Railway Condition Monitoring, Present and Application for Regional Railways

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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). 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. 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).

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.

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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 \( u \) and outputs \( y \) 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 \( u \) 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 \( y \) is used as an input to estimate input \( u \)).

If only outputs \( y \) 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.
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 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?

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

Fig. 4 Input and output relation in railway condition monitoring
- 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

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. 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.

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. Jesussek et al. proposed hybrid EKF to isolate the faults occurring in lateral suspensions. Liu et al. 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. 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.

3.2 Detection of improper running conditions

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-
ment prevention has been studied under this perspective. Xia et al.\textsuperscript{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.\textsuperscript{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\textsuperscript{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\textsuperscript{16}). A detection system, that detects abnormal conditions leading to the flange-climb derailment in sharp curves, is described\textsuperscript{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. Bondarenko et al.\textsuperscript{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.\textsuperscript{19}) to activate emergency braking in freight trains. The development of a vehicle abnormal behavior detection system is described by Koga et al.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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\textsuperscript{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.\textsuperscript{24, 25}) demonstrated the track irregularity monitoring using bogie-mounted sensors. Alfi et al.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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\textsuperscript{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
transform were employed to identify track faults\textsuperscript{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-
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.
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.

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鉄道の状態監視の現状と地方鉄道への展開

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.