Fault Detection for Vehicle Suspensions Based on System Dynamic Interactions

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Abstract: This paper presents a novel method for the fault detection and isolation for rail vehicle suspensions that explores the additional dynamic interactions between different motions of a bogie or body caused by the failure of suspension components by taking advantage of symmetrical mechanical configurations of railway bogies. The study is focused on the monitoring of the vertical primary suspensions of a conventional bogie vehicle to demonstrate the general principle and effectiveness of the proposed method in detecting damper faults, although the technique is equally applicable for suspensions in other directions.

Keywords: fault detection, isolation, vehicle dynamics, suspension, damper

1. INTRODUCTION

Condition monitoring is considered as a novel area of Fault Detection and Isolation (FDI) in railway suspension systems, which is starting to show great potentials (Bruni *et al.*, 2007). A failure to the suspension component may not only increase the wear of wheel and rail, but also affect system stability, deteriorate ride comfort and even endanger passenger safety in extreme cases (Gillespie, 1992). The monitoring of the suspension condition changes in an early stage can prevent further damages, and rapid and effective monitoring techniques are essential to increase vehicle reliability and reduce maintenance cost.

The condition monitoring for vehicle system has drawn increased attention in academic research and some techniques have been recommended in automobile industry. There have been a number of theoretical studies and experimental investigations on different approaches for FDI (Willsky, 1976; Isermann, 2001; Fisher *et al.*, 2003), and in railway applications (Goda *et al.*, 2004, Li *et al.*, 2004; Goodall, 2006; Mei *et al.*, 2007). Most of the studies are concerned with model based techniques which use mathematical models to generate additional output signals and compare with the original measurable parameters. Those methods rely on a well-developed model to estimate the prior and posterior difference of the parameter or the residual between them. Therefore the detection quality is clearly affected by the accuracy and the complexity of the mathematical model (Isermann, 2001).

This paper studies a different and potentially very powerful technique for detecting and isolating suspension faults. The configuration and modelling of a typical bogie vehicle is firstly presented. The principle and development of the proposed fault detection technique are introduced and applied to the bogie vehicle. Only faults in dampers are considered which are much more common than springs failures in practice. Different fault conditions are assessed and computer simulations are used to show how those suspension faults may be detected and identified. The sensitivity to faults and robustness against external condition changes are demonstrated.

2. SYSTEM DESCRIPTION

2.1 Vehicle Configuration

Figure 1 shows the configuration of a conventional bogie vehicle. The vehicle consists of a vehicle body, two bogie frames and four solid axle wheelsets. The main external excitations are track geometries (deterministic input of gradients and curves) and irregularities (random input) transmitted to a vehicle through the wheelsets, but attenuated through the use of suspensions. The primary suspensions are located between the wheelsets and bogie frame, which normally includes coil springs and hydraulic damper in longitudinal, lateral and vertical directions. Normally, same suspension components are used for all suspensions at the four corners of each of the two bogies and therefore the bogie configurations are mostly symmetrical. The secondary suspensions are mounted between the bogie and the vehicle body, which are often comprised of rubber airsprings. The primary suspensions are mainly used to control the running behaviour, whereas the secondary suspensions are designed to ensure good ride comfort of passengers. Similar to the primary suspensions, same airbags tend to be used for the secondary suspensions on both sides (referred to as left and right sides) of each of the two bogies.

Because this paper deals with vertical suspensions, only motions related to vertical dynamics are included in the models which are the bounce, pitch and roll movements of the vehicle body and two bogie frames. Motions in other directions (and corresponding suspensions) are largely decoupled and excluded from the study. The vertical movements of the wheelsets are considered to be constrained to the track surface, which is a normal practice in the study of railway vehicle dynamics.

The natural frequencies and damping ratios of the modes derived from a typical railway vehicle are given in Table 1, where the first three rows show those for the bounce, pitch and roll movements of the bogies and the last three rows those for the bounce, pitch and roll motions of the car body. It is clear that the frequencies of the bogies are above 10Hz and much higher than those of the body modes.

