한국정밀공학회지 제 30 권 7 호 pp. 667-672
July 2013 / 667
J. Korean Soc. Precis. Eng., Vol. 30, No. 7, pp. 667-672
http://dx.doi.org/10.7736/KSPE.2013.30.7.667
ISSN 1225-9071(Print), ISSN 2287-8769(Online)

◆ 특집 ◆ 철도차량 구동장치의 모니터링 기술

고속열차용 감속기 모니터링 시스템 개발

Development of Condition Monitoring System for Reduction Unit of High-speed Rail

이동형 [1,✉], 권석진 [1], 박병수 [2], 조덕영 [3], 김진우 [4]
Dong-Hyong Lee[1,✉], Seok Jin Kwon[1], Byoung-Su Park[2], Duk-Young Cho[3], and Jin-Woo Kim[4]

1 한국철도기술연구원 고속철도연구본부 (High-speed Railroad System Research Center, Korea Railroad Research Institute)
2 케이티엠엔지니어링㈜ 연구소 (Research Center, KTM Engineering Inc.)
3 ㈜솔지 연구소 (Research Center, Solge)
4 한국철도공사 기술연구처 (Research Center, KORAIL)
✉ Corresponding author: dhlee@krri.re.kr, Tel: +82-31-460-5246

Manuscript received: 2013.5.20 / Accepted: 2013.6.20

This paper presents the development of a condition monitoring system that monitors the operating conditions of a reduction unit, such as the bearing temperature, gearbox vibration, and gear oil deterioration, and notifies the operator of potential problems or abnormal conditions. A series of field tests on high-speed rail and conventional lines was performed to identify the characteristics of temperature rise and vibration levels on the reduction unit during operation. The monitoring system was designed based on the proper sensor selection, measurement method, and signal analysis to optimize the interface with the operating system of high-speed trains. Application of this monitoring system to high-speed trains will play an important role in their proper maintenance and safe operation.

Key Words: Condition Monitoring (상태 감시), Reduction Unit (감속기), Abnormal Condition (이상상태), High-speed Rail (고속철도), Vibration (진동)

1. Introduction

The reduction unit or gearbox is equipment used for high speed railway vehicles to transmit motor’s torque to the wheelset, and is one of the major devices permitting the vehicle to run at high speed.

The load applied to the reduction unit during high speed train operation is very large, so the safety and durability of the gears and the reliability of each component are very important. If some faults occur with the reduction unit, the vehicle operation must be stopped. Daily maintenance is thus required and the components of reduction unit must be completely disassembled every 3 years for repair to prevent accidents.

A safety system is installed in the high speed rail to warn of major equipment failure and provide data on the vehicle operating condition. However, there is no safety system concerning the reduction unit, so a risk of accidents always exists. Therefore, recently, a system to monitor abnormal conditions of reduction unit and bogie system in high-speed trains is under development.[1]

The Multilog Online System[2] is an online monitoring system for railway vehicles developed by SKF, based on the online condition monitoring system applied to wind turbines and gearboxes. This system aims to reduce maintenance costs and improve the reliability and safety of railway vehicles. It monitors and alarms those items which could be damaged such as the axlebox bearing, wheel flats, bogie stability and propulsion system condition, e.g. traction motors, gearboxes and cardan shafts. COMORAN® (Condition Monitoring for Railway Applications, KNORR-BREMSE)[3] is a bogie monitoring and diagnostic system built into the railway brake system. This system can monitor and diagnose important items related to safety, such as axlebox bearing, unstable running and derailment. This type of monitoring system is installed on the bogie system and can be monitor representative items of the running system, but it is impossible to perform more detailed monitoring and diagnosis for the reduction unit.

In this paper, we develop online condition monitoring system which can monitor operating state of the reduction unit and notify the situation to operator in case abnormal condition occurs in reduction unit for safe operation of high-speed train. A series of field running test on the high speed and conventional line was performed in order to identify characteristics of temperature rise and vibration change on the reduction unit. In addition, the study for proper sensor selection, measuring method and signal analysis method to apply monitoring system has been carried out and hardware and software, which can interface with operating system of high speed trains, was built.

2. Structure and Damage Characteristics

2.1 Structure

The reduction unit on high-speed train (KTX) is installed between the motor and wheelset to transmit power from the motor to the wheel. The high-speed trainset consists of a total of 12 reduction unit, which is mounted on the motor bogies. The reduction units for high-speed railway vehicle are designed by applying parallel cardan drive system and consist of a Motor Reduction Unit (MRU) and a Axle Reduction Unit (ARU), and a tripod shaft delivering power between the MRU and ARU as shown in Fig. 1.

