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Continuous Measurement of Lateral Wheel/rail Interaction Force Based on PVDF Strain Sensing Technology

[1]Song Ying, [1]Wang Zhi-Chen and [2]Du Yan-liang
[1]School of Transportation Institute,
[2]Structural Health Monitoring and Control Institute,
Shijiazhuang Tiedao University, Shijiazhuang, 050043, China

Abstract: Oscillatory wheel load fluctuation of considerable amplitude is always observed in railway trains traveling at high speed. The study describes a new continuous method for measuring lateral force between wheel and rail without special wheelsets equipped with strain gauges and slip rings or telemeters. Track strain response upon wheel/rail interaction is measured based on PVDF (polyvinylidenefluoride) strain sensors and processed to generate a condition index which directly reflects the train operation condition. This approach is verified by finite element simulation and experimental test and the preliminary results show that this electromagnetic immune system provides an effective alternative for lateral wheel/rail interaction force measurement. The method significantly increases the efficiency of maintenance management and enhances the stability for train operation and more importantly, avoids derailment timely.

Key words: Wheel/rail contact, lateral wheel rail force, measuremen,; PVDF strain sensor, piezoelectric

INTRODUCTION

The basic requirement for the safety of railway transportation system is that derailment during the running of train should be never permitted. Scientists of many countries have made great efforts for the study of derailment mechanism and train running safety (Nagase *et al*., 2002; Takai *et al*., 2002; Durali and Shadmehri, 2003; Barbosa, 2004; Ham *et al*., 2009; Xiang and Zeng, 2005; Braghin *et al*., 2006) but the train derailment phenomenon is far from solved and still many serious accidents due to derailment are often reported. Therefore, it is very important for safe train operation to grasp the actual state of the contact forces between wheel and rail.

Both wheel load and lateral force are important factors for ensuring the running safety of vehicle. For on-board measurement of wheel-rail contact forces, extra devices, such as special wheelsets with strain gauges and slip rings or telemeters are necessary at present and frequent measurement is difficult because of the expensiveness and insufficient durability of such devices. The conventional continuous method also suffers from low sensitivity and high noise. Moreover, more recently developed rolling stock operates at higher speeds and is subject to greater change in wheel load. Therefore, the conventional methods are not sufficiently accurate to evaluate the derailment coefficient. On the other hand, real-time monitoring of wheel/rail contact forces, is very useful for prevention of derailment accidents because such coefficient fluctuates every moment.

A new method based on PVDF strain sensing technology introduced in the study needs no strain gauges and load cells on the wheelset, a piezoelectric polyvinylidene fluoride (PVDF) film is used in this sensor as the sensing element and can realize continuous monitoring of lateral wheel rail contact force. PVDF piezoelectric films are new, valuable materials for sensing application and have attracted people's attention due to their excellent characteristics. Recently, PVDF piezoelectric sensors have been applied in numerous fields, for instance, structural health monitoring, smart material and structure, various force sensors, etc. However, up till now, to the best of author's knowledge, the application of PVDF sensing technology in the field of wheel/rail force measurement needs to be further investigated. The study describes the principle of the continuous measurement method based on PVDF strain sensors and gives the results of preliminary experiment.

MEASURING METHOD OF LATERAL WHEEL/RAIL FORCE

Measurement system: In the study, as shown in Fig. 1, a real-time lateral wheel rail force measuring system is proposed based on PVDF strain sensors. The

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Corresponding Author: Song Ying, School of Transportation Institute, Shijiazhuang Tiedao University, Shijiazhuang, 050043, China