Table 1.Natural frequency and damping of a bogie vehicle

		Freq. (Hz)	Damping
Bogie Mode	Bounce	10.57	0.23
	Pitch	14.07	0.32
	Roll	14.79	0.31
Body Mode	Bounce	0.68	0.16
	Pitch	0.84	0.19
	Roll	0.84	0.19

2.2 The Characteristic of Track Inputs

Apart from intended track features such as gradients, there are considerable random excitations due to track misalignments which may be somewhat different on two sides of a track. In the vertical direction, the random track input is usually described in terms of a power spectrum for the track vertical displacement, which is an approximate function of frequency given by A_r/f_t^2 (Mei, *et al.*, 2001). In this paper, two random inputs that conform to the power spectrum distribution are used in the simulations for the left and right sides of the track, where the difference between the two sides is typically 10% (also in a random manner) of the inputs. The inputs to all the wheelsets are the same, but there are time shifts between them, which are determined by $\tau=2\cdot L_b/V_s$ between the leading and trailing wheelsets of each bogie and $\tau=2\cdot(L_s-L_b)/V_s$ between the trailing wheelset of the leading bogie and leading wheelset of the trailing bogie, where L_b is the half wheel space, L_s is the half distance between the centre positions of the two bogies, and V_s is the vehicle operating velocity.

3. FAULT DETECTION METHOD

Railway vehicles tend to use identical suspension components which result in symmetrical arrangements in the primary or secondary suspensions. A previous study based on the analysis of a simple side view model of a railway bogie shows that the bounce and pitch motions of the bogie are decoupled in normal conditions, but dynamic interactions are introduced once an asymmetry occurs due to a fault at one of the suspensions which may be readily explored for fault detection (Mei *et al.*, 2007). The study in this paper is extended much further than the initial investigation. A detailed and practical scheme for both fault detection and isolation for all vertical primary suspensions is developed to demonstrate a clear link between the level/nature of the interactions and different fault conditions.

Equations 1 – 3 give the equations of motion for the bounce (z_{b1}), pitch (ϕ_{b1}) and roll (ψ_{b1}) movements of the leading bogie in no fault conditions. Clearly the three motions are independent from one another and the primary suspensions do not introduce any interactions. The forces from the secondary suspension affect the bogie bounce (from the total secondary suspension force, or ΣF_s) and roll (from the difference in force between the left and right sides, or ΔF_s), which turn out to be trivial.

$$m_b \cdot \ddot{z}_{b1} + 4c_p \cdot \dot{z}_{b1} + 4k_p \cdot z_{b1} = c_p(\dot{z}_{t1l} + \dot{z}_{t1r} + \dot{z}_{t2l} + \dot{z}_{t2r}) + k_p(z_{t1l} + z_{t1r} + z_{t2l} + z_{t2r}) + \Sigma F_s \quad (1)$$

$$(I_{by}/L_b^2)L_b \cdot \ddot{\phi}_{b1} + 4c_p L_b \cdot \dot{\phi}_{b1} + 4k_p L_b \cdot \phi_{b1} = c_p(\dot{z}_{t1l} + \dot{z}_{t1r} - \dot{z}_{t2l} - \dot{z}_{t2r}) + k_p(z_{t1l} + z_{t1r} - z_{t2l} - z_{t2r}) \quad (2)$$

$$(I_{bx}/B_b^2)B_b \cdot \ddot{\psi}_{b1} + 4c_p B_b \cdot \dot{\psi}_{b1} + 4k_p B_b \cdot \psi_{b1} = c_p(\dot{z}_{t1l} - \dot{z}_{t1r} + \dot{z}_{t2l} - \dot{z}_{t2r}) + k_p(z_{t1l} - z_{t1r} + z_{t2l} - z_{t2r}) + \Delta F_s \quad (3)$$

The main connections between the three motions are the track inputs from the four wheels, where the bounce is excited by the sum of the four, the pitch by the difference of the front and rear two, and the roll by the difference between the two sides of the wheelsets. This balanced condition will no longer be true, if any one of the suspension components becomes faulty which in most