The MRU is connected to the motor and has an idle gear assembled between the pinion and gear to achieve

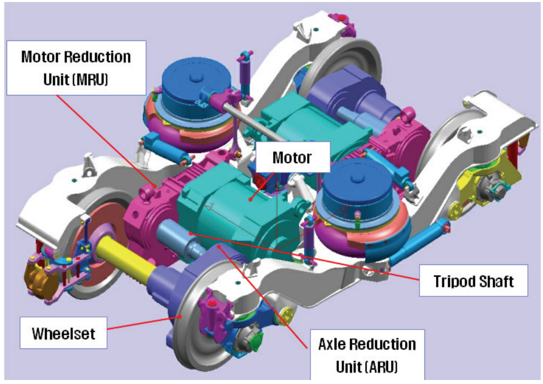


Fig. 1 Schematic view of reduction units, motor and bogie for Korea high-speed rail

adequate separation of centerlines of the motor and output shafts. The gear used in the MRU is a helical gear with a module of 7, a helix angle of 15° and gear ratio of 1.89 (tooth number ratio 41/27 x 51/41).

The ARU is assembled on the axle shaft and is connected to the MRU with a tripod shaft, which transmit torque from a MRU to an ARU. The gear used in the ARU is a spur gear with a module of 8 and a gear ratio of 1.16 (tooth number ratio 51/44). The gearboxes are lubricated with oil bath method, which is rotating gears splash lubricant onto the gear system and bearings.

2.2 Failure and Damage

Because the reduction unit used for railway vehicles is subjected to impact loads by rolling contact between wheel and rail, the impact acting on the gears and bearings are very large compared with the general industrial gearbox. Therefore major damage to the reduction unit of railway vehicle occurs with gears and bearings. For reduction unit of high speed train operating in Korea (KTX), damage, including MRU gear shaft deviation, gear contact fatigue, and input gear shaft failure are of concern.[4]

One example of high speed train reduction unit damage (Shinkansen, Nozomi) in Japan is case failure. Vehicle operation was stopped upon detection of white smoke during service, and an investigation revealed that the reduction unit was damaged as a result of damage to the bearings. Railway service was suspended for over 3 hours as a result.

Another example of train accident due to damage of reduction unit is the derailment of a diesel car in England.[5] The vehicle derailed due to the complete fracture of axle assembled with reduction unit during vehicle service at 151 km/h. The main cause of axle failure was a bearing failure by loose fit between the gear-side output bearing and axle which preceded the overheating of the axle. Railway service was suspended for 50 hours to repair the sleepers and railway tracks damaged in this accident.

3. Development of Condition Monitoring System

The components that damage occurs mainly in gearbox, as shown in Fig. 2, are gear tooth, gear case, bearing, shaft, bolt, and oil.[6] If defects occur to one of these components in gearbox during operation, the gearbox exhibits abnormal conditions such as an increase in noise and vibration, temperature rise and lubrication leakage etc. Therefore, measuring these abnormal conditions with the help of various sensors is one of the best methods for condition monitoring[7] and damage identification of industrial gearboxes. For condition monitoring of reduction unit in high speed railway, vibration of gear case, temperature rise of bearing cover and deterioration of lubrication were selected as the monitoring signal. Noise from gearbox was excluded from the measuring parameter because most of the noise in bogie is generated from wheel-rail rolling contact. A detail description for each monitoring signal adopted in condition monitoring system of reduction unit on high-speed rail is as follows.

3.1 Temperature Monitoring

Generally, heat in the reduction unit is generated by gear contact friction, friction between lubricant and gears, oil churning and friction between oil seal and shaft, and some heat is dissipated to the outside of gear case. The temperature of reduction unit in operation will increase excessively mainly due to bearing damage or lack of lubricant and this abnormal temperature rise can be detected by the monitoring system.