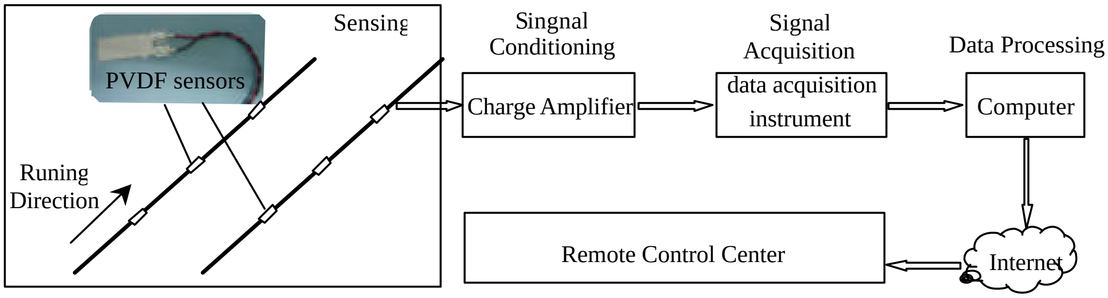
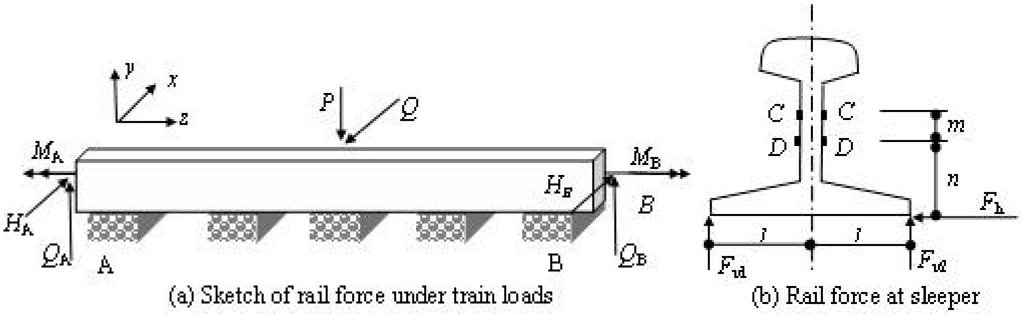


Fig. 1: Sketch of measurement system



(a) Sketch of rail force under train loads

(b) Rail force at sleeper

Fig. 2: Mechanical sketch of rail

measurement system consists of PVDF strain sensors, charge amplifier, data acquisition instrument, computer and vibration signal acquisition, processing and analysis software. Lateral forces are measured by strain values detected by PVDF strain sensors attached on the rail web and the frequency component that solely reveals the quality of the interaction are extracted and processed from the signal. It can measure whole vehicles that run through measuring point because no equipment required on vehicles but only at specified point.

Measurement principles: The simplified model of right rail under train loads is shown in Fig. 2. For force analysis of rail in region A-B, vertical and lateral wheel/rail force P and Q are applied on rail, the reaction forces F_{v1}, F_{v2}, F_h and moments M_A, M_B are applied on sleeper bottom through the under sleeper structure such as rail fastenings and pads. Shear forces and moments on cross section A-B are Q_A, Q_B, H_A, H_B, M_A and M_B as shown in Fig. 2a. Moments at section C-C and section D-D can be obtained as:

$$\begin{aligned} M_C &= F_h \cdot (m+n) - (F_{v2} - F_{v1}) \cdot l \\ M_D &= F_h \cdot n - (F_{v2} - F_{v1}) \cdot l \end{aligned} \tag{1}$$

$$\sum_x F = 0 \qquad Q = H_A + H_B + \sum_{i=1}^{n} F_{hi} \tag{2}$$

In Eq. 2, F_{hi}, denotes the lateral reaction force at each sleeper and n is the number of sleepers between region A-B. It's assumed that stresses on section C-C and section D-D are σ_C and σ_D respectively and that the thicknesses at section C-C and section D-D are nearly equal. Then the bending stiffness $W_C = W_D = W$ = constant. We get:

$$F_h = (M_C - M_D)/m = (\sigma_C - \sigma_D) \cdot W/m \tag{3}$$

Based on the basic piezoelectric equations, the relationship between measured strain and output signal generated by PVDF sensing element is (external electric field is zero as PVDF piezoelectric film being used as a sensor):

$$D_i = d_{ij} T_j (i = 1 \sim 3, j = 1 \sim 6) \tag{4}$$

where, D_i denotes the electric displacement, d_{ij} denotes the piezoelectric constant and T_j is the stress applied on the sensing element. The output signal of PVDF sensor is induced by strains in all directions. The output charge of PVDF sensing element can be expressed:

$$Q = \sum d_{ij} T_j = \sum d_{ij} E_{pvdf} \varepsilon_j S \tag{5}$$

where, S is the effect area of PVDF polar plate, E_{pvdf} is the Elastic Modulus and ε_j is the measured strain. For PVDF piezoelectric film, $d_{31} = d_{32}$, $d_{24} = d_{15}$, other piezoelectric constants are zero. For lateral wheel rail force measurement, according to Fig. 1, the output signal is induced only by the strain in single direction. We have:

$$Q = d_{31} E_{pvdf} \varepsilon_1 S \tag{6}$$

In practical engineering application, a charge amplifier is required to convert the charge signal to voltage signal which is then converted to digital signal by A/D converter, a fully automated monitoring system is formed combining them with data acquisition, processing and analysis software. Assume that K_A is a proportional coefficient of charge amplifier, A_b is an amplification factor of post-processing circuit, the output voltage of the whole circuit can be given by:

$$U_0 = K_A d_{31} E_{pvdf} \varepsilon_1 S A_b \tag{7}$$

Thus, once parameters of PVDF sensor element and circuit are known, one can measure the values of the generated charge, then the lateral wheel/rail force Q can be obtained using Eq. 3 and 7.

FEM ANALYSIS BASED ON ANSYS

A FEM (Finite Element Method) model is developed for calculating the surface stress/strain of rail under vertical and lateral wheel/rail contact forces. The discretely supported 60 kg m^{-1} rail is modeled by solid element. The length of the track model is 8 sleeper bays with a constant sleeper spacing of 568 mm and the boundaries at the two rail ends are simply supported. Each rail pad is modeled as a discrete linear elastic spring. Ballast and subgrade are modeled by solid elements. Train load is modeled by concentrated loading. Load cases are shown in Table 1. Simulation results of PVDF sensors located in different strain measuring points (i.e., location1: at end of a sleeper bay; location 2: Away from mid-span of a sleeper bay 50mm and location 3: Away from sleeper end 50 mm) are also analyzed as shown in Fig. 3.

Based on Case 1 as shown in Table 1, vertical wheel/rail force and train speed keep constant. When lateral wheel/rail force is 30 and 70 kN, the curves of the normal stress σ and shear stress τ at detection points in region A-B with load step in location 8 (Fig. 3) are shown in Fig. 4. It can be seen that the distribution of shear stress increases with increasing lateral wheel/rail force and the distribution of normal stress remains within 3 sleeper bays. As for lateral wheel/rail force measurement, boundary shear forces Q_A, Q_B, H_A and H_B in section A and B (Fig. 2) could be neglected by reducing effective measurement region which can be determined through point-to-point calibrating. The curve of the stress differences between all the up detection points and all the bottom points in region A-B is shown in Fig. 5. Curves of the stress difference on other detection positions (i.e., away from mid-span of a sleeper bay 50mm and at end of a sleeper bay) are also shown in Fig. 5. Curve of detection points being away from sleeper end 50 mm is almost a smooth line which implies the stress difference is independent of time. Figure 5 also shows that the other two kinds of arrangements on detection positions are not satisfactory. Thus according to Eq. 3 and 7, it's reasonable to choose detection point located being away from sleeper end 50 mm.

Based on Case 2 and Case 3 as shown in Table 1, for given lateral wheel/rail force unchanged, simulation results at different vertical wheel/rail forces and different velocities show that vertical wheel/rail force and train speed have insignificant effect on slope of the measured

Table 1: Load cases of simulation

Load case	Vertical wheel/rail force [kN]	Lateral wheel/rail force (kN)	Train speed (km h^{-1})
1	110	30, 40, 50, 60, 70	300
2	60, 70, 80, 90, 100	30	300
3	110	30	200, 250, 300, 350

