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Modelling and Active Control Designing of Trolleybus Catenary-Pantograph System

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Abstract: This paper introduces the 'Active Control of Trolleybus Current Collection Systems (ACTCCS)' research project and a number of early key finding. The goals of this project are to address key operational issues of a trolleybuses catenary-pantograph system in terms of the loss of contact force that causes electrical arcing, power reduction and de-wirement. The causes of this loss of contact force and the proposed solution of an actively controlled pantograph are presented in this paper through dynamic modelling and simulation of trolleybuses catenary-pantograph interaction and the application of an LQI controller. The results show that loss of contact can be eliminated with a small actuation force and this can be traded off against catenary wire displacement.

Keywords: trolleybus, ACTCCS, catenary-pantograph, contact force, pre-load, displacement, de-wirement, LQI

1. INTRODUCTION

A trolleybus system is green at the point of use, economical in comparison to other urban mass transit systems and becoming increasingly popular for public transport applications around the world (The Electric TBUS Group, (2012)). Leeds 'Next Generation Transport' (NGT) project (New Generation Transport, (2016)) has shown that trolleybus systems are once again under consideration for public use in the UK since their disappearance in the 1960s.

The design of overhead current collection devices on a trolleybus is conservative in nature and, due to the passive manner in which the pantograph locates on the overhead wires, there are major operational issues, such as: electrical arcing (damaging the wire and the collector (White, (2012)) due to variable uplift force; a high probability of de-wiring at junctions (potentially causing wires to be brought down with subsequent danger to human life (White et al, (2010)); the associated difficulty of manual rewiring; inflexible operation; and unsightly overhead webs at road junctions.

A potential solution for reducing, or even completely removing the risk of electrical arcing and de-wirement, is a concept being explored of 'Active Control of Trolleybus Current Collection Systems' (ACTCCS), which is a potential performance enhancement for the next generation trolleybus and eHighway (Siemens AG, (2014)) systems.

Active control of pantographs is a concept already explored for full-scale railway applications (Sanchez-Rebollo et al, (2013))(Lin et al, (2007)). Though railway and trolleybus systems are fundamentally similar, they differ in their running dynamics. Therefore, a dynamic analysis of existing a passive pantograph system is performed to quantify the associated benefits and risks (specifically related to arcing and de-wirement). The paper explores an active control algorithm to reduce variation in uplift force and vertical displacement.

In section 2, modelling and simulation are described for the existing passive catenary-pantograph combination. Section 3 shows the application of LQI (Linear Quardatic Integral) control, introduced to reduce the uplift force and displacement and is compared to the passive case, with conclusions of the study drawn in Section 4.

2. MODELLING AND SIMULATION OF CATENARY-PANTOGRAPH SYSTEM

2.1 Simulation Modelling Method

The goal of this dynamic model is to provide baseline performance measures of a typical in-service pantograph system. By creating a simulation model comprising of coupled sets of equations capturing the relevant system dynamics, a number of data sets can be created over a range of operating conditions with relative ease. This will then provide metrics for comparison against the proposed active solution. It is considered that the key dynamics are captured in the vertical direction, and movements in any other plane are in this case ignored.

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The catenary-pantograph interaction is of key importance to electric railway vehicles and trolleybuses, and is a key non-linear dynamic property that should be accounted for in the simulation model. This dynamic interaction is a coupled vibration governed by the contact force which depends on the running speed and catenary-pantograph system configuration. A static contact force pre-load (F_{sc}) between the catenary and pantograph is essential in the modelling for keeping the contact force at reasonable level and reducing variation(Houde, (2005)). This force is complex to model as during contact between the pantograph collector and the catenary, the stiffness is experience due to the lifting of the cable. This stiffness that is a not only a function of the vertical displacement, but also the position in relation to each stanchion. Furthermore, should the system become decoupled (in that the collector head undergoes de-wirement), the total stiffness experienced by the collector head is reduced. In conditions such as this, a bouncing mode may occur before a consistent contact force is re-established.

The model assumes that there is no disturbance to the vehicle body from the road (previous preliminary investigations showed this to be minimal for the purpose of this study) and that the stiffness and damping parameters of the pantograph are constant.

2.2 Modelling of trolleybus catenary-pantograph system

A schematic of a typical trolleybus catenary-pantograph system is shown in Fig.1 that has a number of similarities to overhead current collection systems in rail applications with the main difference in the single overhead line, rather than an interaction of messenger and contact wires.