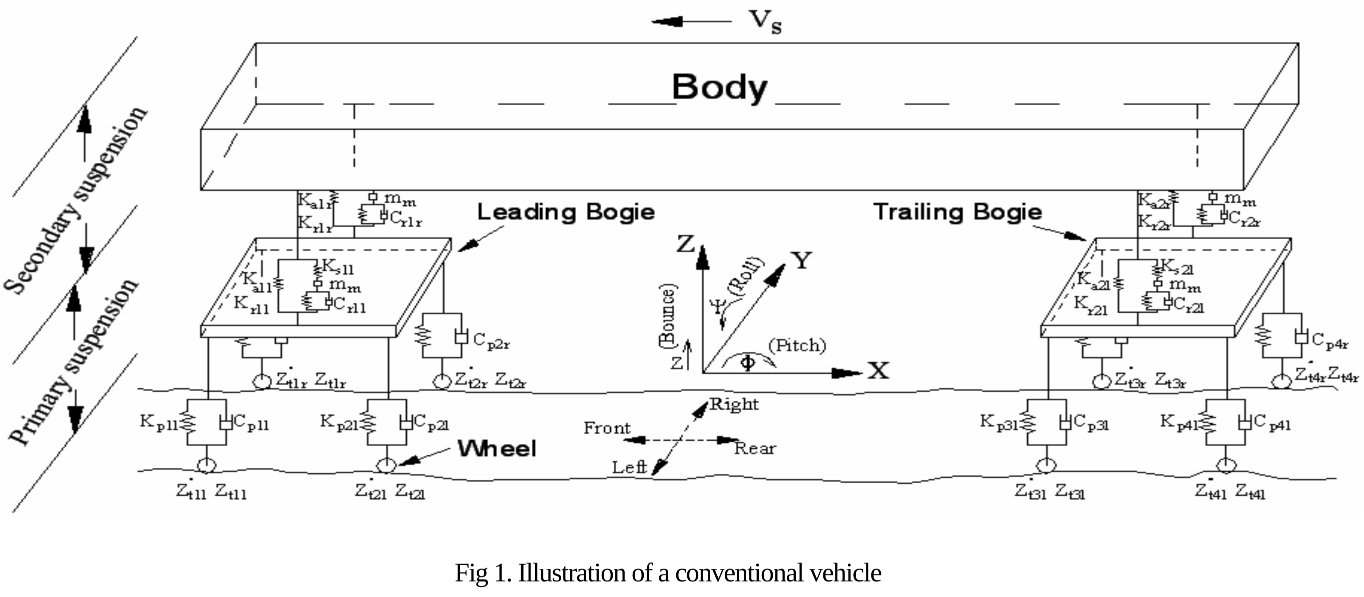

Fig 1. Illustration of a conventional vehicle

cases reduces the damping coefficient. Therefore the cross correlations between the three motions of a bogie will vary with the level as well the location of unbalances, especially at no time shift (due to excitations of the input at the same wheel) and to time shift $\tau=2\cdot L_b/V_s$ (due to the time delay between the leading and trailing wheelsets of the same bogie, which is fixed for any given speed).

Figure 2 shows the overall scheme of the proposed fault detection and isolation method.

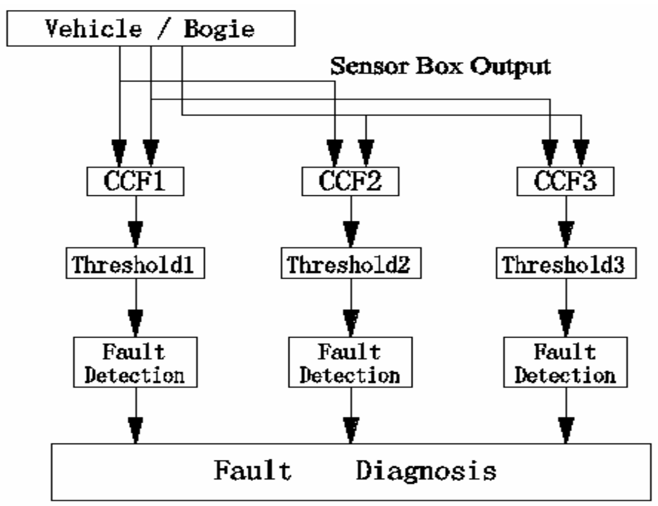

Fig 2. Proposed Fault Detection and Diagnosis Scheme

A single sensor box may be mounted onto the bogie frame to provide the measurements of the bounce, pitch and roll accelerations (Charles, *et al.*, 2006). This type of the sensor box often consists of one accelerometer (for bounce) and two gyros (for pitch/roll velocities), so the pitch and roll accelerations be derived from the rate of change in pitch and roll gyros. The cross correlation (CCF1, CCF2, CCF3) between any two of the three signals are computed using equations 4-6. There are additional benefits to compute cross correlation coefficients as given in equations 7-9 instead of the cross correlations which will be further explained in the performance assessments.

