· Proceedings of the 23rd International Conference on Automation & Computing, University of Huddersfield, Huddersfield, UK, 7-8 September 2017

The Validation of an ACS-SSI based Online Condition Monitoring for Railway Vehicle Suspension Systems using a SIMPACK Model

Fulong Liu, Fengshou Gu and Andrew D. Ball
Centre for Efficiency and Performance Engineering
School of Computing and Engineering，University of Huddersfield, Huddersfield, UK, HD1 3DH
fulong.liu@hud.ac.uk, f.gu@hud.ac.uk, a.ball@hud.ac.uk

Yunshi Zhao and Bo Peng
Institute of Railway Research
School of Computing and Engineering，University of Huddersfield, Huddersfield, UK HD1 3DH
yunshi.zhao@hud.ac.uk, bo.peng@hud.ac.uk

***Abstract*—To enhance the safe operation of modern railway vehicles, an online condition monitoring scheme is proposed for vehicle suspension systems. The core technology of the scheme is based on the average correlation signals based stochastic subspace identification (ACS-SSI) algorithm which allows system identification to be implemented reliably with output signals only that have strong noise and nonlinearity in vehicle applications. To validate the scheme, a series simulation studies were carried out based on a more realistic bogie model, developed in SIMPACK, under typical random excitations including vertical, lateral, rolling and gauging directions. ACS-SSI is then applied to the signals from the model under common faults in the bogie suspensions to identify the system parameters. The agreeable results obtained by comparing the identified results with that calculated by SIMPACK shows that the proposed scheme performs reliably in obtaining the system parameters: modal frequency, damping and shape that are required for online diagnosis.**

Keywords—railway vehicle suspension; online Condition Monitoring; ACS-SSI

I. INTRODUCTION

Condition monitoring system is indispensable for a modern railway system operating with ensured safety and reliability. Many condition monitoring methods have been studied by different researchers, which are commented in general review works of [1-4]. Based on these reviews, the condition monitoring methods can be divided into two main groups, on-board and track-side techniques. The track-side monitoring systems can only provide monitoring at selected positions along the track while on-board techniques have the capability to provide real time detection of defects and early warning alarms[1]. Obviously, on-board methods have more advantages to fulfil condition monitoring for railway vehicles, especially for vehicle's online condition monitoring methods which are able to reflect the conditions in real-time. Hence, a new on-board technique was proposed in this paper for rail vehicle online condition monitoring.

Reference [1] presented a satisfactory review on the on-board condition monitoring methods. It concludes that the on-board methods can be allocated into model-based and signal-based. The model-based methods mainly include: inverse modelling methods[5], Kalman filter[6, 7], extended Kalman filter, unscented Kalman filter[8] and Rao-Blackwellised particle filter[9, 10]. Each model-based method has its adaptable conditions and drawbacks. Generally, model-based methods are mainly limited by three factors: proper initial values during partial linearization, unknown noises and model uncertainty caused by the nonlinear parameters [1, 3].

Another sort of on-board method is signal-based techniques which analyze output signals directly to achieve fault detection and identification. The signal-based techniques can be divided in more detail: time-domain method, frequency-domain method, time-frequency domain method and correlation-based method [1, 11, 12]. The signal-based methods have two main drawbacks limited their application. First of all, the effective and efficient indictor for a specify fault is difficult to find. Besides, a pre-built database including fault-relevant features under normal condition and all possible fault conditions should be constructed, which contains heavy workloads, to fulfill systems' condition monitoring.

Particularly, this study investigates a new system identification method developed by Chen, et al[13, 14], denoted as average correlation signal based stochastic subspace identification (ACS-SSI), to achieve online

This study is partially supported by China Scholarship Council (CSC)

condition monitoring for railway vehicle suspension systems. ACS-SSI is an effective output only system identification algorithm and successfully used for road vehicles' online condition monitoring.