The temperature rise of reduction unit mounted on the Korea high-speed rail (KTX) in service was measured in order to review the operating conditions of temperature monitoring system. Fig. 3 shows the test result of

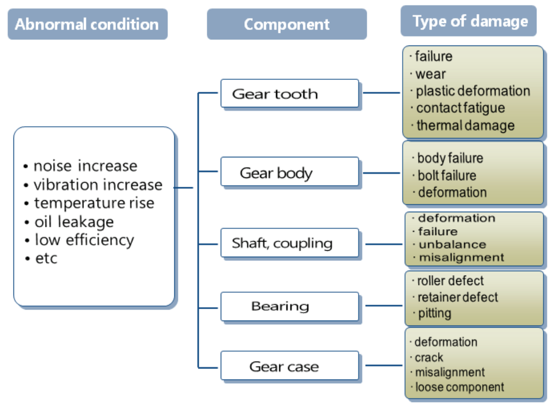


Fig. 2 Some typical damage and abnormal condition in gearbox

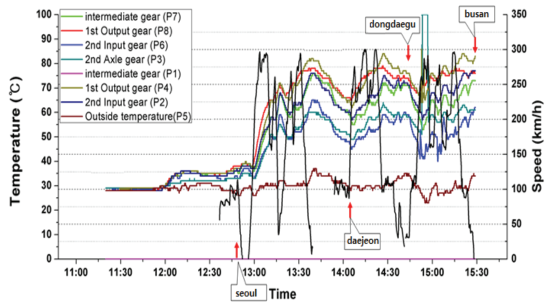


Fig. 3 Temperature rise in the reduction unit in Gyeongbu line

temperature rise measured on the bearing cover of reduction unit while the vehicle was in service on the Gyeongbu Line. The test result show that as the vehicle speed increase the temperature of bearing cover increase, and the maximum temperature occurs after the vehicle run its maximum speed. The highest temperature measured indicate 78℃ at the bearing cover of MRU idle gear, 83℃ at the bearing cover of MRU output gear, and 76℃ at the bearing cover of ARU input gear.

In technical specification of motor reduction unit and axle gear reduction unit on bench test, the stabilized temperatures at bearing cover and oil defined as not be exceeded 80℃ maximum considering ambient temperature.[8] So, the measuring range of temperature sensor was set to be a min. of -55℃ and a max. of 150℃. The IC type temperature sensor (AD590) is adopted in temperature monitoring system because it has advantage such as low price, linearity of data, and no additional

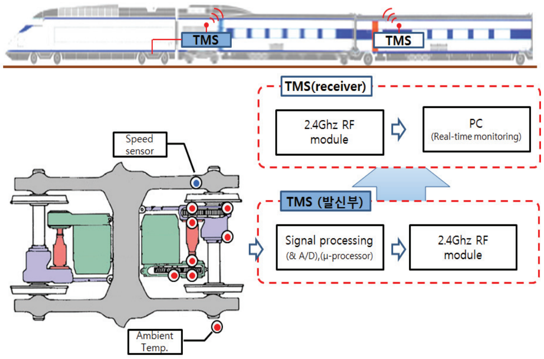


Fig. 4 Locations of temperature sensor and a system block diagram of temperature monitoring system

circuits, etc. The system was designed to measure temperature changes in reduction units and to transmit the temperature data wirelessly and to diagnose operating condition.

Fig. 4 shows the location of temperature measurement in reduction unit and a system block diagram. The temperature monitoring system consists of a sensor and a signal processing device (transmitter and receiver). The selected measurement locations include bearing cover of reduction unit, the gear oil and the ambient temperature. Device for signal processing is consist of current-voltage converter, Analog to Digital converter (ADC), μ-processor, wireless communication device, Universal serial bus (USB) interface device, display. The output current signal of the temperature sensor can be converted to the voltage signal and amplified using operational amplifier in accordance with changing temperature at every second. The amplified signal is converted to a 10bit digital code by analog to digital converter in the μ-processor (Atmega128) at conversion time of 260μs sampling per second. 2.4Ghz Transceiver RF Module at the lower part of a vehicle send the data to the receiver into carbody. Received data is transport to computer using Universal Serial Bus. Also, monitoring program with diagnosis algorithm can be analysis and save the abnormal condition of reduction gearbox units in real time.

3.2 Vibration Monitoring

In the reduction unit, vibration is always present under normal operating conditions; but the level of

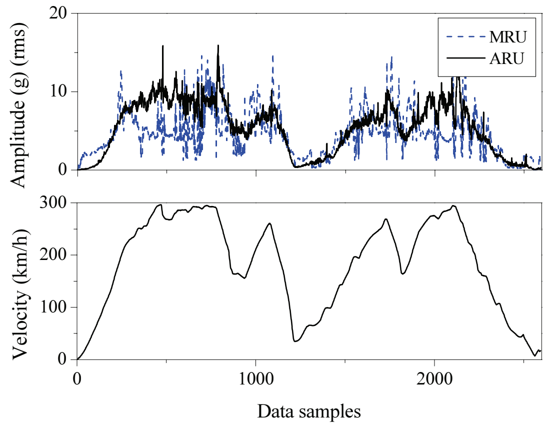


Fig. 5 Vibrations of reduction unit in Gyeongbu line (between Gwangmyung and Daejeon)