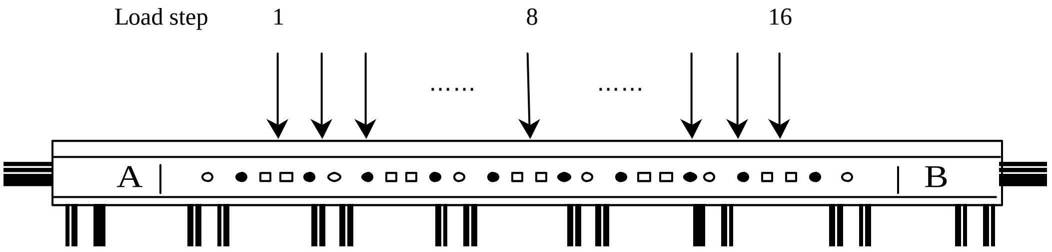


Fig. 3: Schetch of sensor locations and loadsteps

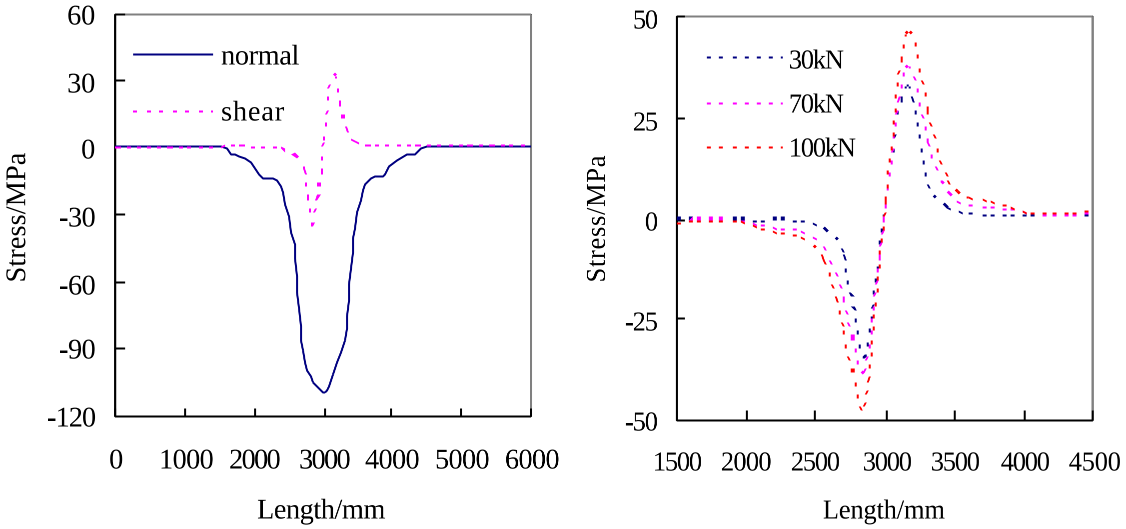


Fig. 4(a-b): Normal stress and shear stress distribution curves, (a) Lateral wheel/rail force 30 kN and (b) Shear stress with different lateral wheel/rail forces

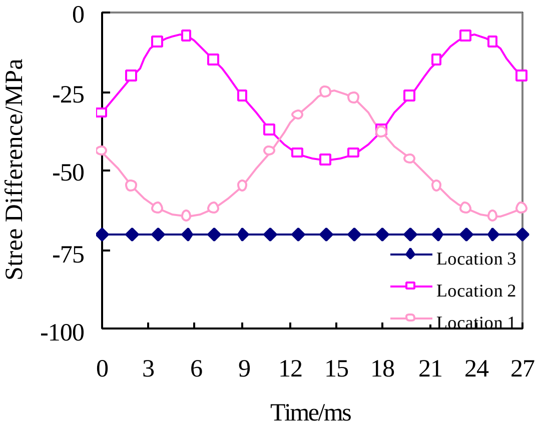


Fig. 5: Stress difference curve

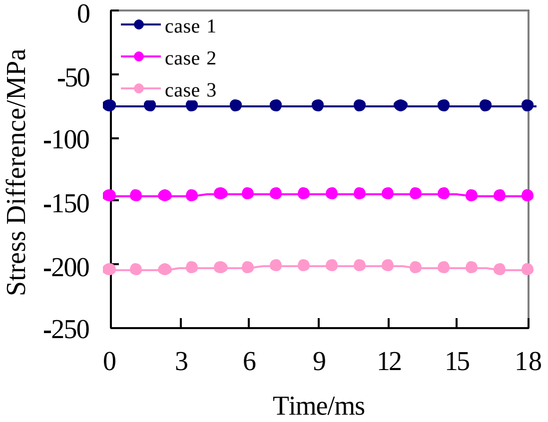


Fig. 6: Stress difference curves in different Load Cases

curve, as shown in Fig. 6. The stress differences increase with increasing lateral wheel/rail force. It's concluded that lateral wheel/rail force can be calculated from Eq.(3) and Eq. 7:

(Case 1: P = 100 kN, Q = 30 kN, v = 200 km h^{-1};
Case 2 : P = 80 kN, Q = 70 kN, v = 300 km $^{-1}$;
Case 3: P = 60 kN, Q = 100 kN, v = 350 km h^{-1})

EXPERIMENT AND RESULTS

The properties of the PVDF strain sensor have been investigated experimentally. A photograph of the experimental test is provided in Fig. 7. The parameters of PVDF sensing element used here are as follows: Length by width by thickness is 20×10×0.24 mm, capacitance is 84 pF, d_{33} is 24±1 pC/N and E_{pvdf} is 1.2×10^3 MPa. The output signal of the PVDF strain sensor was compared to the output signal of strain gauge used in conventional methods.