The conventional stochastic subspace identification (SSI) methods can only treat stationary vibration scenario. In other words, conventional SSI method have to satisfy the white noise assumption. However, this is unnecessary for ACS-SSI, which is one of the main advantage of ACS-SSI compared with others output-only system identification methods. With such a merit, it makes ACS-SSI has the capability to achieve online condition monitoring for vehicle suspension systems which always have non-stationary responses with the road irregularity inputs. The details of this method can be found in [13-15].

However, as there is significant differences between road and railway vehicles in terms frequency range, damping characteristics and excitation mechanisms. Therefore, this paper focus on the validation of the ACS-SSI for the railway vehicle. A SIMPACK model was developed firstly to obtain system responses under different excitations and parametric conditions which are known. Then the responses are applied with the ACS-SSI method to obtain the system parameters so that a comparative study can be made with the known conditions and hence validate the performance of the identification performance.

II. SIMPACK MODEL AND SIMULATIONS

A. SIMPACK Model

SIMPACK is a powerful multi-body dynamic simulation software. With its wide ranges of built-in functions and graphical representation, it has shown outstanding performance for analysing the dynamic behaviors of many engineering systems such as the railway vehicles [6]. In this study, a bogie model with two wheelsets was developed in SIMPACK, shown as Fig 1 to obtain the responses on the four corners. The main parameters of this model are presented in Table.1, which are typical for passenger vehicles.

Four virtual sensors were employed to acquire the vibration signals on the four corners of the bogie frame, shown as Fig.1. This model carried out a simulation of the bogie running on the track continued for 240s under the speed of 100km/h and the sampling frequency of sensors was 500Hz. Then, the vertical acceleration signals from the four virtual sensors were chosen as the original signal for ACS-SSI process. The identification results would be presented in the next section.

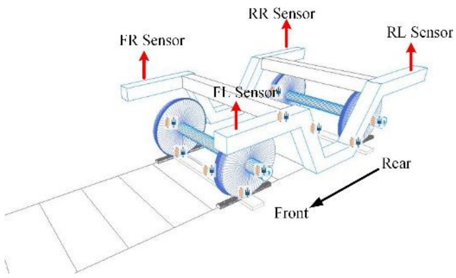

Fig.1 SIMPACK Bogie 3D Model

Table.1 Main Parameters of Bogie[10]

Parameters	Values
Bogie Mass	3000kg
Bogie Roll moment of inertia	1500kg m^2
Bogie Pitch moment of inertia	2500kg m^2
Bogie Yaw moment of inertia	2800kg m^2
Wheelset Mass	1000kg
Wheelset Roll moment of inertia	1200 kg m^2
Wheelset Pitch moment of inertia	100 kg m^2
Wheelset Yaw moment of inertia	1200 kg m^2
Wheel Radius	0.46 m
Gauge	1.5 m
Wheelbase	2.5 m
Vertical Stiffness of Primary Suspension	6×10^5 N/m
Vertical Damping Coefficient of Primary Suspension	6000 Ns/m

B. Different Simulation Conditions

In this study, three different simulation conditions were carried out. The first case was all parameters of the primary suspension were under normal conditions. The second simulation was the stiffness of the front right spring was reduced by 50% and the third one was the damping coefficient of front right damper reduced by 75%.

C. Excitation Characteristics

The vibrations of railway vehicle are mainly caused by the irregularities of the track. The irregularities of track including deviations in vertical, cross level, lateral and gauge. Obviously, the vertical deviations will cause vertical vibrations. The cross level means the vertical deviations of left and right track in the same plane and this will cause roll motion of the vehicle while the roll motion is an important factor for the vertical vibration. In other words, the cross level will cause vertical vibration as well. The lateral motions of railway vehicle mainly caused by lateral and gauge irregularities. This study focus on the vertical vibration characteristics of the bogie caused by the track irregularities.

The excitation of this model was realized by setting the track as the fifth-grade American irregularity. The track random irregularities are loaded by power spectrum density (PSD) function, Equation (1)-(3)[16].

