ISSN 0386-1678

Report of the Research Institute of Industrial Technology, Nihon University
Number 102, 2018

Railway Condition Monitoring, Present and Application for Regional Railways

Hitoshi TSUNASHIMA*

(Received November 11, 2017)

Abstract

Monitoring the conditions of railway asset is essential for ensuring the railway safety. Condition monitoring can be considered to be a part of the well-established area of Fault Detection and Isolation (or Identification). Condition monitoring is mainly applicable to system that deteriorate in time. The aim of condition monitoring is to detect and isolate deterioration before it causes a failure. This paper presents the application of condition monitoring technologies to vehicle suspensions and railway track. The theory, concepts, implementation status and application for regional railways are summarized with the key trends appeared in recent international railway conferences and discuss with a future look.

Key Words: Railway, Condition monitoring, FDI, Kalman filter, Track

1. Introduction

Condition monitoring can be considered to be a part of the well-established area of Fault Detection and Isolation (or Identification) (FDI)[1]. Condition monitoring is mainly applicable to system that deteriorate in time. The aim of condition monitoring is to detect and isolate deterioration before it causes a failure[2, 3](**Fig. 1**). Condition monitoring for railway system has been developed and various application was appeared in railway technology conferences.

STECH is the international railway technology conference originated in Japan. After the success in Yokohama, Japan (1993), Birmingham, UK (1996), Tokyo, Japan (2003), Chengdu, China (2006), Niigata, Japan (2009) and Seoul, Korea (2012), the 7th International Symposium on Speed-up and Sustainable Technology for Railway and Maglev Systems (STECH2015) was held in Chiba, Japan (2015)[4].

The conference covers topics of: vehicles, electrical and electronic systems, infrastructure, safety technology and accident analysis, boundary problems, maglev and linear motor drive technology, urban transportation, traffic planning, customer environment and service, environment and energy, Intelligent Transportation Systems(ITS), operation management, condition monitoring, maintenance.

Figure 2 shows the number of papers presented in STECH conferences from 2003 to 2015. It should be noted that topics of condition monitoring and maintenance has been increasing rapidly since 2003.

* Professor, Department of Mechanical Engineering, College of Industrial Technology, Nihon University

