CONTINUOUS MONITORING OF ESSENTIAL COMPONENTS AS A MEASURE TO INCREASE THE SAFETY OF RAIL TRANSPORT

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ABSTRACT

The paper looks at the essential components in rail transport such as Axles and Pantograph and gives the detail of the systems used in monitoring their operation. The continuously measured data such as Torque on the main gearbox shaft or load/acceleration on the Pantograph enables diagnostics of such systems on routinely operating trains. Variations from the expected values are being detected early and corrected to avoid compromising passenger safety.
A theoretical model is proposed which includes all the components in the traction system and their dynamic influence on each other. The model studies the traction system with the view on the interaction between the wheel and the rail interface.
The paper discusses the system designed for monitoring the transmitted torque and bending moments in the rail vehicle axle as a mean for identification of any abnormal loading.
Pantograph failures due to complex interactions between the overhead line (OHL) and pantograph structure cause significant problems to railway industry worldwide.
This paper also describes the design, development and test results from the first fully proven Pantograph Monitoring System which is now deployed on routinely operating trains in the UK.
In both applications monitoring data instantly captured by the embedded systems. The system uses two subcomponents: Digital Processing Module (DPM) and the Receiving Signal and Relay Unit (RSRU), which is installed in a secure location inside the carriage. The DPM uses Bluetooth communication to report any unexpected events to the RSRU, which is equipped with an on-board GPRS module to allow instantaneous access and remote interrogation from any location worldwide. The data collected will enable the reliability of the component under operation to be assessed.
Any high alarm events are instantaneously transferred to the train to warn the operator and the control centre about potentially harmful event which require immediate attention. This will in turn increase safety of the travelling passengers from any consequences of developing failures.
Keywords: bluetooth communication, bogie gearbox, condition monitoring, flat wheel, modelling rail–wheel interaction, monitoring system, pantograph failure, traction system.

1 INTRODUCTION

The development in the rail technology has created a relatively safe and economical transport system. The rail–wheel interface is considered to be a very important aspect of operation of any rail traction system. Problems such as rail head fatigues, rail surface spalling, rail surface roughness, wheel flats and other damage may lead to wide-spread damage in the rail–wheel interface resulting in an accident.

As the wheels in the bogie are driven by a motor through a gearbox, it becomes necessary to analyse the whole traction system to assess the interaction between the rail and the wheel. Any input force at the interface will influence the dynamics of the driving system which in turn would affect the behaviour of the rail–wheel contact.

There are different possibilities of failure on the rail as explained by Cannon [1]. The complete cross-section break may result from lower toughness due to cold weather and the fact that the longitudinal stress is large due to wheel sliding on the rail. The defect inside the rail head known as 'piping cavity' or a horizontal cracking with transverse cracking in the rail head

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usually results from manufacturing defect. Foot transverse fatigue cracks are usually initiated from galling [wear and corrosion] at a rail support [chair or base-plate]. The fatigue cracks are often difficult to detect and rail fracture commonly occurs as suggested by Cannon [1]. Another technique has been used in [2] to exploit the dynamic reaction between different vehicle modes caused by component failures in the system. This model, however, does not involve a complex mathematical modelling.

Wu et al. [3] says that wheel flats fatigue is caused by worn flats on the wheel tread. This kind of situation usually happens in conditions of poor adhesion at the wheel–rail interface, such as when leaves cover the railhead during the autumn. Wheel flats introduce a relative displacement input to the wheel–rail system in the same way as roughness causing high levels of noise or impact loading that leads to damage of the components. The impact from flats would increase the stress levels to twice the nominal wheel load. This in turn increases the contact pressure-Hertzian stress resulting in plastic yield in the rail–wheel material producing excessive noise and discomfort for passengers and eventually fast deterioration of the railway infrastructure.

The first section of this paper will deal with a theoretical model of the whole traction system. In the following section the most recent method for monitoring the power transmission from the motor to the wheels through the gearbox will be looked at. The proposed monitoring system will go in detail about torque measurement in the main shafts and the transmission of the measured data through telemetry.