Vertical excitation:

$$S_v = \frac{kA_v\Omega_c^2}{\Omega^2(\Omega^2 + \Omega_c^2)} \tag{1}$$

Lateral excitation:

$$S_a = \frac{kA_a\Omega_c^2}{\Omega^2(\Omega^2 + \Omega_c^2)} \tag{2}$$

Roll and gauge excitation:

$$S_c = S_g = \frac{4kA_v\Omega_c^2}{(\Omega^2 + \Omega_c^2)(\Omega^2 + \Omega_s^2)} \tag{3}$$

Where $k = 0.25$ when calculating the dynamic response of the railway vehicles. The other parameters of the fifth-grade American track irregularity are given as follows according to [16]:

$A_v = 0.2095 cm^2 \cdot rad/m$; $A_a = 0.0762 cm^2 \cdot rad/m$;

$\Omega_s = 0.8209 rad/m$; $\Omega_c = 0.8245 rad/m$.

III. ACS-SSI Identification Result

A. Signal Characteristics

Three cases of the bogie suspension systems were conducted by the SIMPACK model, given in section 2(B). The original vertical (z-direction) acceleration signals of normal and abnormal (FR spring and damper Fault) suspension are shown as Fig.2. It can be seen that the vibrations at the four corners of the bogie are stochastic in vertical direction. Furthermore, it can be seen that the process of vehicle running on the track are almost stationary but with some big pulses.

A serious simulations of the model running at different speeds under normal conditions were carried out in SIMPACK. The root-mean-square (RMS) values of vibration signals of the four channel at corners of the bogie frame are presented in Fig 3. It shows that the vibration amplitudes became bigger along with the increase of speeds. It can also be seen that the vibration amplitude of the same wheelset at left and right side are the same but they are different of front and rear wheelsets. Therefore, the simulations of abnormal suspensions were repeated three times under the same speed (100km/h) by choosing different random seeds in the SIMPACK and then average the RMS values to ensure the accuracy of vibration amplitudes. The results are given in Fig 4. It can be seen that the RMS values are various. Moreover, it shows that the vibration amplitudes are smaller when the spring stiffness reduced, particularly the front right of the bogie frame where near the fault spring. In contrast, the vibration amplitudes of bogie frame are bigger when the suspension system has a failure component on the damper.

Fig.5 shows the power spectrum density (PSD) of the vertical vibration signals of the three suspension conditions. It indicates clearly that the main power of this vibration is in a low frequency range, which below 10Hz. It also shows that vibration amplitudes of bogie with fault damper is bigger than normal conditions, especially the position of front-right (FR) with a fault damper.

To improve the signal noise ratio (SNR) and suppress the non-stationary condition, correlation signals between channels are employed as the inputs for ACS-SSI method. An average of the correlation signals can improve the SNR in a further step. In order to ensure each part of the signals include all characters of the real signals, the signals cannot be divided into too short. At the same time, average times were expected to be more to improve the SNR. Therefore, the 240s original signals were divided into six parts and then the correlation signals of each part were calculated. Lastly, the correlation signals of each channel were averaged. Front-left (FL) sensor was chosen as the reference channel to ensure that the correlation signals can be averaged..