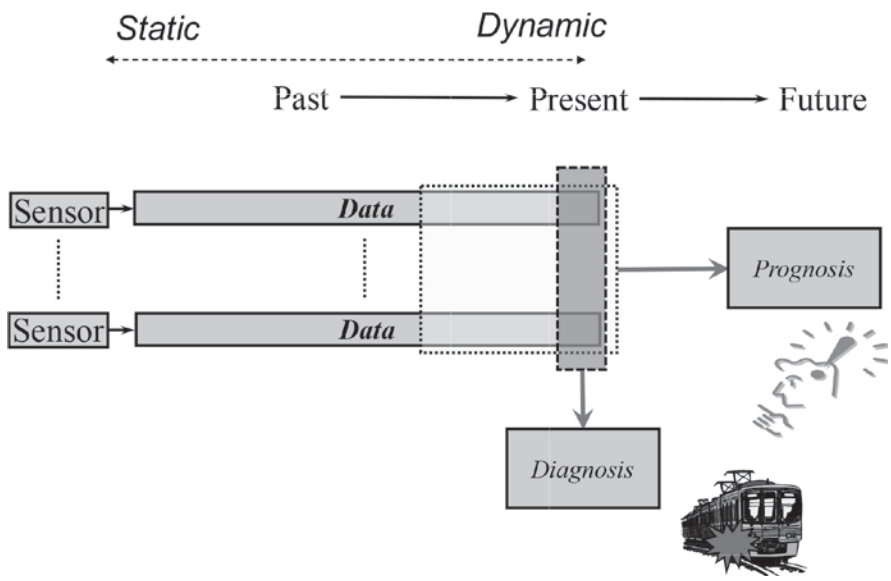

Fig. 1 Prognosis and diagnosis

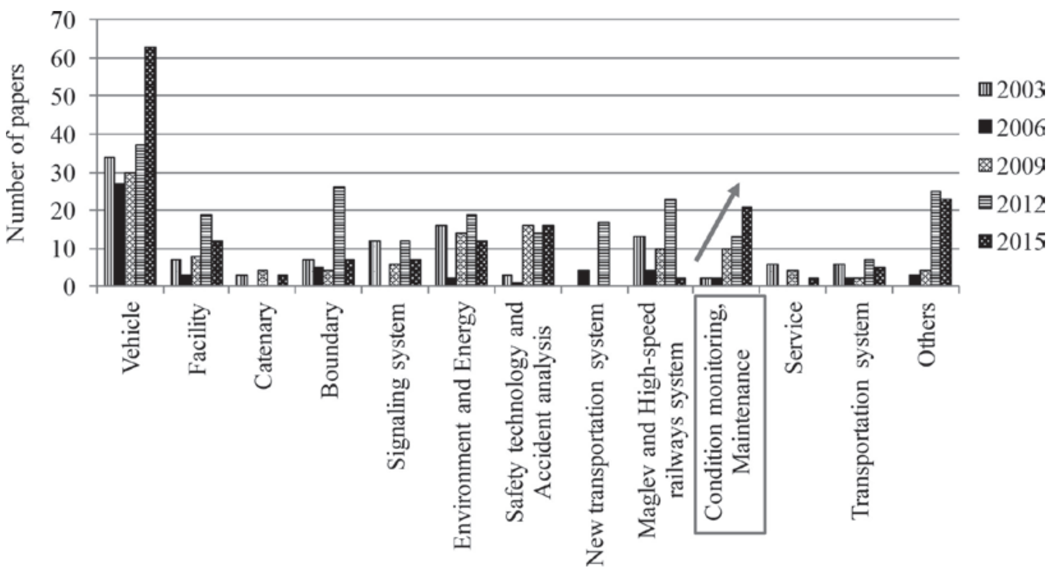

Fig. 2 Papers presented in STECH conference from 2003 to 2015

2. Concepts and application of condition monitoring

Figure 3 shows a general scheme of FDI or condition monitoring. The outputs are the measured signals, and the inputs are any relevant inputs. The disturbances are (unmeasured) excitations that affect the system.

In general, we are dealing with a dynamics system, regarded as asset, with measured inputs $\boldsymbol{u}$ and outputs $\boldsymbol{y}$ which is subject to possible faults. We should note that the unknown disturbance d will be applied. If we can obtain a physical model of the asset and input $\boldsymbol{u}$ is available, model based techniques can be applied. This approach includes: parameter estimation technique, parity equation, observer/Kalman filter, particle filter, multiple model, inverse approach (output $\boldsymbol{y}$ is used as an input to estimate input $\boldsymbol{u}$).

If only outputs $\boldsymbol{y}$ is available, signal processing (non-model) based method can be used. This type of fault detection techniques includes: frequency selective filter, spectral analysis, max. entropy, wavelet analysis, vibration analysis (amplitude, phase). As others type of approach, we can use: quantitative model (expert system, FTA), PCA, ICA.

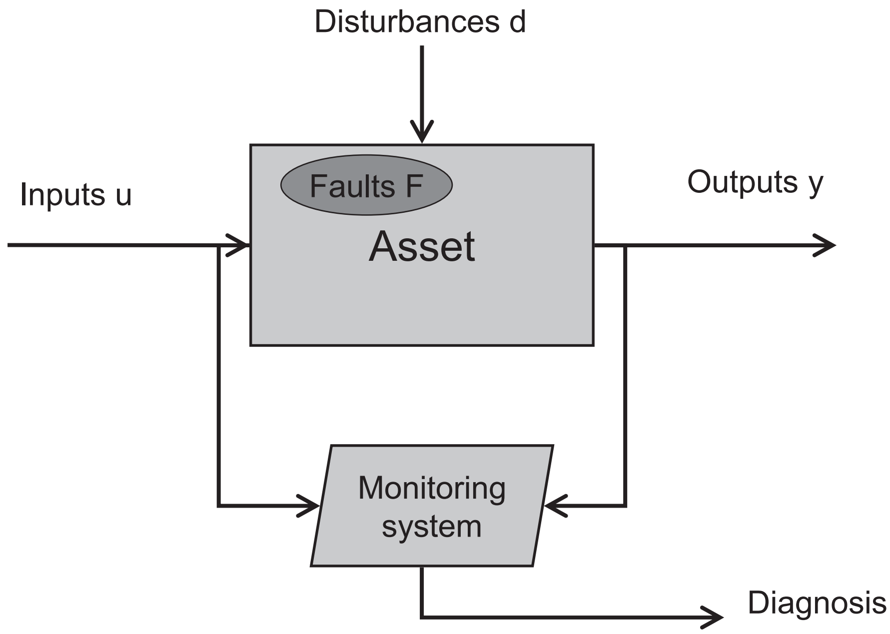

Fig. 3 Generalized fault detection or condition monitoring scheme [2, 3]