$$R_{BP}(m)=\sum_{n=1}^{N}\ddot{z}_b^2(n+m)\cdot\ddot{\phi}_b^2(n) \tag{4}$$

$$R_{BR}(m)=\sum_{n=1}^{N}\ddot{z}_b^2(n+m)\cdot\ddot{\psi}_b^2(n) \tag{5}$$

$$R_{PR}(m)=\sum_{n=1}^{N}\ddot{\phi}_b^2(n+m)\cdot\ddot{\psi}_b^2(n) \tag{6}$$

$$C_{BP}(m)=\frac{R_{BP}(m)}{\sqrt{R_{BB}(0)\cdot R_{PP}(0)}} \tag{7}$$

$$C_{BR}(m)=\frac{R_{BR}(m)}{\sqrt{R_{BB}(0)\cdot R_{RR}(0)}} \tag{8}$$

$$C_{PR}(m)=\frac{R_{PR}(m)}{\sqrt{R_{PP}(0)\cdot R_{RR}(0)}} \tag{9}$$

For a fixed step size Δt, the time window $T=N\cdot\Delta t$ should be selected far greater than Δt so that there is sufficient amount of data to produce consistent results. In this paper, a step size Δt for simulation is set to *1ms* and the time window is chosen to *2s*.

The output of each of the cross correlation (or cross correlation coefficient) calculations is compared to a pre-defined threshold for fault detection, and the outcome of the all three channels will then be used to identify which one of the dampers has failed. On-line real time detection is possible by computing running cross correlations or coefficients with a moving time window of data.

One important basis for the new method is that the probability of two or more identical components (used at different locations) failing at the exactly same time, in the same manner and to the same degree may be considered extremely low.

4. PERFORMANCE ASSESSMENTS

4.1 Use of Cross-Correlations (CCF) in Fault Detection

Figure 3 compares cross correlation between the bounce and pitch accelerations in no fault and when the damping coefficient of the front-left damper is reduced to 50% of its nominal value. Figure 4 shows a comparison of bounce/roll correlations between the two conditions and Figure 5 give that of pitch/roll correlations. The vehicle speed is 50m/s, and the time delay between the track inputs at the leading and trailing wheelsets of a bogie is calculated as 0.05s.