Pantographs are the single contact point between the rolling stock and the catenary. Good contact must be maintained under all running conditions to make sure seamless collection of power. The higher the speed, the more difficult it is to maintain good contact.

In Europe the overhead line infrastructure is designed for lifespan of 30–50 years plus. This has resulted in the selection of specific materials such as pure carbon or copper and graphite impregnated carbon for the critical pantograph contact strips. However, these materials present the drawback of wearing very rapidly, increasing the need for intense regular maintenance.

Traditionally European railways support a maintenance strategy based on inspecting and replacing pantograph heads rather than focusing on the overhead infrastructure. Problems with overhead line during contact with the pantograph strip can promote wear and damage to the pantograph carbon element. There are reports of pantograph heads needing replacement after a single journey on high speed trains. Therefore, a monitoring system for an accurate identification of the overhead line geometry faults and their locations is extremely valuable. The method for continuous monitoring of the Pantograph load is discussed with details of the latest innovative data transmission.

2 MODELLING THE WHOLE TRACTION SYSTEM

A typical bogie system has been shown below which is used to carry the coach (Fig. 1).

The system is complicated with a gearbox located on the wheel axle asymmetrically. A motor fixed with bogie is connected to the gearbox. The bogie is supported by four pairs of springs and dampers on the wheels. The bolster springs [between bogie frame and bolster] allows the bogie to rotate relative to the train body, isolating the body from vibration generated by the bogie, and transmitted traction force from the bogie to the body.

Different models of the bogie have been studied. Figure 2 presented by Shimamune [4] shows a DDM (Direct Drive Motor) system for a JR East conventional commuter train.

In order to prevent the DDM from being rotated by reaction force, a link-like reaction force receiving rod is used to connect the motor enclosure with the bogie frame. This

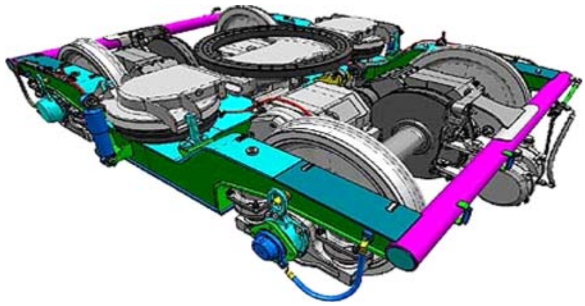

Figure 1: Typical bogie.

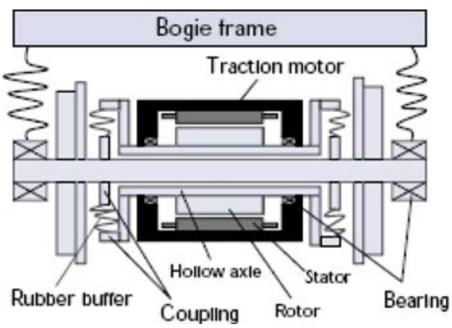

Figure 2: Typical model for bogie.

model focuses on rotation of the wheel axle, so that the system can be treated as a linear spring system.

Gearbox dynamics due to elasticity and backlash in the gear has often played an important role on the wheel axle between two wheels. The gearbox includes a gear which is fixed on the axle of the wheel shaft and pinion which is excited by asynchronous motor always engaged together inside the gearbox.

The proposed model of the bogie including all the components is shown in Fig. 3.

All the major components are marked. *X* and *Φ* indicate linear and angular displacement, respectively. Linear and torsional stiffness are shown as *k* and *K*, respectively, with mass moment of inertia as *J*.

The lumped mass parameter model proposed for the bogie is shown in Fig. 4.