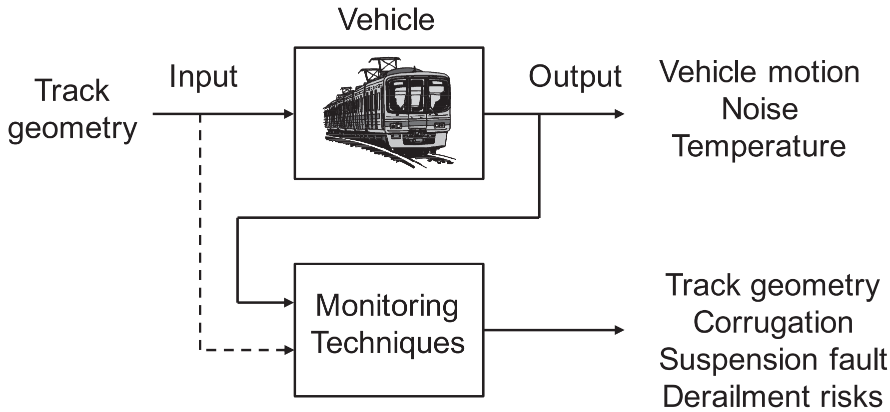

Fig. 4 Input and output relation in railway condition monitoring

Artificial intelligence (AI) becomes one of the "hot" zones recently. This approach includes: fuzzy logic, Neural Network (NN), Support Vector Machine (SVM). Machine learning is a technique concerned with learning from data and using them to make predictions. Deep Learning, which uses layered Deep Neural Networks (DNNs) is a new area of Machine Learning. It is expected that Deep Learning based on the big data analysis will be an another approach for condition monitoring.

In railway condition monitoring, vehicle components, track condition and derailment are attractive targets for monitoring. **Figure 4** shows the relation between inputs and outputs in the railway condition monitoring. In general, input should be track geometry (track irregularity, corrugation) and outputs include vehicle vibration, acoustic noise or temperature etc. Using monitoring technology, we want to find out degradation of suspension, derailment risks or track faults such as track irregularities and corrugation. Track geometry will be included in the unknown state, which should be estimated, in track geometry estimation.

In addition to these, we need to think:

- What and when do you want to find faults? Diagnosis or prognosis?
- What should be measured to find faults?
- What can we measure?
- Is sensor fusion necessary?

- Can we find the condition change in time?
- Relation between degradation level and measured data, risks, maintenance criteria
- How to extract the hidden signal?
- How to process big data.
- Who will use it? (In general, railway operator doesn't know much about condition monitoring theory.)

3. Trends of condition monitoring in railway vehicle and tracks

3.1 Detection of faults and degradation in suspension components[2)]

Currently condition monitoring strategies related to suspensions begin to focus on the combination of signal processing and model-based assessments. Model-based techniques are equipped with the potential capacities to reveal the unknown parameters in quantitative forms.

Model-based fault detection and diagnosis method has been widely used. Charles et al. have proposed estimation of wheel-rail profile and low adhesion using the Kalman filter approach[5, 6)]. The Rao-Blackwellised Particle filter technique is applied to estimate the damping coefficients of lateral and yaw dampers in secondary suspension and the wheel conicities[7)].

A suspension parameter identification strategy based on extended Kalman filter (EKF) is used to develop a health monitoring system for lateral suspensions of ETR500 high-speed train[8)]. Jesussek et al.[9)] proposed hybrid EKF to isolate the faults occurring in lateral suspensions. Liu et al.[10)] proposed Recursive Least Square (RLS) algorithm to identify multiple suspension parameters simultaneously. This algorithm was evaluated in the field test using E464 locomotive.

Mori et al.[11)] proposed a fault detection technique for railway vehicle suspension by interacting multiple model approach. The interacting multiple model method based on Kalman filter is used to monitor faults occurring in the lateral and yaw dampers of the bogie. This method incorporates a set of Kalman state estimators representing different failure modes and a mode-matching filter to identify the mode probability **(Fig. 5)**. Non-interactive multiple Kalman filters was used to detect faults in the suspension system of the vehicle[12)].

3.2 Detection of improper running conditions[2)]

On-board condition monitoring of railway vehicles can be used to identify improper running conditions that may affect ride safety: derailment of an axle, hunting instability, overheating of an axlebox etc. It is desirable to detect running condition that may lead to derailment of an axle in their early stage and take appropriate actions before vehicle goes to a non-recoverable derailing stage. Condition monitoring for derail-