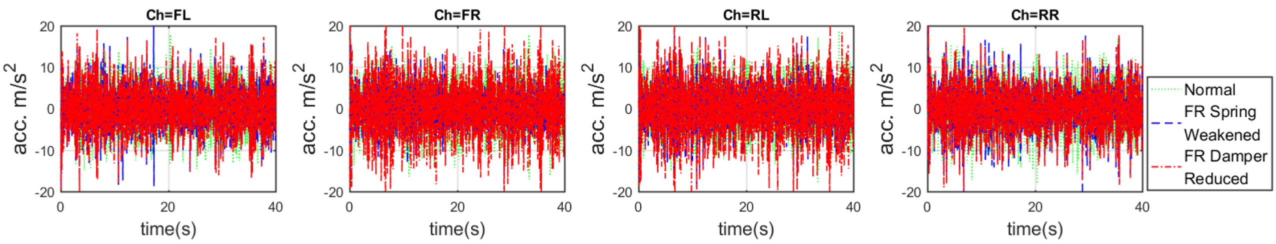

Fig.2 Original Vertical Acceleration Signals

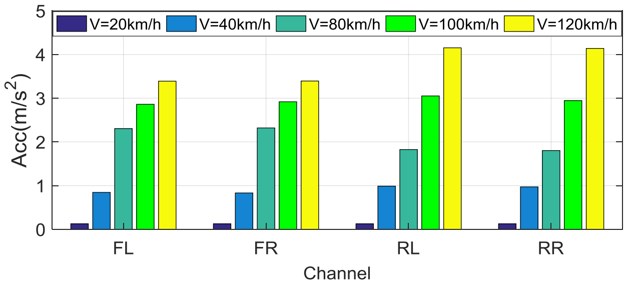

Fig.3 RMS Values under Normal Conditions in Various Speeds

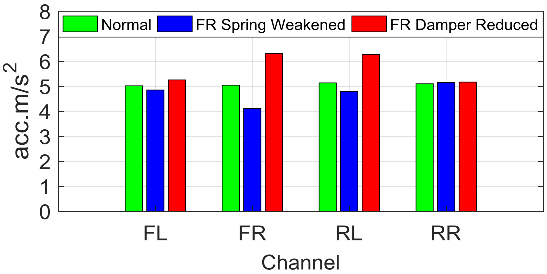

Fig.4 RMS Values of Suspension under Different Conditions (100km/h)

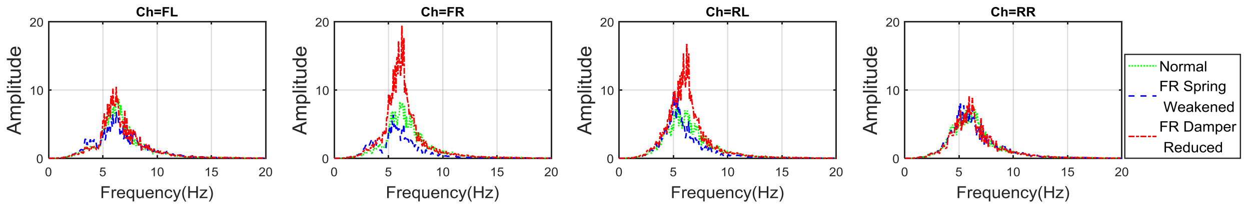

Fig.5 PSD

B. *ACS-SSI for Normal Suspension*

The SIMPACK model includes 24 degree of freedoms. All modal parameters of this model were calculated while only the bogie frame related modes were presented in Fig.6. Meanwhile, the modes identified by ACS-SSI method are also given in Fig 7. This result used the virtual signals of the SIMPACK model running under the speed of 100km/h.