Assuming m_1 and m_2 represent the effective mass of Left Hand Side (LHS) wheel and Right Hand Side (RHS) wheel, the equations for linear and angular displacement of LHS and RHS wheels could be written as below where suffix *w*, *sh*, *GB* indicate wheel, shaft and gearbox, respectively.

$$m_1 \ddot{x}_{w_1} = k_s \left(x_1 - x_{w_1} \right) + c_{w_1} \left(\dot{x}_1 - \dot{x}_{w_1} \right) - R_1 \quad (1)$$

$$J_{w_1} \ddot{\varphi}_{w_1} = -k_{w_1} \left(\varphi_{w_1} - \varphi_{GB} \right) - c_{sh_1} \left(\dot{\varphi}_{w_1} - \dot{\varphi}_{GB} \right) - T_1 \quad (2)$$

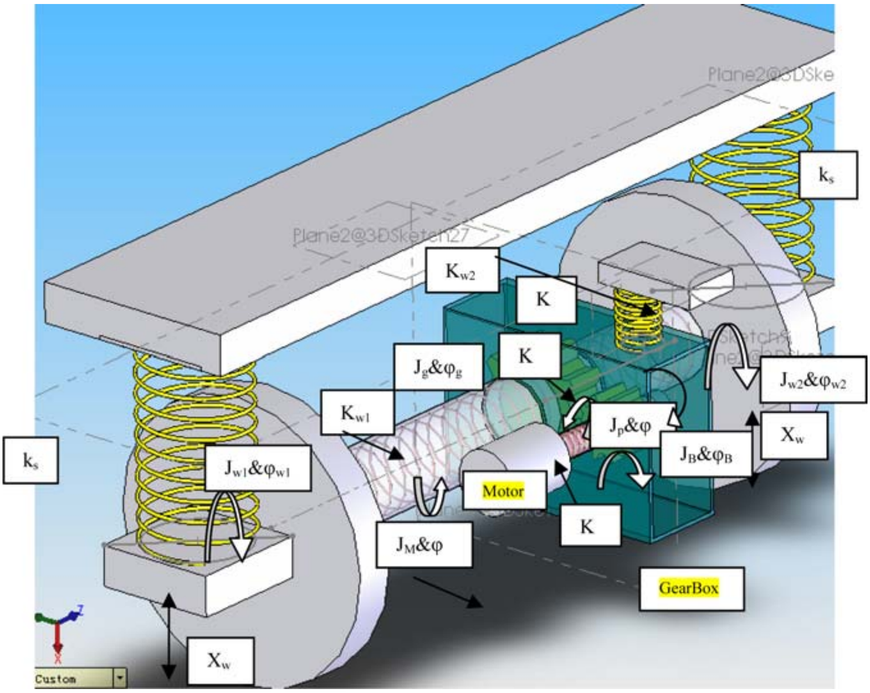

Figure 3: Arrangement of the components.

$$m_2\ddot{x}_{w2_1} = k_s\left(x_2 - x_{w_2}\right) + c_{w_2}\left(\dot{x}_2 - \dot{x}_{w_2}\right) - R_2 \tag{3}$$

$$J_{w_2}\ddot{\varphi}_{w_2} = -k_{w_2}\left(\varphi_{w_2} - \varphi_{GB}\right) - c_{sh_2}\left(\dot{\varphi}_{w_2} - \dot{\varphi}_{GB}\right) - T_2 \tag{4}$$

The reactions on rail–wheel interface R_1 and R_2 a contact stiffness between the two components is considered using the Hertzian constant.

Traction force T is affected by R_1 and R_2 and coefficient of friction μ.

$$T_1 = \mu R_1 \tag{5}$$

$$T_2 = \mu R_2 \tag{6}$$

The displacement of LHS Bogie x_1 and RHS Bogie x_2 can be written as:

$$M\ddot{x}_1 = -k_s\left(x_1 - x_{w_1}\right) - c_{w_1}\left(\dot{x}_1 - \dot{x}_{w_1}\right) \tag{7}$$

$$M\ddot{x}_2 = -k_s\left(x_2 - x_{w_2}\right) - c_{w_2}\left(\dot{x}_2 - \dot{x}_{w_2}\right) \tag{8}$$

The gear and pinion, connected by their teeth, can be modelled as a mesh spring system on the contact surface. The gear has a mesh stiffness k_m that comes from the connection between pinion and gear, angular rotation of gear is φ_g, pinion is φ_p, gearbox is φ_B, inertial of the gear is J_g, radius of gear is r_g, pinion is r_p.