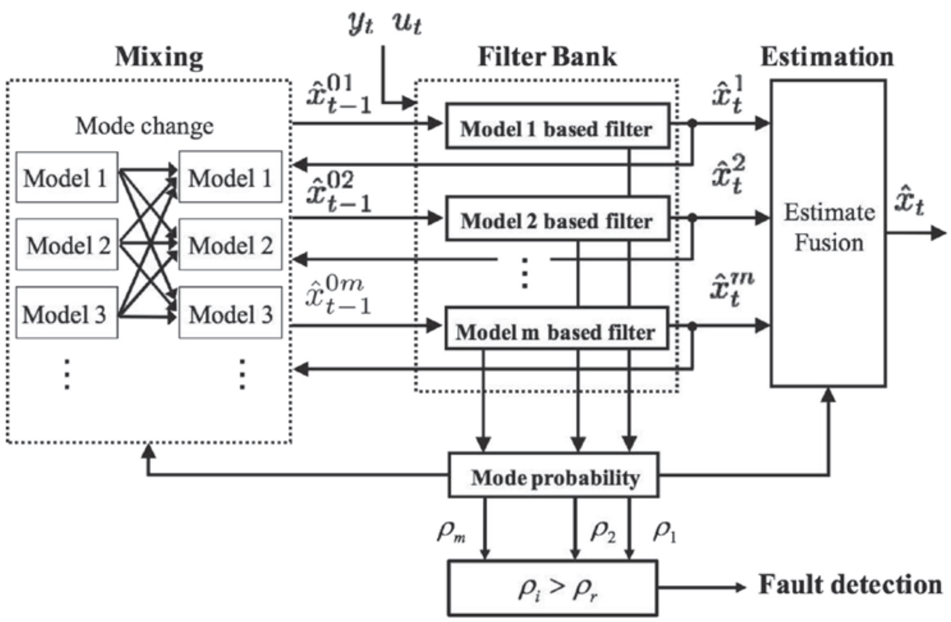

Fig. 5 Fault detection by interacting multiple model

ment prevention has been studied under this perspective.

Xia et al.[13] proposed an "inverse wagon model" to estimate the L/V ratio of lateral over vertical wheel-rail contact forces as well as the ratio of the dynamic over quasi-static vertical load. Matsumoto et al.[14] proposed on-board monitoring method of contact force, friction coefficient and derailment coefficient using non-contact gap sensors. Tokyo Metro introduced PQ monitoring bogies equipped with non-contact gap sensors into commercial lines from 2009[15]. They introduced the bogies into Marunouchi Line, Tozai Line and Chiyoda Line. A large amount of data has been collected and analyzed to show the daily and monthly changes of the derailment coefficient[16]. A detection system, that detects abnormal conditions leading to the flange-climb derailment in sharp curves, is described[17].

A possible perspective for derailment detection could be to identify a derailment condition after it has occurred. This will not of course provide a possibility to prevent derailment, but it is important to avoid additional risks to the vehicle and the track. This perspective is particularly important for freight trains. Boronenko et al.[18] performed numerical simulations and line experiments to identify the levels of bogie vibration that are induced by the derailment of an axle in a freight car. The same concept was applied by Hubacher et al.[19] to activate emergency braking in freight trains. The development of a vehicle abnormal behavior detection system is described by Koga et al.[20] The system was designed to detect derailment, overturning and collision using sensors installed on the vehicle body to measure tri-axial acceleration.

Friction coefficient between wheel and rail surface is an important factor for longitudinal control of a railway vehicle. Hubbard et al.[21] propose a system for the on-board detection of low-adhesion condition during normal operation of a vehicle. A model-based approach that uses a Kalman-Bucy filter and a non-model based approach were evaluated using BR Mark3 coach. Zhao et al.[22] used a technique using an unscented Kalman filter to estimate the creep force and the friction coefficient.

3.3 Track Condition Monitoring

TRENDS

Monitoring railway track geometry from an in-service vehicle has been attractive in the past decade[23]. Track geometry measurement systems using in-service vehicles has been developed around the world but they are still in the developing stage. Checking the same track over and over again gives an opportunity for obtaining track geometry degradation. The obtained information can be fed back to the track maintenance section to take necessary actions.

Several kinds of track faults can be detected by measuring the acceleration of bogies. Weston et al.[24, 25] demonstrated the track irregularity monitoring using bogie-mounted sensors. Alfi et al.[26] proposed a technique for estimating long wavelength track irregularities from on-board measurement.

If track faults can be detected in-cabin, condition monitoring of track irregularities will be much easier. As the distinctive signal of track faults are hidden in car-body vibration, signal processing is necessary for the acceleration measured in-cabin to detect track faults. Tsunashima et al.[27, 28] demonstrates the possibility to estimate the track geometry of Shinkansen tracks using car-body motions only. A Kalman filter was applied to estimate track irregularity from car-body motions. Tsunashima et al.[29] developed a system that attempts to identify vertical and lateral track irregularities using accelerometers placed on the car-body of in-service vehicles. This system also provides a function to listen for corrugation faults using acoustic sensor (a microphone). An approach has been tested to detect squats by listening rolling noise using microphones[30].

SYSTEM EXAMPLE

Figure 6 shows a schematic overview of the track condition monitoring system for regional railways, which is easily applicable for railway operators with low cost. **Figure 7** shows the on-board sensing device used in the track condition monitoring system.

This system is divided into a vibration measurement unit and an analysis unit. The vibration measurement unit utilizes a compact on-board sensing device to measure the vehicle vibration from within the car itself during ordinary commercial operation. The analysis unit uses track condition monitoring software to extract the requisite information from the measured data, and then computes assessment values to diagnose the track condition. Time-frequency analysis based on wavelet

