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Original Citation

Stow, Julian, Cooney, Neil, Goodall, Roger M. and Sellick, Rebeka (2017) The use of wheelmotors to provide active steering and guidance for a light rail vehicle. In: The Stephenson Conference: Research for Railways, 25th-27th April 2017, London, UK. (Unpublished)

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The use of wheelmotors to provide active steering and guidance for a light rail vehicle

J. Stow[1], N. Cooney[2], R. Sellick[3] and R.M. Goodall[1]

[1] University of Huddersfield, Institute of Railway Research
[2] SET Ltd.
[3] TRL Ltd

ABSTRACT

Whilst conventional, rigid axle railway wheelsets are inherently simple, reliable and relatively inexpensive, they have well known limitations with regard to the competing requirements of steering and stability. A wide range of mechanical and mechatronic solutions have been proposed to overcome these limitations and to allow near-radial steering in sharp curves. This paper discusses some considerations in the design and development of wheelmotor active steering technology for light rail vehicles (LRVs), where each wheel incorporates a traction motor which can be driven independently of the other. This arrangement is considered to have some advantages over similar mechatronic approaches which use actuators in the primary longitudinal / yaw suspension.

INTRODUCTION

This paper discusses some considerations in the design and development of wheelmotor active steering technology for light rail vehicles (LRVs).

Conventional wheelsets, where the wheels have a coned or profiled tread and are mounted on a rigid axle, have dominated the design of locomotives and rolling stock for nearly 200 years. They are inherently simple, reliable and relatively inexpensive.

However, conventional wheelsets also have some important drawbacks. The rigid axle results in a force feedback mechanism between left and right wheels. Although this plays an important part in steering the wheelset, it can result in a violent, self-exciting lateral/yaw oscillation of the wheelset, known as hunting, once a certain critical speed is reached [1]. The critical speed is dependent on the equivalent conicity and the inter-axle suspension stiffness and damping. Therefore a wheelset requires a high equivalent conicity and low suspension stiffness to achieve flange-free curving in sharp curves, but this will also result in a low critical speed. Achieving the correct balance between steering and stability is one of the key aspects of vehicle dynamic design.

Conventional axles cannot usually achieve a fully radial position in a curve, as their yaw movement is necessarily restrained by the plan view primary suspension. As a result, they curve with an angle of attack. The steering forces generated are large, typically greatly exceeding those generated by normal traction and braking. These forces in turn generate wear and rolling contact fatigue (RCF) imposing significant maintenance costs and ultimately limiting the life of wheels and rails. Furthermore, there is a practical limit to the equivalent conicity which can be generated, very high conicities resulting in unacceptably low critical speed and high contact stresses. In sharp curves, the wheelset must therefore rely on its flange to guide it around the curve. Flange contact leads to high levels of wheel and rail wear and demands lubrication.

In an effort to overcome these limitations, early railway engineers developed a variety of passive force steered bogies [2] which used mechanical linkages to force the wheelset to adopt a radial (or near radial) position within a curve. More recently, considerable work has been undertaken to develop active primary yaw suspensions [3, 4, 5]. In these designs, hydraulic or electro-mechanical actuators, driven by a controller, are used to move the wheelset to the desired yaw angle to achieve optimal steering. The controller requires some form of sensor input, usually to measure or infer the lateral position of the wheelset within the track gauge. Active yaw suspensions of the type described overcome the steering / stability trade-off inherent in conventional wheelsets, since they no longer rely on the rolling radius difference generated between wheels to provide the steering effect. In curves, the wheelset is moved to a near radial position; a very small angle of attack is retained in order to generate the creep forces necessary to steer the wheelset into a central position. As a result, longitudinal forces due to curving become very small, leading to large reductions in wear and RCF damage and flange free curving can be achieved on very sharp curves. On straight track, the control system provides the necessary actuator movements to guide the wheelset in response to lateral track irregularities. The stability of the system no longer depends on the interplay of yaw suspension stiffness and equivalent conicity, but is dependent on the design of the control system. A well designed controller can provide stable operation at far higher speeds and over a much wider range of conditions than is possible with a conventional wheelset.

ACTIVE PRIMARY YAW SUSPENSION USING WHEELMOTORS

An alternative approach to the design of an active primary yaw suspension is to use an arrangement whereby each wheel incorporates a traction motor which can be driven independently of the other. The wheels may or may not be mounted on a common axle. If they are, this is purely to provide a convenient bearing arrangement and the wheels are free to rotate independently of each other. In this case the wheelmotors act as the actuators in the suspension, the steering effect being provided by applying a differential torque between the wheel-pairs. A control system, similar to that described above, provides the necessary commands to the motors.