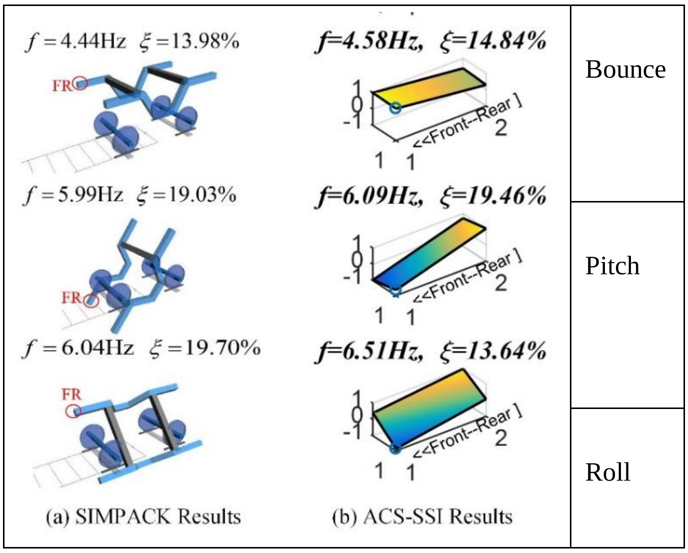

Fig.6 Modes under Normal Conditions

It can be seen that the three mode shapes of bounce, pitch and roll were identified by ACS-SSI method. The natural frequencies of bounce and pitch have a good coherence between the two methods, only with 3.15% and 1.67% errors, respectively. However, the roll frequency has bigger deviation, which is 7.78%. Furthermore, the deviations of damping ratio of bounce, pitch and roll between SIMPACK and ACS-SSI results are 6.15%, 2.26% and 30.76%, respectively.

To verify the effectiveness of ACS-SSI in a further step, a serious simulations of the bogie with normal suspension running under different speeds were carried out using the model in SIMPACK. Then the ACS-SSI was employed to identify the modal parameters through the collected virtual acceleration signals. The results are presented in Table 2. It can be seen that ACS-SSI has the capability to identify the mode shapes, frequencies and damping with an acceptable errors. This result indicated the possibility of ACS-SSI used for online condition monitoring for vehicle systems because the vehicle always travelling with a changing speed.

Table.2 ACS-SSI Results under Different Speeds

V	Mode 1 (Bounce)		Mode 2 (Pitch)		Mode 3 (Roll)	
(km/h)	*f (Hz)*	*ξ*	*f (Hz)*	*ξ*	*f (Hz)*	*ξ*
40	4.61	12.02%	6.09	10.01%	6.21	12.21%
80	4.42	16.58%	5.93	18.01%	6.02	21.71%
100	4.58	14.84%	6.09	19.46%	6.51	13.64%
120	4.49	14.07%	5.60	15.88%	6.49	13.32%

The estimation of damping ratio has larger deviation compared with the frequency. The main reason for that is the calculation of damping ratio is under a great many of assumptions. Therefore, the criterion of damping value for the stabilization diagram was given a bigger value to avoid spurious modes. In other words, the identification results are acceptable if the mode shapes and resonance frequencies are accurate enough. Based on these analysis, it indicates that the ACS-SSI could have the potential to be an effective method to estimate the modal parameters of bogie with output signals only.

C. *ACS-SSI for Suspension with Weakened Spring*

In order to verify the effectiveness of ACS-SSI for condition monitoring of railway vehicle suspension systems, simulations of suspension under different conditions were conducted. The first scenario was by reducing (50%) the stiffness of front-right spring of primary suspension. The result is shown in Fig 8. This result applied ACS-SSI on the data obtained from the SIMPACK model in the velocity of 100km/h.

