# Coupled Dynamics of Pantograph-Catenary System during Multiple Pantograph Operation

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## 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. The present research has aimed at studying the coupled dynamics between the pantograph and the overhead catenary through mathematical modelling. The analysis begins with calculating the response of a viscoelastically supported infinite string subjected to a number of moving concentrated loads using the Fourier transform method. Loading point displacement analysis shows that a leading load always affects the trailing loads. The validity of this simple model representing the catenary may be questionable when the phase velocities of travelling waves in the wires of the system are comparable. Hence, a periodically supported two-string model with sandwiched viscoelastic layer is also proposed. Travelling wave solution has been employed to find the steady-state response of the system. The inclusion of the messenger wire dynamics reveals the far-field characteristics of the catenary, which has been absent in the single string model. However, the viscoelastic layer representation of droppers in both of these models limits the analysis in the low-frequency regime. The contribution of flexural rigidity of the contact wire, neglected in the string models, is also investigated with an axially tensed Euler-Bernoulli beam under moving harmonic load. Proper non-dimensionalisation schemes reveal that below the critical speed (same as phase velocity), the bending stiffness has little effect on the far-field of the continuum, but exhibits significant impact in the vicinity of moving load, thus, resulting in the formation of a boundary layer around it. Moreover, a novel implementation of the Routh-Hurwitz criterion has helped in understanding the generation of high frequency and low amplitude travelling wave in the upstream of the continuum close to the critical speed. The catenary model (infinite single string or two-string model) with moving concentrated loads represents a substructure in the substructure synthesis method employed extensively in this work to study the coupled response of the pantograph-catenary system or the mutual interaction between multiple pantographs. In this method, the pantograph models (the other substructure) are replaced from the catenary model with an equal number of moving loads, and the latter is analysed like a continuum-under-moving-load problem with an intension to compute a coupling parameter. In the present study, the coupling parameter, namely, the dynamic stiffness, has been derived from the infinite single string model of the catenary for further study of pantograph-catenary coupled dynamics. For the analysis of a two-pantograph scenario, three-degree-of-freedom lumped parameter models of pantograph are considered with harmonic base excitation representing the track induced vibration coming to the loco-roof. This simple model predicts that (1) the trailing pantograph may affect the performance of leading pantograph in the low-frequency regime of base excitation, (2) base excitation phase has less effect on contact force, (3) high speed affects the trailing pantograph, and (4) the low-speed behaviours of both pantographs are the same for in-phase and out-of-phase base vibration. Finally, a natural coordinate-based multibody modelling of Faiveley AM-12 pantograph is presented, where the governing equations are derived from a penalty-based formulation using Extended Hamilton's principle. Linearisation of these equations about the static equilibrium state of the system has become straightforward since the penalty function method is chosen for constraint imposition. These linearised equations have been used with dynamic stiffness to study the dynamic interaction between several pantographs during multiple pantograph operation.

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