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Ngigi, R. W., Pislaru, Crinela, Ball, Andrew, Fengshou, Gu and Anyakwo, Arthur

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PREDICTIVE CONTROL STRATEGIES USED TO SOLVE CHALLENGES RELATED TO MODERN RAILWAY VEHICLES

R.W. Ngigi*, C. Pislaru, A. Ball, F. Gu, A. Anyakwo

Diagnostic Engineering Research Centre, University of Huddersfield, U.K, Email: roy.ngigi@hud.ac.uk

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Abstract

This paper is an attempt to collate and critically appraise the recent advances in control strategies used to solve challenges related to railway vehicles which present nonlinearities and uncertainties. These strategies concentrate on stability of solid axle-wheelsets, guidance for wheelsets to provide the function of track following and curving to reduce all unnecessary creep forces and associated wear/noise. The focus is on active primary and secondary suspensions, braking and traction sub-systems. This paper examines potential new and efficient applications of modern predictive control methods, analysis tools and techniques which could be used in effective and reliable condition monitoring systems allowing informed decision making on maintenance and renewals activities.

1 Introduction

The study of rail vehicle dynamics requires a comprehensive understanding of electrical, mechanical, control engineering aspects of various interactions between the different sub-systems. The next generation of vehicles must achieve the ‘four Cs’ (carbon, cost, capacity, customers) so they need to have high performance and ultra proficient control systems in order to be energy efficient and produce less pollution. The development of reliable on line fault detection and condition monitoring of these dynamic systems is becoming increasingly important and the employment of predictive control strategies could be considered a significant part of this process.

A number of techniques have been developed in recent years and this paper is an attempt to collate and critically appraise the recent advances in control strategies used to solve challenges related to railway vehicles. These strategies concentrated on stability of solid axle-wheelsets, guidance for wheelsets to provide the function of track following and curving to reduce all unnecessary creep forces and associated wear/noise. The main sub-systems which have been studied refer to active primary and secondary suspensions, braking and traction sub-systems. The analysis of the theory, concepts and results is done in order to determine the best use of each method for various practical applications of railway vehicles which present nonlinearities and uncertainties.

The combination of control strategies and monitoring techniques should be more robust against uncertainties of external condition changes. The complex nature of railway vehicle dynamics require the employment of appropriate methods (such as extended Kalman filter, particle filter, etc.) for nonlinear non-Gaussian state estimation so that the vehicle condition monitoring system should be able to detect and isolate incipient faults. This paper examines possible novel and proficient applications of modern predictive control methods, analysis tools and techniques with the purpose of increasing the dynamic performance of railway vehicles.

Section two focuses on the recent studies related to the stability of rail vehicle subsystems. The modern control strategies for active primary and secondary suspensions are presented in Section three while Section four contains the analysis of contemporary control methods for braking and traction subsystems. Section five presents a comparison between various control strategies related to rail vehicle dynamics when a systems approach is employed. The reasons why the explicit model predictive algorithm is more suitable for the implementation in multibody vehicle dynamic software packages are explained. Then Section six discusses the details of condition monitoring techniques used to evaluate various parameters related to high-speed railway vehicle dynamics and strategies for proactive condition-based maintenance.

2 Stability of rail vehicle subsystems

The nonlinear nature of the railway vehicle system is due to the uncertainties and the complex interaction of the various subsystems. The wheelsets are coupled to the other parts of the rail vehicle by springs and dampers in order to stabilise the wheelset when it oscillates due to track irregularities or in curves. The lateral and longitudinal springs and dampers are an important feature of the bogie system because the oscillations are damped for a slight lateral or yaw movement and the wheelset moves back to its central position. It is known that at lower speeds, the vehicle oscillations undergo a decaying oscillatory motion in the presence of a disturbance, but at higher speeds, the oscillations leads to a limit cycle whereby the amplitude is limited by the flange contacts or wheel slippage on the rails. For a rail vehicle to meet the stability criterion while operating at higher speeds, it needs to be fitted with excellent suspensions. This would aid the rail vehicle in negotiating curves by minimising the forces acting between wheel and rail [1]. More importantly, the parameters associated with this phenomenon are not known exactly because they vary due to different running conditions.