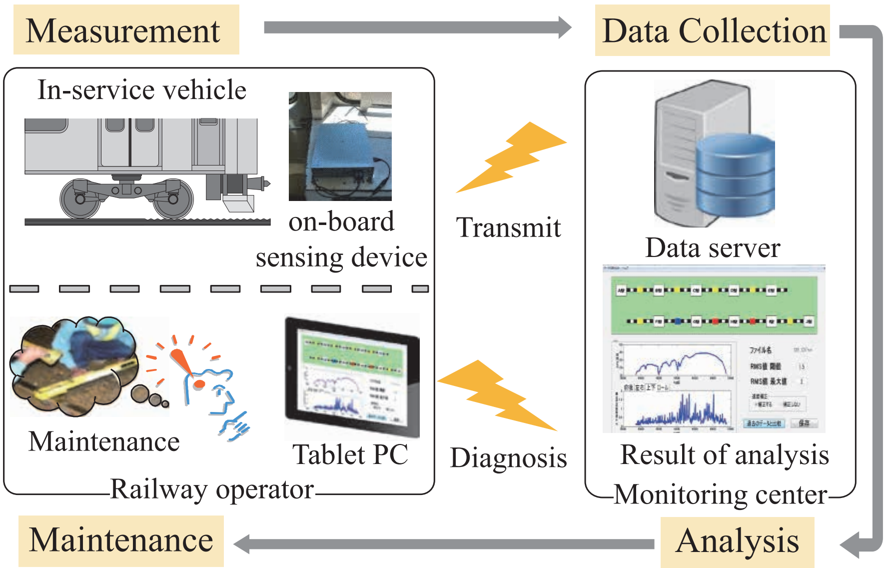

Fig. 6 Track condition monitoring system using in-service vehicle

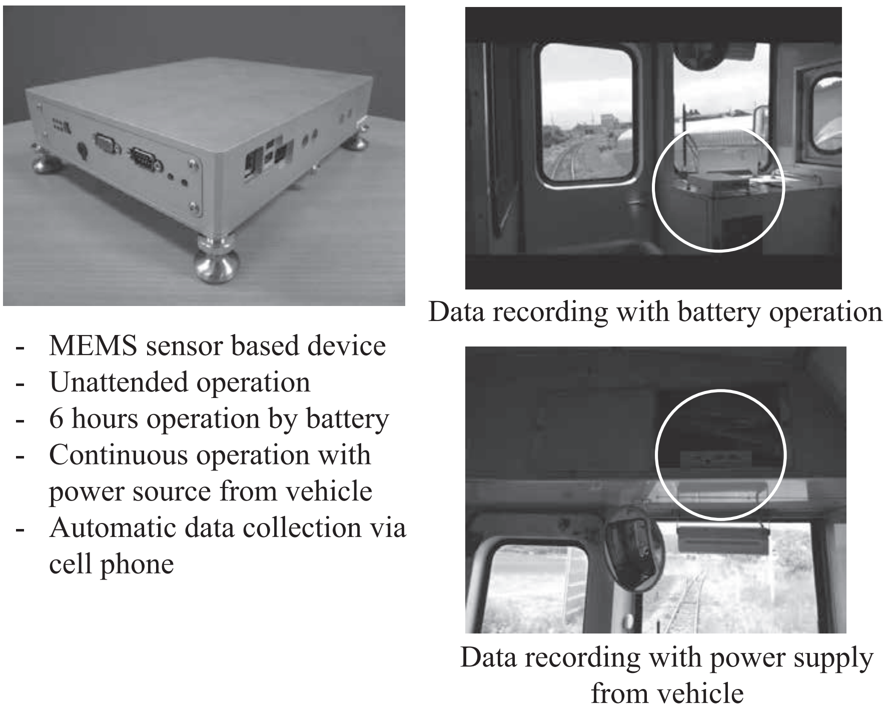

Fig. 7 On-board sensing device

transform were employed to identify track faults[31, 32].

The measured data obtained from the measurement unit are transmitted to the analysis unit either by a cellular telephone channel or by writing to external media. **Figure 8** shows an example of track condition analyzed from the automatically collected data. The track condition is indicated by color according to the degradation level for every 10m sections. The number of times where vehicle vibration level exceeds the limit are calculated and normalized by the total number of runs (lower part of Fig. 8 (b)). This figure is used for identifying the section where continuous monitoring is necessary.

The diagnostic results, Fig. 8, produced by the track monitoring software are used to provide feedback to railway operators through online channels via smart-