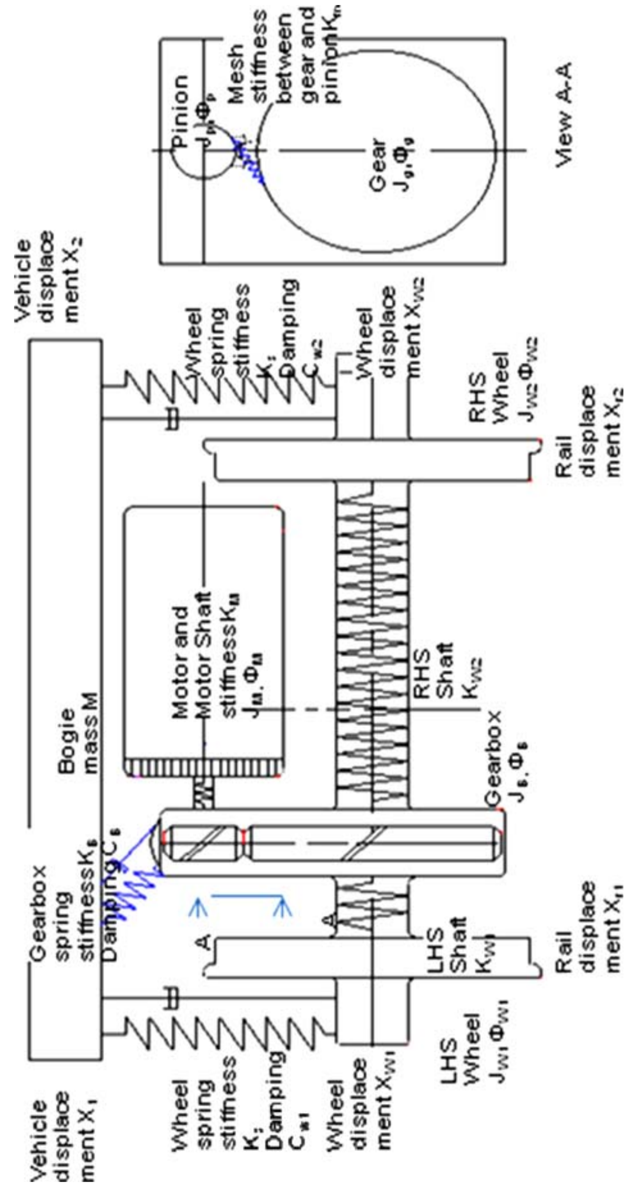

Figure 4: Proposed model.

$$J_g \ddot{\varphi}_g = -k_{w_1}\left(\varphi_g - \varphi_{w_1}\right) - c_{sh_1}\left(\dot{\varphi}_g - \dot{\varphi}_{w_1}\right) - k_{w_2}\left(\varphi_g - \varphi_{w_2}\right) - c_{sh_2}\left(\dot{\varphi}_g - \dot{\varphi}_{w_2}\right) - k_m r_g\left(\varphi_g r_g + \varphi_p r_p - \varphi_B r_g\right) \quad (9)$$

The pinion gets mesh stiffness k_m that comes from the connection between pinion and gear, angular rotation of gear is φ_g, pinion is φ_p, gearbox is φ_B, inertial of the pinion is J_p, and the tortional vibration from the motor.

$$J_p \ddot{\varphi}_p = -k_m r_p \left(\varphi_g r_g + \varphi_p r_p - \varphi_B r_g\right) + k_M \left(\varphi_M - \varphi_p\right) - c_M \left(\dot{\varphi}_p - \dot{\varphi}_M\right) \quad (10)$$

The motor is joined to the pinion by the motor shaft, which has the inertia J_M, and torsional stiffness K_M.

$$J_M \ddot{\varphi}_M = -k_M \left(\varphi_M - \varphi_p\right) - c_M \left(\dot{\varphi}_M - \dot{\varphi}_p\right) \quad (11)$$

There is a spring with the linear stiffness k_B and damping c_B between the bogie frame and gearbox itself; the inertial of the gearbox is J_B (Fig. 5).