Selamat et al [2] demonstrate that the proper design of the vehicle's primary suspension system can overcome the instability caused by the conical (or profiled) shape of a solid-axle railway wheelset. The simulation results show that the self-tuning linear-quadratic regulator performed better than the fixed-gain linear-quadratic regulator for both the conical and profiled wheelsets. So the primary suspension control performance could be increased when the estimated values of the time-varying wheelset parameters are used in the feedback controller design process.

Several control techniques do not interfere with the natural curving and centring of the wheelset and allow the stabilisation of the kinematic oscillation associated with the railway wheelset [3]. In the active yaw damping technique, the actuator generates a yaw torque proportional to the lateral velocity of the wheelset. The active lateral damping method is an alternative control method employing a lateral force proportional to the yaw velocity of the wheelset. Both control techniques require sensors, controllers, and actuators for practical implementations.

3 Active primary and secondary suspensions

A standard structure of the four-axle vehicle with two bogies is generally used in railway industry due to the demand of high speed rolling stock and better ride quality [4]. The vehicle stability, running behaviour and passenger ride comfort should be considered when designing, analysing and implementing the suspension and guidance systems for the control of vehicle dynamics. There are adverse forces at the wheel-rail contact present in traditional passive or mechanical suspension systems, which are used to achieve the required operating performance. This disadvantage can be overcome by using active suspension systems which include electronic controllers, sensors, actuators to enhance and/or replace the springs and dampers from the mechanical system. Also the active suspension system can adapt to various levels of speed and improve the ride quality without having to change the suspension components. Viereck et al [5] describe the behaviour of modern tilting trains with active or semi-active secondary suspension used for improving the ride quality, active primary suspension for guidance improvement and active tilting for increasing the forward speed. So the active suspension systems could play an important role in the control strategies aiming to improve the dynamic performance of the rail vehicle.

Goodall and Mei [6] describe several strategies for controlling the wheelset kinematics through the active primary suspensions: active yaw or lateral damping for the stability control of solid-axle wheelset; steering control through actuators which ensures that the wheelset forms an appropriate yaw angle with respect to the bogie. The yaw damping method requires lower actuation force and power to improve the ride quality whereas whilst the lateral damping method requires higher actuation forces and power [7]. The performance of these suspensions is measured by the reduction of creep forces and wear at the wheel-rail interface when the train travels at low speeds. The wheelset kinematics should ensure the running stability and coping with high frequency track irregularities at high speeds.

The same authors analyse the active control strategies for secondary suspensions aiming to improve passenger comfort: sky-hook damping; softening of suspension stiffness; low-bandwidth control through active leveling. The modal control approach uses one actuator to control the lateral mode of a vehicle and other actuator to manage the bounce and pitch modes in vertical direction. Also a yaw torque can be applied at the secondary suspension level in order to increase the critical speed and curving abilities of the bogie [8]. It is obvious that the adoption of modern mechatronic technologies on rail vehicles will ensure higher service speed for the same cant deficiency sensed by the passengers and increased ride safety.

4 Braking and traction subsystems

Yu et al [9] show that the design of traction systems is dependent on the knowledge of the adhesion force acting on the wheel-rail interface. The nonlinearity feature of this force (adhesion) is related to the creep and the contact conditions between the wheel and rail. The wheel slips when the mechanical torque in the wheels is higher than the adhesion torque required at the wheel-rail contact. This slip is dangerous because it can lead to the traction system underperforming. So re-adhesion schemes are needed to reduce the wheel slippage. The traction torque can be treated as a disturbance so a state observer can be used for the estimation and control procedures. Controller design is not trivial in this case because the observers have low performance being designed on assumption basis.

Mei et al [10] propose a method of detecting and controlling the slip conditions from the dynamic behaviour of wheelset. Generally the details about wheelset rotation and longitudinal motions are considered as sufficient in traction controls. However the study of the dynamic motions of rail wheelset should include the wheel—rail contact mechanics and the influence of contact conditions on the relevant modes. This detection of wheel slip/slide and re-adhesion control of AC traction motors in rail vehicles could be employed in the modern traction/braking control systems to maximize the use of adhesion in poor contact conditions.