The full model is formed and expressed in three equation-groups which are: the varying catenary geometry with displacement equations 1 and 2 (Kia et al, (2010)); the dynamic force balance equations 3 and 4; and the contact forces 5 and 6.

$$Z_c(t) = \frac{g \cdot \rho}{2T_c}\left[(v \cdot t)^2 - (v \cdot t) \cdot L_{ws}\right] \quad (1)$$

$$K_c(t) = k_{mean}\left(1 - a\cos\frac{2\pi}{L_{ws}} v \cdot t\right) \quad (2)$$

where $k_{mean} = \frac{k_{max}+k_{min}}{2}$ and $a = \frac{k_{max}-k_{min}}{k_{max}+k_{min}}$

$$m_1\ddot{z}_1 = - b_1\dot{z}_1 - k_1 z_1 + b_2(\dot{z}_2 - \dot{z}_1) + k_2(z_2 - z_1) + F_l(t) \quad (3)$$

$$m_2\ddot{z}_2 = -b_2(\dot{z}_2 - \dot{z}_1) - k_2(z_2 - z_1) - F_c \quad (4)$$

in which

$$F_c = K_c(t)[z_2 - Zc(t)] + F_{sc} \quad (5)$$

$$F_{sc} = \frac{k_1 k_2}{k_1 + k_2} \cdot \frac{H_{od} - H_{cw} + Z_c(t)}{1 + \frac{k_1 k_2}{K_c(t)(k_1+k_2)}} \quad (6)$$

Full definitions of the symbols used throughout the paper can be found in the Appendix, Table A.1 - Definition of Terms.

A key system parameter missing from available literature was that of the pantograph-rod spring stiffness (k_1). An number of practical measurements were taken from a representative range of applications in an attempt to yield a 'nominal' value. Measurements were obtained from: "Crich Tramway Village" (Crich Tramway Village, (2016)) on a 1950s vintage tram with similar pantograph-rod architecture; at "The Trolleybus Museum at Sandtoft" (Sandtoft Transport Centre Limited, (2016)) on two trolleybuses; and at Stagecoach Supertram Maintenance Depot in Sheffield on a modern tram with an LR33D Brecknell Willis pantograph. The effective average stiffness was found to be $k_1 \approx 40$N/m.

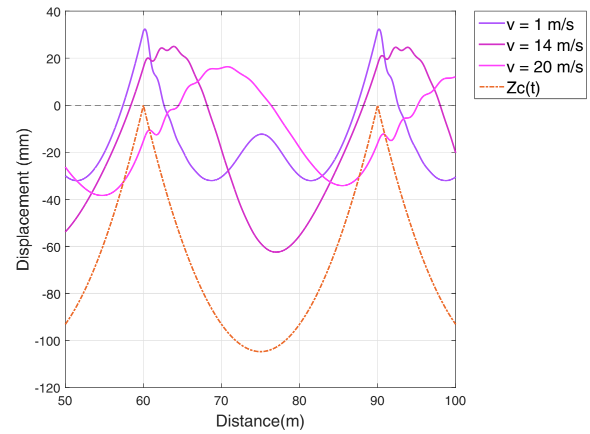

Fig. 2. Collector Head displacement for Passive Simulation Models at v = 1 m/s, 14 m/s and 20 m/s

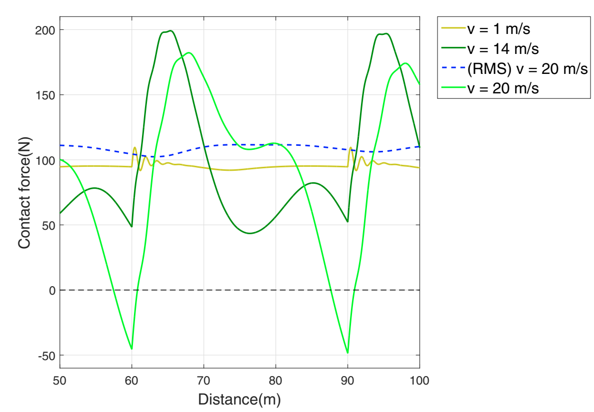

Fig. 3. Contact force for Passive Simulation Model at 1m/s, 14m/s and 20m/s

2.3 Model simulation and analysis

The descriptive equations were implemented in a Matlab/Simulink environment to simulate the transit of the vehicle in three operating conditions defined by different forward speeds. These relate to specific situations; low velocity in depot (1m/s), medium velocity on street (14m/s) and the highest velocity in operation (20m/s). For comparison the displacements and contact forces are plotted against distance of travel to demonstrate the effect of the pantograph interacting with the variable stiffness across the fixed spacial interval catenary assembly. The results are shown in Fig.2.

At a low vehicle speed of 1m/s the contact force (F_c) remains nearly constant around 100N, which is close to measured static contact force (117N) from a comparable LR33D type pantograph. The variation of contact force