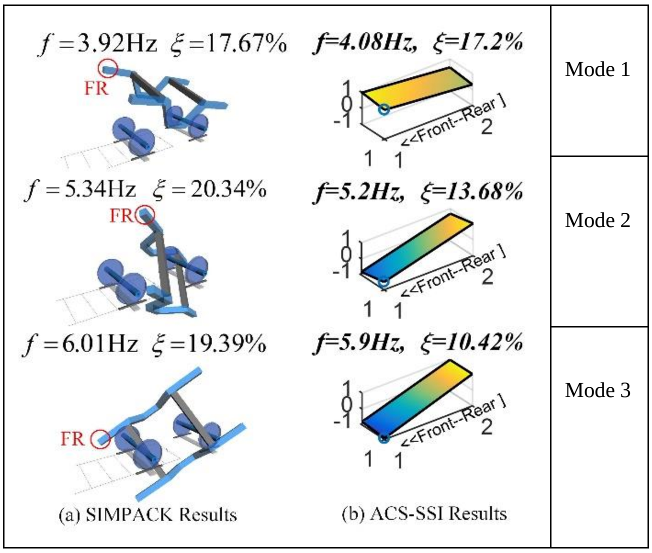

Fig.8 Modes under Front-Right (FR) Spring Weakened

It shows that ACS-SSI identified the three modes related with the bogie frame which calculated by SIMPACK. Obviously, although the three modes are not in regular with bounce, pitch and roll, the ACS-SSI results have a good coherence with SIMPACK in mode shapes. The second and third mode looks like the same in ACS-SSI results. However, the difference can be seen clearly in SIMPACK through the animation function. The second mode is the bogie frame roll around the diagonal of front-left and rear-right and the third mode is roll around the other diagonal of the frame. The second and third modes looks like the same could be caused by phase is not considered in ACS-SSI. The deviations of natural frequencies between SIMPACK and ACS-SSI of the three modes are 4.02%, 2.68% and 1.95%, respectively. The damping inaccuracies are much small compared with normal condition. They are 2.75%, 32.74% and 46.27% of the three modes. The results indicates that ACS-SSI could have the capability to identify the spring fault.

D. *ACS-SSI for Suspension with Fault Damper*

The second abnormal scenario was by setting the damping coefficient of the front-right damper to 25% of the normal value. The results obtained from SIMPACK model and ACS-SSI are presented in Fig 9. The speed of the SIMPACK model was also setting at 100km/h.

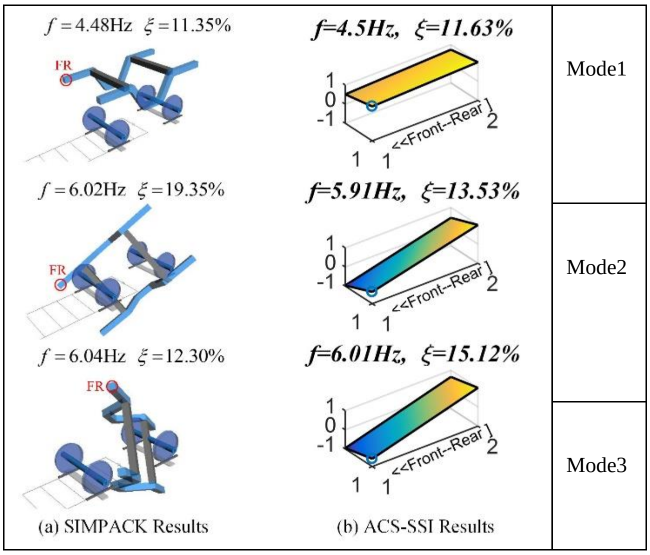

Fig.9 Modes under Front-Right (FR) Damping Reduced

It can be seen that the results of the two methods have a good coherence in mode shapes and a little bit like the results of suspension with spring fault. Both of them are not in regular with bounce, pitch and roll like the results of normal condition. The second and third mode shapes looks like the same but they are different， which are also similar to the modes appeared in spring fault scenario. The mode shape of the first mode is a bit like bounce and the frequency is also close bounce frequency of the bogie under normal condition. The deviations of frequency and damping ratio of the first mode between SIMPACK and ACS-SSI are small, which are 0.38% and 2.45%, respectively. Moreover, the natural frequency deviations of second mode between the two methods is 1.79% and it is also very small for the third mode, only 0.59%. Additionally, the damping ratio errors of second and third mode of the two methods is 30.84% and 22.95%, respectively. It can be seen that the ACS-SSI is capable to identify the mode shapes and natural frequencies accurately when the suspension has damper fault.

From the previous investigation for the three different scenarios of the rail suspension, it shows that ACS-SSI has the capability to accurately identify system’s mode shape and frequencies. Although the deviation of damping is bigger, the results are still acceptable. Hence, it can be concluded that the ACS-SSI could be used to online monitor the conditions of railway vehicle suspension systems.