A free conical wheelset rolling round a curve will adopt a radial position to the curve. However, when the wheelset is constrained by the suspension in a bogie, the longitudinal stiffness of the plan view primary suspension must be overcome in order to move to a radial position. The resistance to wheelset yaw provided by these longitudinal stiffnesses is usually described as the primary yaw stiffness (PYS). How close the wheelset comes to radial steering (zero angle-of-attack) will depend upon the PYS, the curve radius, cant deficiency and the available conicity.

In an independently rotating wheelset arrangement (such as a wheelmotor pair), the absence of a rigid axle means that little longitudinal creep force can be generated by the coning of the wheels and an alternative means of guiding the wheel-pair is required to avoid flange contact. In the case of the wheelmotor, the guidance is provided by applying a torque differential between the wheels as shown in Figure 1.

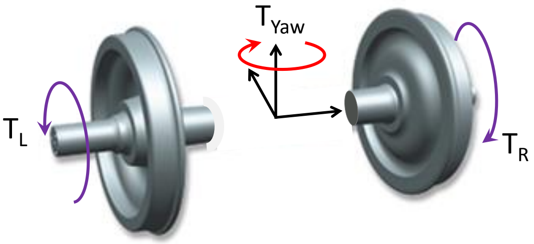

Figure 1: Torques acting on a wheelmotor pair

Figure 1 shows torques acting on a wheelmotor pair. T_L and T_R are the *wheelmotor torques* which are applied individually to each wheel. The difference between these torques, the *differential* torque in turn creates a *yaw torque* T_{yaw} on the wheel-pair. In order to achieve good steering in curves, yaw torque must be great enough to overcome the PYS (shear the longitudinal suspension) to position the wheel-pair radial to the curve. In Figure 1, T_L and T_R create a differential torque by acting in opposite directions. However, the differential torque may also be created by having both torques acting in the same direction but being of different magnitude. If the torque differential is zero, the wheel-pair will not be able to steer.

The longitudinal force which can be generated at the wheel-rail contact by a wheelmotor is limited by the rating of the motor (either continuous or peak) and also by the available wheel-rail friction (adhesion). Some of the available power and adhesion is required to accelerate and brake the vehicle.

Figure 2 shows a wheelmotor developed for this application by SET Ltd in Derby, UK. Previous studies [6,7] have shown this approach to be feasible from a control viewpoint, whilst recent work has focussed on the design of suitable suspension arrangements, development of a hardware controller and the demonstration of a full scale system on a light rail vehicle.

Figure 2: Wheelmotor developed by SET Ltd.

MOTOR AND CONTROL SYSTEM

The SET Wheelmotor is an innovatively designed permanent magnet synchronous machine. It employs a large diameter multipole motor arrangement to deliver precise control of significant tractive effort. It is well suited to a wide operational speed range and therefore does not require any form of gearbox. It can also be operated as a very efficient generator and under braking can potentially recover a considerable amount of energy, for storage and subsequent reuse.

Figure 3 shows a schematic of the SET actively-steered wheelmotor system. Each bogie on the vehicle is provided with a separate controller which receives sensor data to allow the lateral position of each wheel pair within the gauge to be determined. Separate inverters are provided for each of the four wheelmotors and the controller sends a current demand signal to each of the four inverters to achieve the desired instantaneous torque differential between each wheel pair.

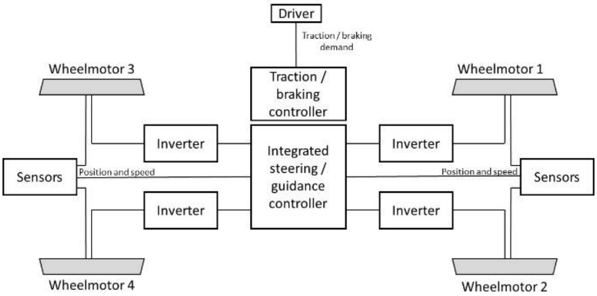

Figure 3: Actively steered wheelset system schematic

The controller has to provide a number of functions:

- Steering – to move the wheelpairs to a near radial position as they negotiate long wavelength track features (curves, transitions, switches and crossings), whilst maintaining the wheelpair as close as possible to the track centreline.
- Guidance – maintaining the stability of the wheelset over the full range of operating conditions and speeds.
- Traction, including traction control under low adhesion conditions
- Braking, including wheel slide protection under low adhesion.