The dynamics of a railway vehicle is highly interactive so it is important to understand the connections between the structure dynamics and active functions and their influence on the overall performance of the vehicle. Several authors [9, 10] propose a systems approach with an integrated control between the active steering of wheelset and traction control which interact at the wheel-rail contact points.

The main functions of the braking subsystem are to decelerate or stop the rail vehicle when needed by its operator. The electric brakes are more economical than the mechanical ones because they do not utilise frictional elements [11]. As the traction motor is used to accelerate the rail vehicle, during braking, it acts as a generator. The dynamic electric braking systems contain traction motors which behave as a generators and the power generated is dissipated as heat. The regenerative braking principle is becoming a more common application in the design of bogies owing to the fact that the generated energy is not lost.

5 Control strategies related to vehicle dynamics

Optimal control [6] is a model-based control approach used for active secondary suspensions control. It enables the optimisation of ride quality and suspension deflection by choosing suitable weighting factors for body acceleration, suspension deflection and actuator force.

The integrated control design of active primary suspensions means the design of separate controllers for the stability and steering/guidance. This is a complex control problem with multi-objective nature and robust control methods [6] can be successfully employed to solve it. H-infinity control method can be used to solve the deviations of creepage and conicity from their nominal values. H2 optimal control method could provide the missing curving action for independently-rotating wheels or maintain the natural curving of solid-axle wheelset.

Model predictive control (MPC) refers to a class of control algorithms that utilise the explicit model to predict the future response of a plant. At each control interval an MPC algorithm attempts to optimise future plant behaviour by computing a sequence of future manipulated behaviour [12].

The process of estimating the states of a system from noisy measurements is a necessity norm for the application of control and condition monitoring strategies. Kalman filter is an optimal filter which can be used for linear systems with noise because it provides a recursive solution to minimum variance problem given the prior knowledge of the initial states, noise and disturbances [13].

Although Kalman filter has been widely accepted for on-line state estimation of systems that are linear, it has also been applied to nonlinear system, especially in the railway industry [14] in form of the extended Kalman filter. This filter revolves around the linearization of the nonlinear system around the recent mean and covariance estimates.

Control strategies for improving the dynamic performance of the vehicle on track can be simulated by comparing the response of different controllers designs (such as H-infinity and optimal control) for estimation the states of the system and for controlling parameters such as the suspension deflection, body acceleration, stability, ride comfort and curving performance. At the present moment, these control strategies rely on model reduction of the system states such as track irregularities, load changes and track features.

The Kalman filter shows poor convergence in presence of a constrained nonlinear system [15]. With a system like the railway vehicle, the model predictive control strategies are more suitable for addressing its nonlinearities and constraints while keeping the optimisation window finite. So the main advantages of MPC are as follows:

- Constraints are included in the controller design
- Setpoint can be closer to the constraints
- The process operation is improved
- The method is suitable for MIMO systems

However a mathematical model (including body and suspension components) representing the vehicle dynamics of the systems is needed.

Predictive control strategies overcome this disadvantage because they do not have restrictions imposed on the number of measured states (such as the track features, track irregularities and load changes). However due to the computational effort of MPC algorithms, their use is only limited for relatively slow dynamics of the system. One solution is to use explicit MPC to obtain the solutions that are not dependent on solving the optimization problem at each time step [16]. Thus real time online simulations speed can be reduced significantly so the explicit MPC algorithm is more suitable for the implementation in multibody vehicle dynamic software packages (such as VAMPIRE, SIMPACK, VTISM, etc.). They enable the development of vehicle dynamic models which simulate the vehicle-track interaction. The user should include values for track features and irregularities and load changes. The software packages generate simulated values for body acceleration, suspension deflection, stability and curving performance [6].

Evans and Berg [17] underline that it is difficult to measure forces, creepages and contact stresses with varying wheel wear continuously through a test site. They demonstrate that the simulated results from multibody vehicle simulation software packages provide a better representation of the effect of the wheel-rail contact parameters on the vehicle dynamic behaviour. However these packages assume that the suspensions, creepages and contact forces are linear (this is not the case of real vehicles travelling on the track). These issues will be solved by future versions of rail vehicle dynamics simulation packages which are under development.