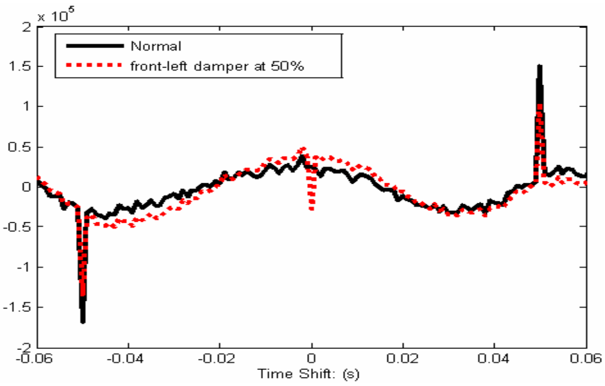

Fig 3. CCF between bounce and pitch accelerations

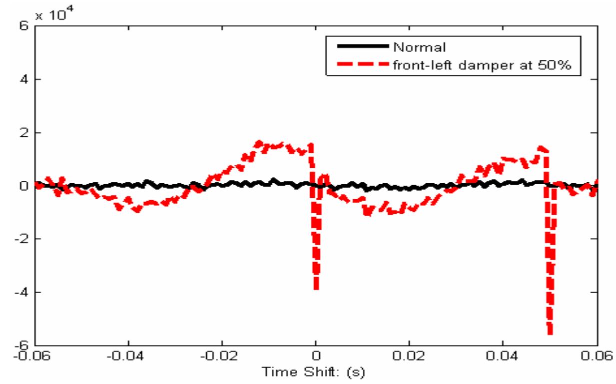

Fig 4. CCF between bounce and roll accelerations

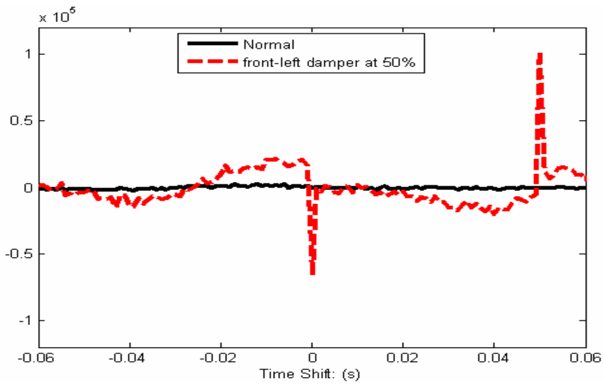

Fig 5. CCF between pitch and roll accelerations

It is clear that the main changes occur at three points of the time shift 0, -0.05s and +0.05s. In normal conditions, the two peaks at the +/-0.05s in Fig 3 indicate the level of correlation between the bounce and pitch accelerations caused by the inputs to the two wheelsets (the same input, but with a time shift of 0.05s). There are no delays between the two sides of the bogie, and therefore no significant correlations are observed in the no fault condition.

The dynamic interactions caused by the fault condition reduce the level of correlation at the time shifts t=+/-0.05s, but cause a new (negative) spike at t=0. The latter is due to the imbalance between suspensions at the leading and trailing wheelsets as the effect of input at the leading suspensions can no longer cancel out that at the trailing suspensions. Similar spikes are observed at t=0 (negative) and t=0.05s (negative) in Fig 4, and at t=0 (negative) and t=0.05s (positive) in Fig 5 due to the same reasons.

When the damper fault occurs at a different position, e.g. the rear-right on, the effect of the dynamic interactions on the cross-correlations is equally obvious, but the pattern of the changes is different as shown in Figs 6-8. In this case the peak at t=0 becomes positive for the bounce/pitch and bounce/roll cross correlations. The bounce/roll CCF also results in a positive peak at t=-0.05s (rather than a negative one at t=0.05s as in the previous case). The pitch/roll CCF gives a positive peak at t=-0.05s (rather than t=0.05s).

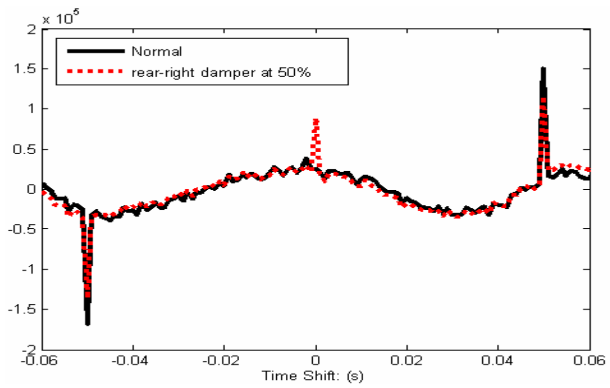

Fig 6. CCF value between bounce and pitch accelerations

The detection of the spikes and their level of changes provide an essential indication of the suspensions conditions, but the differences between the different faults can be used to help and locate where a fault has occurred.

There is a sinusoidal component in some of the cross correlations which is caused by one of the bogie modes. The oscillations tend to become larger when the level of a fault becomes worse due to reduced damping to the bogie.

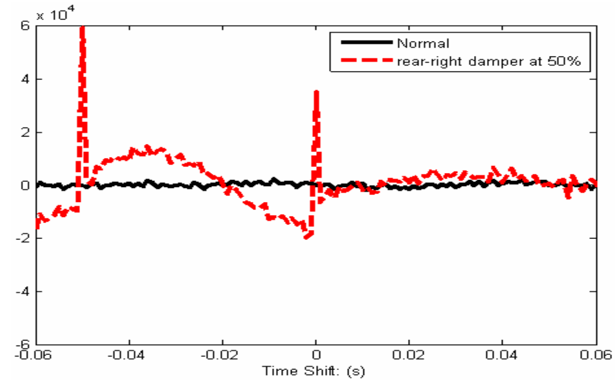

Fig 7. CCF value between bounce and roll accelerations

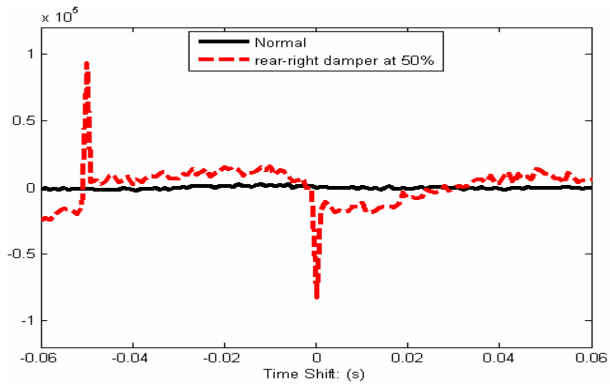

Fig 8. CCF value between pitch and roll accelerations

4.2 On Line Fault Detection with Running CCF

For on line (real time) detection, running cross correlations will have to be used to find changes at the three specific time shifts. Figs 9 and 10 show the running CCFs of the bounce/pitch and bounce/roll accelerations respectively, where the damping coefficient of the front left suspension is reduced by 50% at the simulation time t=6s.