IV. CONCLUSIONS

A new method named ACS-SSI for online condition monitoring was examined for the online monitoring of the condition of railway vehicle suspension. In order to reduce the cost at the first step of this study, a SIMPACK model was developed to acquire the virtual vibration signals (acceleration signals) on the bogie frame. The virtual acceleration signals obtained at the four corners of the bogie frame were used as the original signals for ACS-SSI to identify the modal parameters which can be used for online condition monitoring. The results show that ACS-SSI has the capability to accurately identify the mode shapes and natural frequencies but with large differences in damping estimation. As common faults on the system can induces changes in modal frequencies and modal shapes, it means that the proposed method is possible to diagnoses such faults. In other word, the ACS-SSI has the potential to be an effective method to achieve online condition monitoring for railway vehicle suspension. In addition, it also shows that the SIMPACK model provides a convenient and efficient implementation of dynamic analysis.

V. ACKNOWLEDGEMENT

This study is partially supported by Chinese Government Graduate Student Overseas Study Program, China Scholarship Council (CSC).

REFERENCES

[1] Li, C., et al., *An overview: modern techniques for railway vehicle on-board health monitoring systems.* Vehicle System Dynamics, 2017: p. 1-26.

[2] Ngigi, R., et al. *Modern techniques for condition monitoring of railway vehicle dynamics*. in *Journal of Physics: Conference Series*. 2012. IOP Publishing.

[3] Bruni, S., et al., *Control and monitoring for railway vehicle dynamics.* Vehicle System Dynamics, 2007. **45**(7-8): p. 743-779.

[4] Alemi, A., F. Corman, and G. Lodewijks, *Condition monitoring approaches for the detection of railway wheel defects.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 2016: p. 0954409716656218.

[5] Sun, Y.Q., C. Cole, and M. Spiryagin, *Monitoring vertical wheel–rail contact forces based on freight wagon inverse modelling.* Advances in Mechanical Engineering, 2015. **7**(5): p. 1687814015585431.

[6] Wei, X., H. Liu, and L. Jia. *Fault detection of urban rail vehicle suspension system based on acceleration measurements*. in *Advanced Intelligent Mechatronics (AIM), 2012 IEEE/ASME International Conference on*. 2012. IEEE.

[7] Hussain, I., T. Mei, and R. Ritchings, *Estimation of wheel–rail contact conditions and adhesion using the multiple model approach.* Vehicle System Dynamics, 2013. **51**(1): p. 32-53.

[8] Zhao, Y., B. Liang, and S. Iwnicki, *Friction coefficient estimation using an unscented Kalman filter.* Vehicle System Dynamics, 2014. **52**(sup1): p. 220-234.

[9] Li, P., R. Goodall, and V. Kadirkamanathan, *Estimation of parameters in a linear state space model using a Rao-Blackwellised particle filter.* IEE Proceedings-control theory and applications, 2004. **151**(6): p. 727-738.

[10] Li, P., et al., *Estimation of railway vehicle suspension parameters for condition monitoring.* Control engineering practice, 2007. **15**(1): p. 43-55.

[11] Liang, B., et al., *Railway wheel-flat and rail surface defect modelling and analysis by time–frequency techniques.* Vehicle System Dynamics, 2013. **51**(9): p. 1403-1421.

[12] Mei, T. and X. Ding, *Condition monitoring of rail vehicle suspensions based on changes in system dynamic interactions.* Vehicle System Dynamics, 2009. **47**(9): p. 1167-1181.

[13] Chen, Z., et al., *Characterizing the dynamic response of a chassis frame in a heavy-duty dump vehicle based on an improved stochastic system identification.* Shock and Vibration, 2015. **2015**.

[14] Chen, Z., et al., *1650. The average correlation signal based stochastic subspace identification for the online modal analysis of a dump truck frame.* Journal of vibroengineering, 2015. **17**(4).

[15] Liu, F., et al., *A validation study of ACS SSI for online condition monitoring of vehicle suspension systems.* Vibroengineering Procedia, 2016. **10**: p. 369-375.

[16] Wang, F., J. Zhou, and L. Ren, *Analysis on track spectrum density for dynamic simulations of high-speed vehicles.* Journal of the China Railway Society, 2002. **24**(5): p. 21-27.