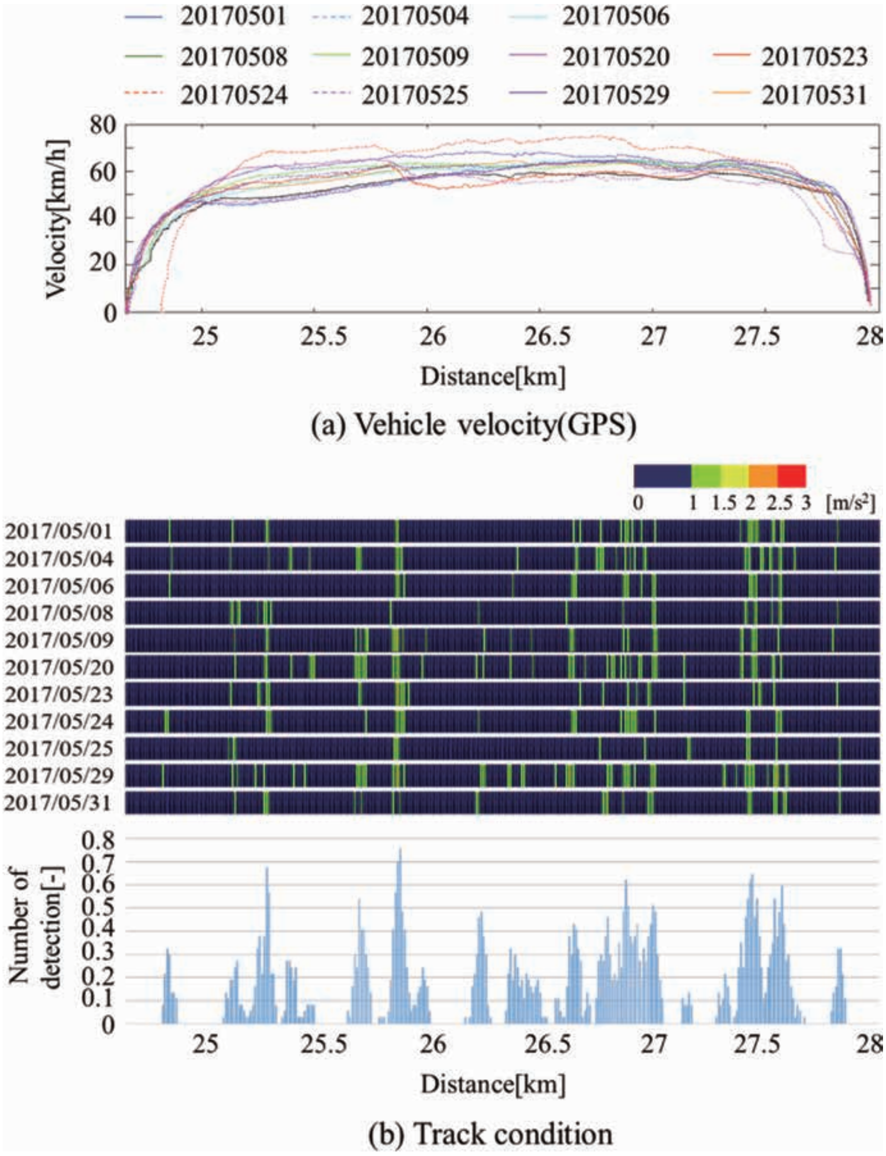

Fig. 8 Results of track condition monitoring for a regional railway

phones or tablet computers. Railway operators can use this information to establish the track maintenance priorities, thus facilitating the maintenance planning and work.

In addition, the real-time measurement of vehicle vibrations during commercial operation allows for rapid response, such as emergency track inspection and maintenance, in situations when vehicle vibration observations detect irregularly large deviations from standard control values. Thus, the use of this monitoring system to perform continuous monitoring of vehicle vibrations allows early detection of deterioration or other track irregularities, thus enabling railway operators to conduct effective maintenance work. Some sections, which exceed the limit of RMS value of acceleration, were targeted as the intensive monitoring section. After the maintenance work in the sections, the quality of the maintenance work can be evaluated by this system.

Introducing the system for many regional railway lines, we can establish the monitoring center, as shown in **Fig. 9**, that can monitor the track condition all the time. We can manage the monitoring information to plan the effective maintenance work.