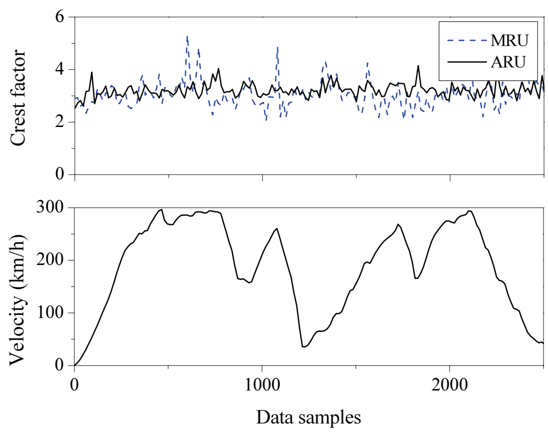
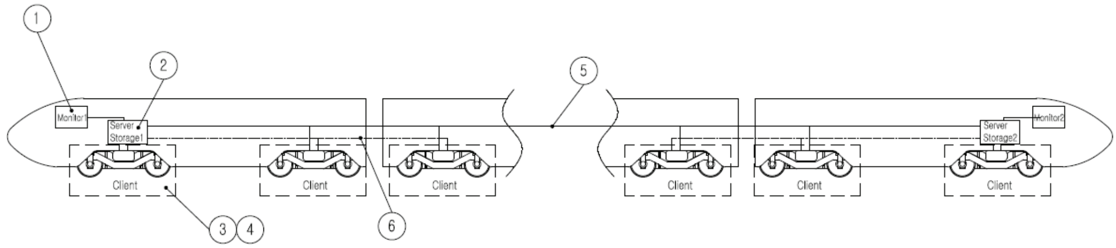


Fig. 6 Trend of crest factor of reduction unit vibration in Gyeongbu line (between Gwangmyung and Daejeon)

vibration usually increase with deterioration or fault of the machine component such as gear, bearing and shaft. Vibration from the gears may increased by gear wear, failure, surface damage, misalignment, and component resonance, while vibration from the bearings may increased by improper mounting, misalignment, improper lubrication, bearing fatigue, corrosion and foreign particle contamination. Therefore, it is possible to recognize the condition of reduction unit by continuous monitoring of vibration during operation.

A series of field running test on the high speed and conventional line was performed in order to identify the characteristics of vibration change on the reduction unit.



①: System Monitor, ②: Server Storage, ③: Sensor, ④: Client Box, ⑤: Lan Cable, ⑥: Power Cable, ⑦: Junction Box

Fig. 7 Schematic of vibration monitoring system

Fig. 5 shows the vibration levels produced by MRU and ARU during service on the high speed line between Gwangmyung and Daejeon. The vibration produced by the reduction unit shows a tendency that it is increase according as the vehicle speed increases and the level of vibration on ARU installed in an axle is greater than that on MRU. Since this level of vibration on time domain varies according to vehicle speed, it is difficult to set as a vibration criterion for abnormal conditions. Therefore, the dimensionless parameters such as crest factor or kurtosis are often used for condition monitoring.

Fig. 6 shows the level of crest factor on the high speed line between Gwangmyung and Daejeon. The crest factor (peak/rms) of reduction unit of high speed railway vehicle usually indicates a value between 3 and 5.

In addition, it seems more affected by railroad conditions than speed, because the peak value is larger during Honam Line service than Gyeongbu Line service. As a result of frequency analysis, the gear mesh frequency (GMF) was well observed for the MRU and ARU.

The vibration monitoring system consists of a sensor, client, and server as shown in Fig. 7. The vibration monitoring system uses an ICP type acceleration sensor considering the applicability, and monitors gearbox vibration in the vertical and axial directions. The client monitors the vibration state of each power bogie and reduction unit, and delivers the vibration data immediately by communicating with the server. The client is installed on the power bogie where the reduction unit is mounted, and measures data produced by 8 vibration channels in 4 reduction units, 1 bogie vibration channel and 1 axle speed channel per driving bogie. A total of 6 clients are installed per trainset.