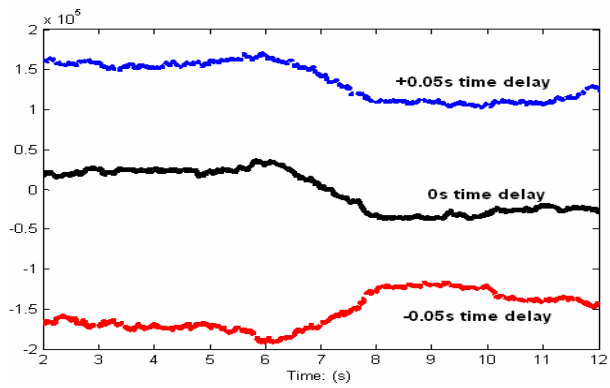

Fig 9. Running CCF value with bounce and pitch accelerations

The changes in CCFs at the relevant time shifts are clearly linked to the assumed fault condition, but the bounce/roll CCF appear to be more sensitive to the fault than the bounce/pitch one.

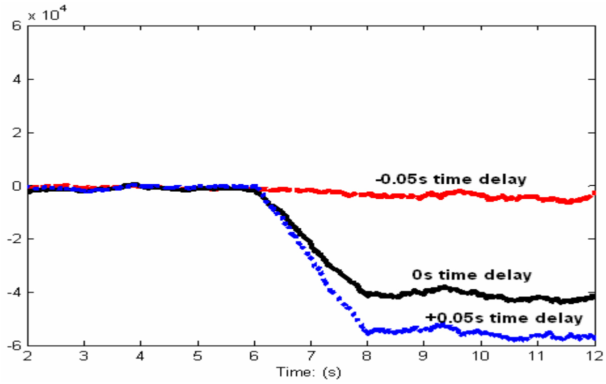

Fig. 10. Running CCF value with bounce and roll accelerations

4.3 Use of CCF Coefficients

There are two robustness issues in practical implementation of the proposed technique using cross correlation calculations – both are related to the level of input excitations but in different ways. One is that the actual geometry of the track may vary from one section of a track to another. Although track irregularities may be considered as random noises, real measured data suggest that there are sometimes variations in the magnitude. Also there are other types of changes such as joints and switches. Those variations will cause certain fluctuations in the input excitations and consequently in the output of the CCF calculations – some of the effect may be observed in Figs 9 and 10. The other is that the travelling speed of rail vehicles is not necessary constant. Changes in speed will change the level of excitations for the same track, which can affect the cross correlations more than fault conditions. Threshold levels for fault detection may be adjusted according to speed, but tuning would be difficult and track specific.

The effect of the variations can be removed by using cross correlation coefficients, which are relative quantities as illustrated in equations 7-9. Fig 11 shows the CCF coefficient of the bounce/roll accelerations. The changes at the time shifts of t=0 and t=0.05s are similarly sensitive to the fault (the coefficient of the front left damper is reduced by 50% at t=6s), but are more consistent (or smoother) compared to the CCFs in Fig 10.

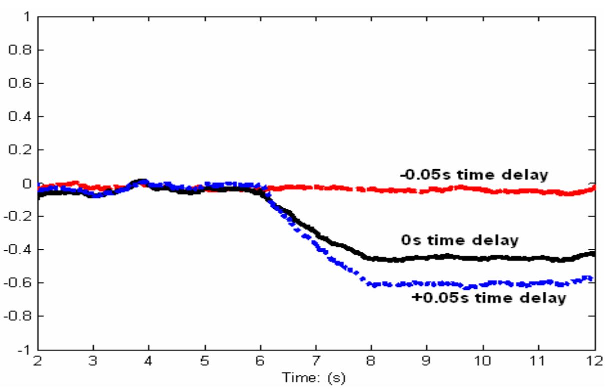

Fig 11. CCF coefficient between bounce and roll accelerations

Fig 12 compares the bounce/roll cross correlations at the speeds of 25m/s and 50m/s, where the difference is self-evident even though the fault condition is the same. In Fig 13, however, the effect of the fault on the cross correlation coefficients at the different speeds is virtually the same.