6 Condition monitoring technologies for modern rail vehicles

The report produced by Brickle et al [18] contains the conclusions of RSSB commissioned research to identify and evaluate automated wheelset condition monitoring (WCM) systems. There are eight functional categories of WCMs:

- Wheel profile monitoring systems - high-speed digital cameras capture images of the wheel and specialised software analyses them in order to determine the parameters of the wheel profile and wear on trains.

- Wheel impact detectors (accelerometers, strain gauges, etc) – measure the defects on the track surface (such as shelling, spalling, flat etc.) which could produce impact loads on it as the wheel passes the defective region.

- Bogie performance detectors - static and dynamic loads are applied to wheelset in order to identify the condition that contributes to unusual rail loads.

- Tread condition detectors - use non-destructive methods to detect any discontinuity (breakings, cracks) on the tread surface of the wheel.

- Hot axle bearing - thermal sensors detect any imminent fault with bearings by analysing the amount of generated heat. The hot wheel detectors are used to detect stuck brakes while cold wheel detectors are for detecting failed brakes.

- Acoustic bearing defect detectors - estimate early bearing defects by analysing the sound signature produced by bearings of a passing train. The detector use microphone array to record this sound.

- Brake pad inspection system - use machine vision technology to determine the wear rate (high or low), uneven wear or missing brake pads.

- Automatic vehicle identification systems - send radio frequency energy to a certain area of the track and the tags within that area reflect part of this energy back. The systems are usually used to analyse the trend and wear patterns from the track side.

The emerging technologies that may be available in the future for effective wheelset condition monitoring are:

- Acoustic-based inboard bearing defect detection
- Displacement sensor-based bogie hunting detection
- Laser-based ultrasonic cracked axle detection
- Automated ultrasonic-based cracked wheel detection
- Train fault detection system image acquisition

Brickle et al [18] underline that a more proactive approach in railway maintenance philosophy is requested by the interested parties and stakeholders. Therefore the trend is to develop and implement an intelligence-based WCM maintenance strategy where an integrated network of WCM detector systems is feeding a centralised database which generates alerts and reports. So the wheelset components are automatically inspected and proactive condition-based maintenance can be performed to detect component failures at their early stages, to prevent further deterioration in performance and guarantee timely repair/replacement of faulty components.

The authors of this paper envisage that the explicit MPC algorithm could be employed by automated proactive condition-based maintenance systems in the future. More research will be done to determine the degree of feasibility of this solution because the availability of reliable condition monitoring systems should enable the replacement of scheduled regular services with maintenance on demand - leading to substantial savings in the total life cycle costs.

6 Conclusions

This paper is an attempt to collate and critically appraise the recent advances in control strategies used to solve challenges related to railway vehicles. These strategies concentrated on stability of solid axle-wheelsets, guidance for wheelsets to provide the function of track following and curving to reduce all unnecessary creep forces and associated wear/noise. The main sub-systems which have been studied refer to active primary and secondary suspensions, braking and traction sub-systems. The analysis of the theory, concepts and results shows the best use of these methods for various practical applications of railway vehicles which present nonlinearities and uncertainties.

The combination of control strategies and monitoring techniques should be more robust against uncertainties of external condition changes. The complex nature of railway vehicle dynamics require the employment of methods such as extended Kalman filter, particle filter, etc. for nonlinear non-Gaussian state estimation because the vehicle condition monitoring system should be able to detect and isolate incipient faults. This paper shows possible applications of explicit MPC algorithms which could be employed by automated proactive condition-based maintenance systems in the future. It is recommended to consider the combination between the explicit MPC with multibody vehicle simulation software packages with the purpose of increasing the overall dynamic performance of railway vehicles.

Modern railway industry requires high performance and ultra efficient control systems for the integrated provision of traction and steering, and condition monitoring systems focused on immediately useful diagnosis and condition-based maintenance. The advantages of predictive control methods make them suitable options for effective and reliable condition monitoring systems allowing informed decision making on maintenance and renewals activities.

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