Inevitably, the controller is required to prioritise some functions over others depending on the prevailing operating conditions and available adhesion.

SUSPENSION MOVEMENTS

The longitudinal displacement required at each axlebox to achieve a radial position can be easily calculated for a range of curve radii and a given bogie wheelbase. Note that this is purely a function of geometry and is independent of the suspension type or stiffness. For example, using a 1.22m bogie wheelbase, less than 4mm longitudinal suspension displacement is required to achieve radial alignment of the wheel-pair for curves shallower than 150m radius. It is likely that this could be accommodated by a conventional suspension. The required displacement increases rapidly as the radius tightens. Below 75m radius the displacement across the suspension is greater than 8mm and reaches 25mm for a 25m radius curve. On the basis of geometry alone, this suggests that radial steering is not possible in the sharpest curves using a ‘conventional’ suspension arrangement that could be packaged in the limited space typically available on low-floor trams.

It has been demonstrated that one of the principle benefits of wheelmotors, the ability to greatly reduce wheel and rail wear in very sharp (<100 m radius) curves, can only be achieved if an extremely low PYS is employed. A wheelmotor bogie for a light rail vehicle must therefore:

- Be very much softer than is usual in the primary yaw direction to ensure that the wheelmotor pairs can generate sufficient torque to steer to a near radial position without exceeding the maximum motor torque;
- Accommodate the large yaw displacements necessary for near-radial steering whilst retaining sufficient longitudinal stiffness to transmit the traction and braking loads.

BOGIE DESIGN

The bogie developed for the initial wheelmotor trials is shown in Figure 4.

The primary vertical suspension comprises two coil springs per axlebox. The top of these springs bear on a plate which is interposed between the spring and a matching plate on the bogie frame. These surfaces provide a low friction bearing which allows the wheel-pair to adopt the large yaw angle required for near radial steering in sharp curves.

An axle bridge is provided to join the two wheelmotor stators together. The centre of the axle bridge is connected by means of rose-joints to a pair of A-frames mounted to the bogie frame. This arrangement provides a high lateral and longitudinal stiffness but a low stiffness in the vertical and yaw directions. The primary roll stiffness principally arises from compression of the coil springs. In common with many light rail vehicles, no primary damping is provided. Longitudinal bumpstops are provided at each axlebox to limit the yaw rotation of the wheel-pairs to ±30mm, the displacement required to negotiate a 12m radius curve.

This bogie has provided a useful basis for undertaking initial development and testing. It has recently been succeeded by a more elegant design which replaces the axle bridge arrangement with a structure that allows the low floor capability of wheelmotor bogies to be full exploited.

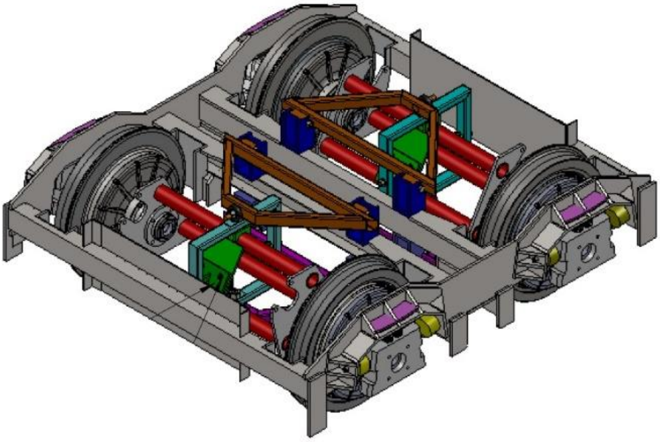

Figure 4: Tram 636 prototype bogie

EHICLE AND CONTROLLER CO-SIMULATION

Extensive use has been made of vehicle dynamics and controller co-simulation to explore the dynamic behaviour of SET wheelmotor suspensions and to develop and tune the steering and guidance controller. Vehicle dynamics simulations have been undertaken using SIMPACK whilst the controller was modelled using MATLAB/Simulink. The SIMPACK interface module SIMAT allows results to be exchanged with a given time step between the SIMPACK vehicle model and the Simulink control model.