The client analyzes the real-time vibration signal into vibration parameters and delivers the results to the server. Delivered vibration parameters include rms, Overall, Peak-to-Peak, 1x, GMF, Crest Factor, Envelope, BPFI (ball pass frequency inner) and BPFO (ball pass frequency outer). The Server is installed on the front and rear of the railway vehicles. One server carries out arithmetic operations and terminal and data storage, and the other server acts as a terminal only. The server synchronizes client access and collects the analyzed vibration parameter data via Ethernet. The server diagnoses machine operating conditions using the vibration parameter data received and displays the analysis result to the user.

3.3 Lubrication Monitoring

The physical and chemical characteristics of lubricant gradually change as a result of the heat produced by friction or contact between metal parts, metal abrasion particles, oxygen, and moisture in the air. If water is mixed into the lubricating oil, its viscosity gradually changes and the gear can become damaged, so water must be removed or gear oil shall be replaced. In addition, if the lubricating oil is insufficient through leakage, the lack of effective lubrication leads to mechanical wear or damage in reduction unit. It is therefore very important to continuously monitor the state of the lubricant to detect abnormal conditions in advance and also to extend component life of reduction unit.

In case of reduction unit of high speed railway vehicles, gear oil is periodically collected and analyzed to check oil condition, but oil deterioration is only determined through the quantity of iron, which is an abrasion component produced by contact between metal parts. This kind of component analysis requires expensive analysis equipment and takes a long time to perform. Therefore, a system to monitor oil conditions in real time by installing deterioration detection sensor in the reduction unit is developed.

The oil monitoring sensor was selected from among many commercial sensors after water, iron, temperature, and oxidation tests were conducted in the laboratory. The selected sensor (Argo-Hytos sensor) has a good result on correlation test with water, iron and oxidation, and it is suitable for reduction unit service conditions. The oil monitoring sensor is mounted to the oil injection hole because the process or drilling of gear case is not needed. The lubricant condition monitoring system was designed to send a warning signal if the permittivity and relative humidity are higher than the limit value. In addition, since the system can inform the remaining lubricant life by calculating its degradation level on the basis of temperature, electric conductivity and permittivity, the oil change or maintenance period can be more accurately estimated.

4. Conclusion

In this paper, a condition monitoring system of the reduction unit, which can monitor operating condition and notify the situation to operator in case abnormal condition occurs, is developed for safe operation of high-speed rails. The condition monitoring system consists of system to monitor bearing temperature, gearbox vibration and gear oil deterioration.

The temperature monitoring system consists of a sensor and a signal processing device (transmitter and receiver), and can monitor temperature of bearing cover, gear oil and ambient temperature of reduction unit. The vibration monitoring system consists of a sensor, client, and server, and monitors gearbox vibration in the vertical and axial directions. The client monitors the vibration state of each power bogie and reduction unit, and delivers the vibration data immediately by communicating with the server. The server diagnoses machine operating conditions using the vibration parameter data received and displays the analysis result to the user. The Lubricant condition monitoring system measures the permittivity and relative humidity of gear oil, notifies user a warning signal in the case of over limit value.

When this monitoring system is applied to the high speed trains, it can play an important role in safe operation of high-speed rail and the measured data from this are expected to be used as the basis data for the maintenance.

REFERENCE

1. Müller, L. and Sunder, R., "Onboard monitoring and diagnostics of bogies in high-speed trains," http://www.istec-gmbh.de/sites/default/files/Onboard%20monitoring%20and%20diagnostics%20of%20bogies%20in%20high-speed%20trains.pdf
2. Kure, G. and Schmiechen, R., "Solutions for railway bogie condition monitoring," Evolution magazine, No. 1, pp. 25-27, 2010.
3. Knor-Bremse Group, "COMORAN - Condition Monitoring for Railway Applications," 2010.
4. Jung, D., Lee, Y., and Kim, E., "A study of maintenance measures of the KTX decelerator," Proc. of the 2009 Spring Conference of the Korean Society for Railway, pp. 1191-1197, 2009.
5. Rail Accident Investigation Branch, "Passenger Train Derailment near East Langton," 2010.
6. JSME, "Design for Gear Strength," Jpn. Soc. Mech. Eng., 1991.
7. Nam, Y., Kim, H., Yoo, N., and Lee, J., "Development of a Wind Turbine Monitoring System using LabVIEW," J. Korean Soc. Precis. Eng., Vol. 20, No. 5, pp. 92-98, 2003.
8. Gec Alsthom Transport S. A., "Mounting Technical Specification: Motor Reduction unit and axle gear reduction unit," ST13-223-101, 1996.