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The benefits of mechatronically-guided railway vehicles: A multi-body physics simulation study☆

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ABSTRACT

Mechatronically-guided railway vehicles are of paramount importance in addressing the increasing interest in reducing wheel-rail wear and improving guidance and steering. Conventional passively-guided rail vehicles are limited by the mechanical constraints of the suspension elements. Currently, a typical rail vehicle suspension needs to be sufficiently stiff to stabilize the wheelsets while being complaint enough to negotiate curved track profiles. The suspension is therefore a compromise for the contradictory requirements of curving and stability.

In mechatronic vehicles, actuators are used with the conventional suspension components to provide additional stiffness or damping forces needed to optimise a vehicle for a wide variety of scenarios, and not rely on a sub optimal combination of passive components.

This research demonstrates the benefits of active guidance and steering when compared to a conventional vehicle using simulation results from a multi-body simulation software Simpack. It also provides insights into the relative performance of the mechatronic schemes. The Simpack modeling allows for a complex model with high fidelity, which provides an additional level of proof of the control algorithms working on a real rail vehicle. Each vehicle is assessed in terms of guidance on straight track, steering on curved track, actuation requirements and wheel-rail wear. Significant benefits are demonstrated in one of the guided vehicles with independently-rotating wheelsets.

1. Introduction

This paper presents a comparison of a number of mechatronic steering concepts for rail vehicles with conventional bogies and draws comparisons on ride quality, actuation requirements, sensing requirements and track damage, using a conventional passively steered vehicle as a baseline. Ultimately, mechatronics promises a potential transformation of rail vehicles. However, the expectation is that implementations of such technology will be an incremental process and that the most straightforward modifications to a 'conventional' bogie will be a first step, with this paper considering the most applicable steering technology [1].

A typical rail vehicle consists of vehicle body, two bogies and four wheelsets as shown in Fig. 1. The conical tread of a conventional railway wheelset (two wheels solidly connected by an axle) provides a passive vehicle guidance mechanism that has been accepted best practice for nearly two centuries. However, this conical profile also causes an unconstrained solid-axle wheelset to be marginally stable and oscillate along the track in a sinusoidal motion known as 'hunting' [2]. To avoid this problem, the yaw motion of the wheelsets is constrained by a stiff suspension, stabilizing the wheelsets but interfering with the natural curving action of the wheelset. This is a well-known problem and suspensions have to be designed to meet the contradictory requirements of curving and stability at high speeds, with vehicles optimised for a particular operating regime.

In addition to the kinematic steering mechanism, creep forces are generated by the movement of the wheels with respect to the railhead due to 'pure' rolling rarely being achieved by the conical geometry of the wheels. At normal adhesion conditions, lateral creep forces are a function of the lateral wheel-rail displacement and the wheelset yaw angle with respect to the rail, also known as angle of attack. On a curved section of track the angle of attack has to be sufficient to generate enough lateral creep force to balance the centripetal forces [4]. However, conventional wheelsets produce large unnecessary creep forces, particularly in the longitudinal direction due to the stiffness of the yaw suspension. These large creep forces lead to excessive wear (of both the rail head and the wheel tread) and unwanted noise.

Although there have been a number of innovations in bogie design, many authors suggest that passive suspensions have reached an optimum performance which is determined principally by the spring

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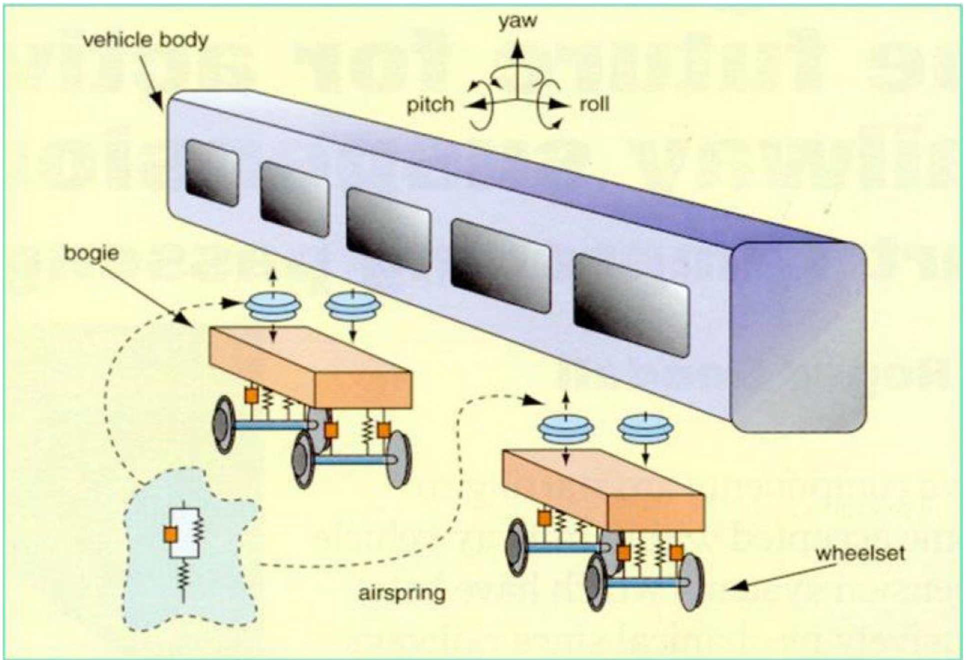