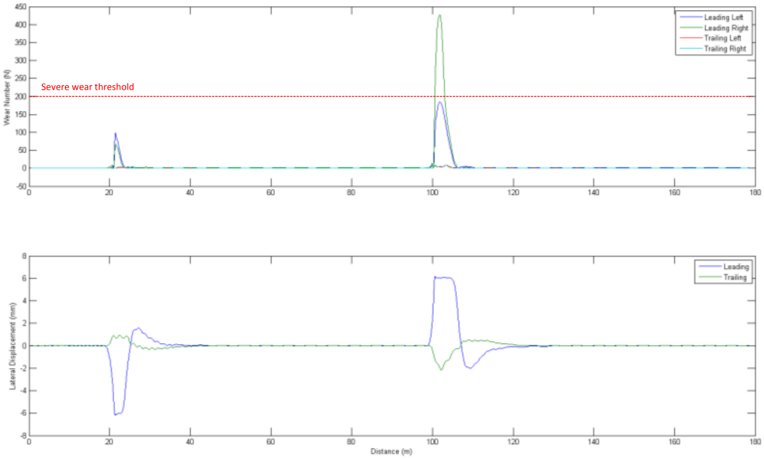

Figure 5: Wheelmotor Bogie, Wear Number (top) and Lateral Displacement of Wheel Pair from Track Centreline (bottom) – 50m Radius Reverse Radius Curve

Figure 5 shows the energy dissipated in the contact patch (Tγ) for each wheel in the bogie and the lateral displacement of the wheelpair whilst negotiating a 50 m radius non-transitioned S-curve. Such a curve represents a very severe test of the vehicle performance. Based on work undertaken by BR Research [8] it is generally accepted that severe wear will occur in the wheel-rail contact when Tγ > 200 N.

DEMONSTRATOR VEHICLE

The initial demonstrator vehicle used to develop and test wheelmotor technology is Blackpool Tramcar no. 636. Built by Brush in 1937, this single car tram (pictured in Figure 6) is very different to a modern LRV. However, its major advantage is its simplicity, both electrically and mechanically, allowing the prototype bogie, traction package and controller to be installed without the need for interfacing to complex vehicle systems. As a development platform, fundamentally it provides a fixed linkage distance between the bogie centres and a vehicle mass to allow the system to be developed and tested.

The tram has been trialled on site at SET and at the Ecclesbourne Valley Railway to allow investigation and calibration of the control system to achieve the steering and guidance objectives.

Figure 6: Blackpool tramcar 636

BENEFITS

Primarily, wheelmotor technology offers the same benefits as any active primary yaw suspension in that it removes the steering – stability trade off associated with a conventional wheelset and described above. It can be readily demonstrated that wheelmotors can lead to a step change reduction in wheel and rail wear and RCF damage and that these benefits can be achieved even in curves as sharp as 12m radius. In addition they are likely to result in reduction or elimination of wheel squeal as near-radial steering avoids operating in the saturated region of the creep force – creepage curve, thus avoiding the stick-slip behaviour in the contact patch which promotes squeal noise.

Wheelmotors offer some benefits beyond those provided by linear actuator based active primary yaw suspensions. These may be summarised as follows:

- They provide the potential for very simple bogie designs as a number of components are no longer required. These include the axle; final drive and yaw dampers.
- Permanent magnet motors such as the SET wheelmotor allow for fully electric braking down to zero speed, also giving sufficient braking effort if motor power is lost. If fully utilised, this would result in further simplification by the elimination of air compressors and friction brake equipment.

These factors may prove decisive when considering the business case for adoption of wheelmotor bogie, as they provide direct benefits for the vehicle manufacturer as well as the infrastructure owner.

As with any engineering solution, there are inevitable trade-offs which must also be considered. In the case of wheelmotors, these include placing the motor on the unsprung side of the primary suspension where it is subject to a significantly worse vibration environment and the need for a separate inverter for each wheel. The sensing requirements to determine the wheelset lateral position in the gauge present some challenges but are comparable to other types of active primary yaw suspension.

CONCLUSIONS

Wheelmotors can be used as actuators in an active primary yaw suspension which can overcome the limitations of a traditional solid axle wheelset. When incorporated in a novel very low PYS bogie they can provide flange-free, near radial steering in curves as sharp as 12m radius. Using such an arrangement on a light rail system would result in a step change reduction of wear and rolling contact fatigue damage on both plain line and switches and crossings.

A significant advantage of wheelmotors over other forms of active primary yaw suspension is the scope they provide to simplify the design and reduce the mass of bogies, particularly if the capability to provide all-electric braking is also exploited.

A demonstrator vehicle has been built and this, together with extensive supporting simulation studies show that the wheelmotor provides a practical solution for real-world applications. Work is continuing to develop the technology for higher speeds and to improve the robustness of the sensing solutions.

ACKNOWLEDGEMENTS

The authors would like to thank the Rail Safety and Standards Board (RSSB) for part-funding recent developments of the wheelmotor through the 'Radical Train' programme.

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