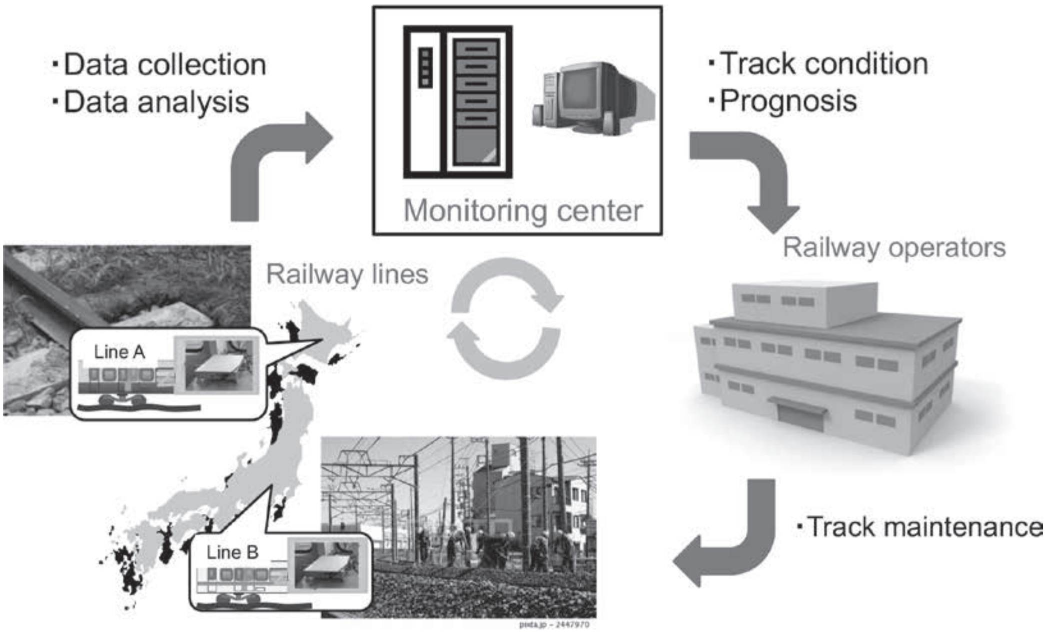

Fig. 9 Track condition monitoring by monitoring center for regional railways

4. Summary

This paper summarizes the application of condition monitoring technologies to vehicle suspensions and railway track. After the description of the applicable technologies, concepts and implementation status, the key trends appeared in recent international railway conferences and journals are commented. Many approaches in condition monitoring are newer, but have been developing rapidly. It is important to have systems that provides useful diagnosis, in particular for condition-based maintenance.

References

1) Patton, R. J., Frank, P. M. and Clark, R. N., "Issues of Fault Diagnosis for Dynamic System," Springer, 2000.
2) Bruni S, Goodall R, Mei TX and Tsunashima H. "Control and monitoring for railway vehicle dynamics," Vehicle System Dynamics, 45:743–799, 2007.
3) Goodall R. M. and Roberts, C., "Concept and Techniques for Railway Condition Monitoring," The International Conference on Railway Condition Monitoring 2006: 90-95, 2006.
4) http://shinsen. biz/stech2015/
5) Charles, G., Goodall, R. and Dixon, R., "Wheel-Rail Profile Estimation," International Conference on Railway Condition Monitoring 2006: 32-37, 2006.
6) Charles, G. and Goodall, R., "Low Adhesion Estimation," International Conference on Railway Condition Monitoring 2006: 96-97, 2006.
7) Li, P., Goodall, R. and Kadirkamanathan, V., "Estimation of parameter in a linear state space model using a Rao-Blackwellised particle filter," IEE Proc.-Control Theory Appl., Vol. 151, No. 6: 727-738, 2004.
8) Alfi, S., Bruni, S., Mazzola, L. and Bionda, S., "Model-based fault detection in railway bogies," Proceedings of the 22nd IAVSD Symposium, 2011.
9) Jesussek, M. and Ellermann, K., "Fault detection and isolation for a nonlinear railway vehicle suspension with a Hybrid Extended Kalman filter," Vehicle System Dynamics, 51:10: 1489-1501, 2013.
10) Liu, X. Y., Alfi, S. and Bruni, S., "An efficient recursive least square-based condition monitoring approach for a rail vehicle suspension system," Vehicle System Dynamics, 54:6: 814-830, 2016.
11) Mori, H. and Tsunashima, H., "Condition monitoring of railway vehicle suspension using multiple model approach," J Mech Syst Transp Logist., Vol. 3, No. 1: 243-258, 2010.