Fig. 1. Components of a railway vehicle [3].

stiffnesses, damper coefficients and their masses [5]. Active control has been suggested for some time now as an alternative way forward. The performance of an active suspension depends on sensors, actuators and the controller design in addition to the mechanical components. The wear due to traction, braking and balancing the centripetal forces is unavoidable, however the wear that is caused by the sub-optimal steering performance of the suspensions can be reduced dramatically by using active suspension concepts.

Active steering could be used to control the angle of attack to reduce the level of creep forces produced. Currently, the angle of attack of the wheels is maintained at acceptable values by bogies which shorten the distance between two wheelsets constrained in yaw. Active steering would make the functionality of bogies redundant, leading to the possibility of bogie-less vehicles which would be mechanically simpler [6]. Without a bogie, train floors could be lowered to create more internal space in the same loading gauge to accommodate double-deck trains in the UK. Active steering presents a range of possibilities from simply retrofitting actuators to current bogies through to completely re-designing vehicles to remove bogies. In this paper, the authors look at an incremental solution that balances the theoretical benefits of redesign with industrial reality. Normal adhesion conditions are considered at which the coefficient of friction has negligible effect on the guidance mechanism. Ideal sensing is assumed with a view that the performance benefits need to be established before the practicalities can be considered.

This paper considers three different active steering strategies that are applied to a full rail vehicle modeled using a multi-body simulation (MBS) software called Simpack. These are: Secondary Yaw Control (SYC), Actuated Solid-axle Wheelset (ASW) and Driven Independently-Rotating Wheelset (DIRW). Previous state-of-the-art papers have reviewed these active steering schemes and the control strategies associated with each [5,7]. The aim of this paper is to assess the performance of these active steering concepts in a non-linear simulation environment which takes into account complex vehicle dynamics and provides a far better representation of a real rail vehicle than previous simplified models. Note that the paper only considers steering and guidance and not traction and braking as the intention is to compare different active steering mechanisms under a broad set of track conditions. Section 2 explains the mechanical configuration of each of the steering concepts. Section 3 explains the vehicle modeling and track inputs used. The track inputs which the vehicle must follow are of two types - stochastic disturbances on a straight track which represent real track irregularities and a deterministic curve profile. The controller design process is explained in Section 4. Classical proportional integral (PI) and phase advance (PA) controllers are chosen for their simplicity and practicability. Finally, in Section 5 the performance of the different strategies is analysed in terms of the lateral/longitudinal creep forces, $T\gamma$ values which indicate wear levels and actuation requirements.

2. Active steering strategies

Control strategies for active steering are concerned with better guidance which eliminates all unnecessary creep forces and associated wheel-rail wear to achieve near-optimal performance of the running gear. In conventional rail vehicles, the front wheelset of the bogie produces large lateral creep forces while negotiating a curve. This poses a risk for derailment through flange climbing and the larger wheelset lateral force sets the limitation on the safe running speed of the vehicle. The lateral creep forces produced by the front and rear wheelsets should preferably be equal and sufficient to balance the centripetal forces. This is one of the conditions that must be satisfied for ‘ideal’ curving [4]. The second condition is that the longitudinal creep forces produced by the wheelsets should be zero, which is indicative of minimal wheel slip.

The active steering strategies discussed in this section involve both solid-axle and independently-rotating wheelsets (IRWs). IRWs produce negligible longitudinal creep forces as the wheels are able to roll at different speeds on the same axle to reduce slip. This is the reason why the power requirement of an IRW mechanism is lower than that of a solid-axle wheelset. The disadvantage is that IRWs require a guidance mechanism which needs to be provided by control action [8]. Traction and braking require that the left and right wheel longitudinal forces are balanced. The following is a description of three of the possible guidance methods that are applied to a bogie system. These are later compared to the passive vehicle model in Simpack described in Section 3.