Dynamic response: As for wheel/rail force measurement in the process of moving train, the measured signal should be reflected by sensors accurately and sensitively. The frequency of sine wave cycle signal by exciter was increasing from 0.1 to 40 Hz in 0.5 Hz steps. The amplitude of sine wave cycle signal was 3 v. The characteristic curve, measured this way, is shown in Fig. 8. The experiments have shown that (1) The output voltage of PVDF sensor and the structure measured strain result in

Fig. 7: Laboratory experimental set up

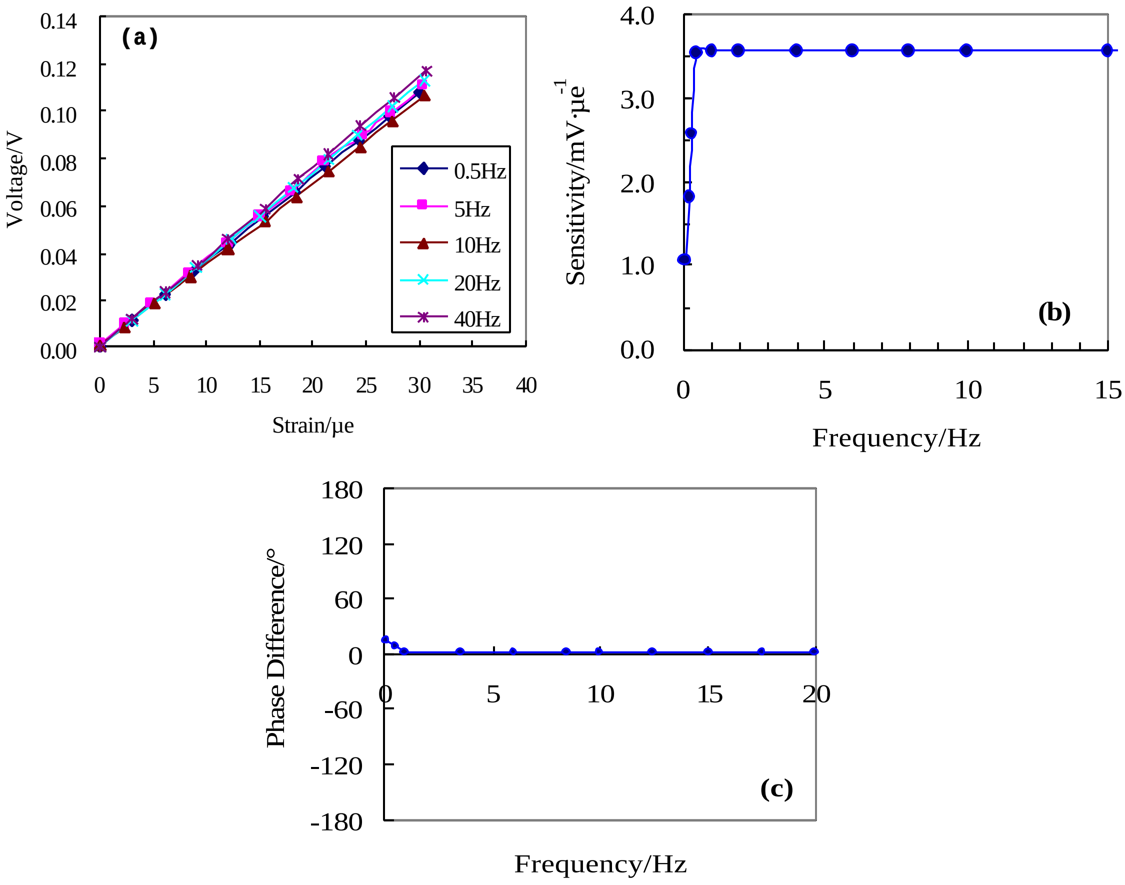


Fig. 8: Dynamic response of PVDF sensor

a linear characteristic curve as shown in Fig. 8a. Strain measurement accuracy is 1 με and nonlinear error is less than 0.1%. The output signal of the sensor changes by less than 0.3% which can be disregarded for the application. (2) The sensitivity of output voltage increases with increasing exciting frequency from 0 to 0.5 Hz and the sensitivity keeps unchanged when exciting frequency is higher than 0.5 Hz as shown in Fig. 8b.