12) Jesussek, M and Ellermann, K., "Fault detection and isolation for a full-scale railway vehicle suspension with multiple Kalman filters," Vehicle System Dynamics, 52:12: 1695-1715, 2014.
13) Xia, F., Cole, C. and Wolfs, P., "A method for setting wagon speed restrictions based on wagon responses," Vehicle System Dynamics Supplement 44: 424-432, 2006.
14) Matsumoto, A., Sato, Y., Ohno, H., Tomeoka, M., Matumoto, K., Kurihara, J., Ogino, T., Tanimoto, M., Kishimoto, Y., Sato, Y. and Nakai, T., "A new monitoring method of train derailment coefficient," International Conference on Railway Condition Monitoring 2006: 136-140, 2006.
15) Iwamoto, A., Matsumoto, K., Yano, K., Fukushima, T., Matsumoto, A., Sato, Y., Ohno, H., Michitsuji, Y., Tanimoto, M. and Shinagawa, D., "Monitoring of Derailment Coefficients "Y/Q" for In-service Trains and the Analysis for the Increase of Curve Safety," Proceedings of the Third International Conference on Railway Technology: Research, Development and Maintenance, Paper No. 64, 2016.
16) Fukushima, T., Yano, K., Iwamoto, A., Matsumoto, K., Matsumoto, A., Tanimoto, M., Michitsuji, Y., Sato, Y., Mizuno, M. and Shinagawa, D., "Derailment Coefficient Data for Commercial Lines Measured by PQ Monitoring Bogies and Methods of Application," Proceedings of International Symposium on Speed-up and Sustainable Technology for Railway and Maglev Systems 2015 (STECH2015), November 10-12, 2015.
17) Sakamoto, M., Lin, S., Suda, Y., Kageyama, M., Koga, S., Kunimi, T. and Kawabe, T., "Study on Improved Sign Detection System of Flange-Climb Derailment by Real Bogie Flange-Climb Experiment," Proceedings of International Symposium on Speed-up and Sustainable Technology for Railway and Maglev Systems 2015 (STECH2015), November 10-12, 2015.
18) Boronenko, Y., Orlova, A., Iofan, A. and Galperin, S., "Effects that appear during the derailment of one wheelset in the freight wagon - simulation and testing," Vehicle System Dynamics Supplement 44: 663-668, 2006.
19) Hubacher W. and Scheiber P., Derailment detector systems for CFF/SBB rolling stock, Rail International, Vol. 31, pp. 31-37, 2000.
20) Koga, S., Miyakawa, K., Kageyama, M. and Shimada, N., "Development of a Vehicle Abnormal Behavior Detection System," Proceedings of the Third International Conference on Railway Technology: Research, Development and Maintenance, Paper No. 78, 2016.
21) Hubbard, P., Ward, C., Dixon, R. and Goodall, R., "Real time detection of low adhesion in the wheel/rail contact," Proc IMechE Part F: J Rail and Rapid Transit, 227(6): 623–634, 2013.
22) Zhao, Y., Liang, B. and Iwnicki, S., "Friction coefficient estimation using an unscented Kalman filter," Vehicle System Dynamics, 52:sup1: 220-234, 2014.
23) Weston, P., Roberts, C., Yeo, G. and Stewart, E., "Perspectives on railway track geometry condition monitoring from in-service railway vehicles," Vehicle System Dynamics, 53:7: 1063-1091, 2015.
24) Weston, P. E., Ling, C. S., Goodman, C. J., Roberts, C., Li, P. and Goodall, R. M., "Monitoring vertical track irregularity from in-service railway vehicles," Proc Inst Mech Eng Part F, J Rail Rapid Transit; 221(F1):75–88, 2007.
25) Weston, P. E., Ling, C. S., Goodman, C. J., Roberts, C., Li, P. and Goodall, R. M., "Monitoring lateral track irregularity from in-service railway vehicles," Proc Inst Mech Eng Part F, J Rail Rapid Transit; 221(F1):89–100, 2007.
26) Alfi, S. and Bruni, S., "Estimation of long wavelength track irregularity from on board measurement," Proceedings of the 4th IET international conference on railway condition monitoring (RCM2008), 2008.
27) Tsunashima, H., Naganuma, Y. and Kobayashi, T., "Track geometry estimation from car-body vibration," Vehicle System Dynamics, 52:sup1: 207-219, 2014.
28) Naganuma, Y, Azami, S. and Tsunashima, H., "Track Geometry Estimation from Car-body Motions of Shinkansen Vehicles," Proceedings of International Symposium on Speed-up and Sustainable Technology for Railway and Maglev Systems 2015 (STECH2015), November 10-12, 2015.
29) Tsunashima, H., Naganuma, Y., Matsumoto, A., Mizuma, T. and Mori, H., "Japanese railway condition monitoring of tracks using in-service vehi-

cle," Paper presented at the 5th IET Conference on Railway Condition Monitoring (RCM 2011), 2011.

30) Schwanen W. and Kuijpers, A., "Early Rail Defect Detection using Sound Measurements," Proceedings of the Third International Conference on Railway Technology: Research, Development and Maintenance, Paper No. 170, 2016.

31) Tsunashima, H., Mori, H., Ogino, M., Azami, S. and Asano, A., "The Application of an On-board Track Condition Monitoring System for Local Railways," Proceedings of the Third International Conference on Railway Technology: Research, Development and Maintenance, Paper No. 65, 2016.

32) Liang , B., Iwnicki , S. D., Zhao, Y. and Crosbee, D., "Railway wheel-flat and rail surface defect modelling and analysis by time–frequency techniques," Vehicle System Dynamics, 51:9: 1403-1421, 2013.

鉄道の状態監視の現状と地方鉄道への展開

綱島　均

概　　要

鉄道施設の状態監視は，鉄道の安全性を確保する上で重要である。状態監視は，これまでに様々な研究が行われてきた異常検知・分離（Fault Detection and Isolation or Identification: FDI）の一分野であると考えられる。状態監視は，主として，時間とともに状態が劣化するシステムに適用可能である。状態監視の主目的は，故障が発生する前に異常を検出し，その原因を特定することにある。本稿では，状態監視技術の車両，軌道系への応用に関して解説する。理論，概念と実用状況，地方鉄道への展開について，最近行われた鉄道の国際会議における主要なトレンドをもとに総括する。

Biographical Sketches of the Author

Prof. Dr. Hitoshi Tsunashima is a professor and the director of Railway Research Center, College of Industrial Technology, Nihon University. His main research expertise includes condition monitoring of railway, multi-body dynamics, human factors and ergonomics. His major research activities are condition monitoring of railway system, application of multiple model approach for vehicle state estimation and control, measurement of brain function using NIRS, Brain-Computer interface (BCI) using NIRS.