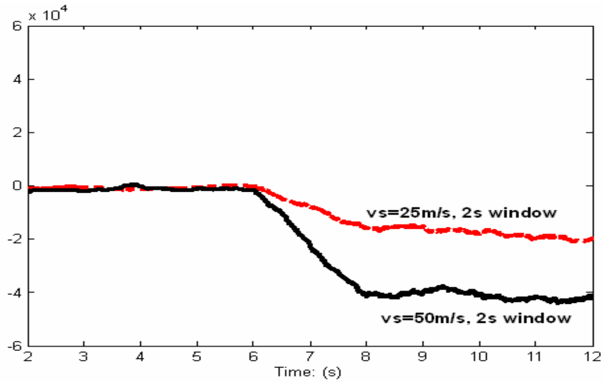

Fig 12. Comparison of bounce/roll CCFs

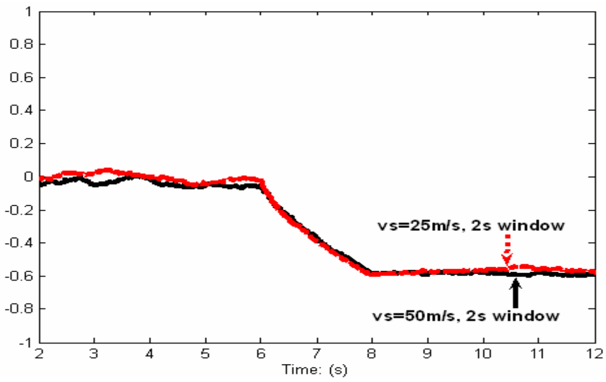

Fig 13. Comparison of bounce and roll CCF coefficients

To study the robustness of the proposed technique against sensing errors, a sensor noise of 1% of the measurement range is also included in the analysis which showed little adverse effect. This is because the noises from different sensors are in general uncorrelated and their effects at the specific time shifts of the cross correlation calculations are expected to be small.

4.4 Fault Isolation

CCF coefficient results of different suspension faults at four corners of the bogie show that the any individual fault may be readily isolated by exploring different ways the CCF coefficients are altered by the different faults. Table 2 shows each fault affects the CCF coefficients of bounce/pitch, bounce/roll and pitch/roll accelerations at the time shift of 0s, where the vehicle speed is set to 50m/s.

Table 2. Changes of CCF coefficients in different fault conditions (at the time shift of 0s only).

CCF coefficient to 50%	Bounce/pitch	Bounce/roll	Pitch/roll
No fault	0	0	0
Front left damper	-0.30	-0.58	-0.56
Front right damper	-0.30	0.57	0.57
Rear left damper	0.31	-0.58	0.56
Rear right damper	0.31	0.57	-0.57

It is clear that any two of the CCF coefficients will be sufficient for the purpose of fault isolation, although some are more sensitive than others. Similar results are obtained for CCF changes at the time shifts t=-0.05 and t=0.05, so there is no shortage of information.

5. CONCLUSIONS

A novel condition monitoring technique for the detection of faulty components in railway suspensions has been developed in this paper. Based on the dynamics study of a conventional bogie vehicle, it is shown that the dynamic interactions between different modes of the bogie frame are introduced by faults in the suspensions and their cross correlations can be used to not only detect but also isolate damper faults. The effectiveness as well as robustness against external disturbances has been demonstrated using computer simulations.

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LIST OF PARAMETERS

A_{rv} – Track roughness factor in vertical direction

B_b - Half wheel space of the vehicle bogie in lateral direction

c_p – Normal damping of each damper in primary suspensions

f_t – Spatial frequency

I_{bx}, I_{by} - Roll and pitch inertia of bogie

k_p – Stiffness of each coil spring in primary suspensions

m_b - Mass of bogie

N – Number of sampled data in each time window

T – Length of the chosen time window

z_{t1l}, z_{t2l} - Left vertical track inputs for front and rear wheels

z_{t1r}, z_{t2r} - Right vertical track inputs for front and rear wheels

Δt – Time step between each sampling