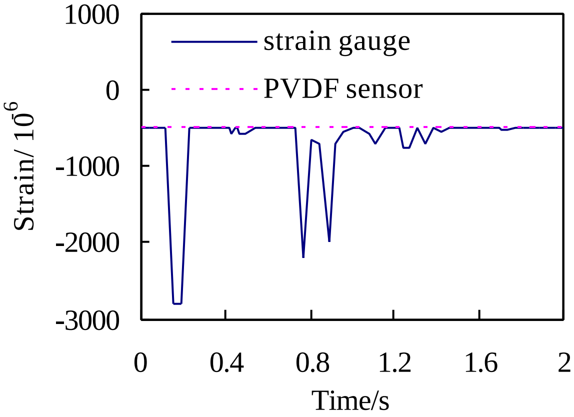


Fig. 9: Performance on EMI

(3) The phase difference of PVDF sensor is nearly 0 with exciting frequency higher than 0.5Hz as shown in Fig.8c. Our experiments have shown that PVDF strain sensor has best real-time monitoring capabilities which can meet the requirements of sensitivity and reproducibility for sensor in railway wheel/rail force measuring.

Electromagnetic interference sensitivity: Strain gauges have been often employed to measure the wheel/rail interaction forces but the performance of these sensors are easily compromised under Electromagnetic Interference (EMI) railroad environment. When structure measured strain is zero, EMI is applied to PVDF sensor and strain gauge by switching interphone within the range of around 3 m. The output signal of the sensors showed that PVDF strain sensor is passive to EMI (Fig. 9). In addition, it turned out that the PVDF sensor has excellent anti-drift performance while the strain gauge has zero drift at room conditions.

CONCLUSION

A continuous lateral wheel/rail force measuring method using PVDF strain sensors to measure the track strain response upon wheel-rail interaction is proposed and developed. The principle of the new method and the FEM analysis based on ANSYS are briefly reviewed, together with experimental test results and discussions. Compared with strain gauges used in conventional methods, one of the advantages of this sensor system is that the sensors installed at the railroad side are passive to EMI.

The method has been proven to be able to continuously measure the lateral wheel/rail force. The system has the advantage of providing real-time and in-service measurement of lateral wheel/rail interaction condition. Moreover, PVDF sensors used in this system are without zero-drift and immunity from EMI is particular suitable for electrified railways with track spanning over tens or even hundreds of kilometers. Further test and verifications with wheel and rail condition data are still required to improve the measurement accuracy. A more intelligent analysis technique and a more advanced PVDF sensor based system are now under investigation.

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REFERENCES

Barbosa, R.S., 2004. A 3D contact force safety criterion for flange climb derailment of a railway wheel. Vehicle Syst. Dyn., 42: 289-300.

Braghin, F., S. Bruni and G. Diana, 2006. Experimental and numerical investigation on the derailment of a railway wheelset with solid axle. Vehicle Syst. Dyn., 44: 305-325.

Durali, M. and B. Shadmehri, 2003. Nonlinear analysis of train derailment in severe braking. J. Dyn. Syst. Measure. Control, 125: 48-53.

Ham, Y.S., D.H. Lee, S.J. Kwon, W.H. You and T.Y. Oh, 2009. Continuous measurement of interaction forces between wheel and rail. Int. J. Precision Eng. Manuf., 10: 35-39.

Nagase, K., Y. Wakabayashi and H. Sakahara, 2002. A study of the phenomenon of wheel climb derailment: Results of basic experiments using model bogies. Proc. Inst. Mech. Eng. F: J. Rail Rapid Transit, 216: 237-247.

Takai, H., M. Uchida, H. Muramatsu and H. Ishida, 2002. Derailment safety evaluation by analytic equations. Q. Rep. RTRI, 43: 119-124.

Xiang, J. and Q.Y. Zeng, 2005. A study on mechanical mechanism of train derailment and preventive measures for derailment. Vehicle Syst. Dyn., 43: 121-147.