used for the necessary calculation are tabulated in Table 3.1. These are the representative data of a real railway catenary system, as mentioned in Section 2.2. The credibility of the homogeneous viscoelastic layer model in representing the distribution of dropper as well as the comparison between the two-wire and single-wire system models of the overhead equipment is also discussed here. One should note from Table 3.1 that the phase velocity of the travelling wave in contact wire (c_1) is higher than that of the travelling wave in messenger wire (c_2) for the given parameters.

Table 3.1: Parameters for the two-string system (Metrikine and Bosch, 2006).

Force applied[a]	Distance	Droppers	Viscoelastic layer[b]	Properties	Phase velocities

[a]Force used for calculation of system response is arbitrary.
[b]Properties of the viscoelastic layer are computed by dividing the dropper properties (available in Metrikine and Bosch (2006)) by average dropper spacing.
[c]μ_1 and μ_2 themselves include $\bar{m}$. The linear density of contact and messenger wires are $\mu_c = 2.175$ kg/m and $\mu_m = 1.5$ kg/m, respectively.

Chapter 4

Wave Propagation in a Beam-String Subjected to Moving Point Load

Chapter 5

Dynamic Stiffness of an Infinite Taut String Supported by a Viscoelastic Layer and Subjected to Moving Loads

Chapter 6

Mutual Interaction between Multiple Pantographs Modelled as Discrete Mechanical Systems

Chapter 7

Multibody Modelling of Railway Pantograph

Chapter 8

Conclusions and Future Work

An electric locomotive or an EMU collects necessary power using one or more pantographs which slide against the overhead system or catenary. The interaction dynamics between a railway pantograph and the catenary is very complex. The disturbance created by the pantograph travels as mechanical waves in the overhead system and increases the chances of contact loss. The situation becomes more complicated when a train is equipped with more than one pantograph. The present work has aimed at capturing this complex dynamics and addressing the scenario of multiple pantograph operation. The study is carried out through mathematical modelling of the individual systems and coupling them using the method of substructure synthesis. It has also been extended to find the importance of bending rigidity of contact cable. This chapter concludes the study with important findings come out from the analysis, the contribution of the thesis and the scope of further research which could be carried out in the future.

8.1 Conclusions

8.2 Contributions of the Thesis

8.3 Scope of Future Work

Appendices

A Results for $N = 2$

B Routh-Hurwitz Criterion

B.1 Routh array

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Submitted in Journal(s) / Under Preparation

- Roy, S., DasGupta, A. and Chakraborty, G. (2021), 'A semi-analytical approach in studying pantograph-catenary coupled dynamics during multiple pantograph operation'.

Curriculum Vitae

The author obtained Bachelor of Engineering degree from the Department of (Discipline name) in (Institute/University name), (Place) in (year). He, then, received Master of Technology degree in (year) from (Department Name) in (Institute/University name), (Place) in the specialisation of (Specialisation name). Thereafter, he completed PhD programme from (Department name), (Institute/University name), (Place) in (year). He has research interest in the field of waves in continuous media and multibody dynamics. He has also published some of his research works in reputed international journals and conference proceedings. He has assisted in two NPTEL online courses, namely, *Mechanism and Robot Kinematics*, and *Kinematics of Mechanisms and Machines* during his doctoral study.

ORCiD ID @ 0000-0002-7784-6309