Vertical mesh force $F_N = F_m$*cos20°; pressure angle between gear and pinion is 20°:

$$F_N = k_m r_g \left(\varphi_g r_g + \varphi_p r_p - \varphi_B r_g\right) \cos 20 \quad (12)$$

$$J_B \ddot{\varphi}_B = -k_B r_B \varphi_B - c_B r_B \dot{\varphi}_B - \frac{r_g}{r_B} F_N \quad (13)$$

The linear spring model of the whole system is therefore, defined by the equations given above using Matlab [5]. With the help of this model the effect of a flat wheel or imbalanced excitation at the motor could then be investigated.

3 MONITORING THE TRACTION SYSTEM

Health monitoring techniques are developed and refined through the past two decades in particular. Typically, vehicle health monitoring is designed in early stages to increase system availability by reporting vehicle operating health and specific subsystem faults to train operator and central control room [6]. For locomotives using diesel engines, various systems have been developed to collect data and diagnose faults with the aim of reducing vehicle maintenance [7].

For fault detection of vehicles, an interacting multiple-model algorithm has been used [8] where the simulation studies have been completed and field verification has been carried out. It is concluded that the vehicle faults, and in particular rail corrugation, can be detected effectively

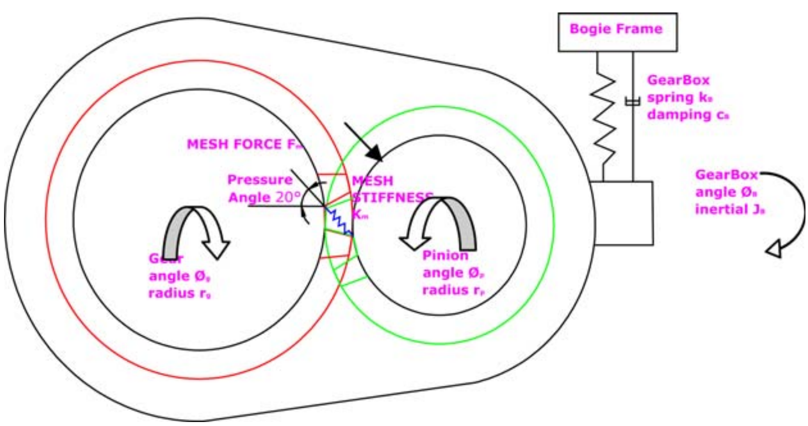

Figure 5: Interaction between gear and pinion.

using this method. Later work [9] has developed a portable condition monitoring system for use on in-service vehicles. The system is able to estimate the irregularities of rail from vertical and lateral acceleration of car body. A GPS system is also used together with to localise the fault on track and monitor developing faults.

Early work carried out in electrically noisy rail traction systems highlighted difficulties with torque measurements on the motorised axle sets resulting from significant Electromagnetic Interference. These initial difficulties prompted the development of miniature strain gauge amplifiers which can be positioned very close to the gauges, avoiding EMI caused by longer strain gauge wiring runs, and miniature telemetry systems designed to cope with the demanding environment. The first prototypes of these amplifiers and strain telemetry transmitters are shown in Figs 6 and 7.

These miniature strain gauge amplifiers and FM telemetry oscillators are a fully configured self-contained system, with stabilised strain gauge supply, strain gauge amplifier, voltage-to-frequency converter and a short-range FM transmitter, which include on-board filters designed for rejection of EMI. These systems can transfer FM data using capacitive, inductive and infra-red signal transmission. The main concept behind using these miniature systems is fitting them in very close proximity to strain gauges, which reduces noise pick-up from the connecting wires. It is noted that the small size of these systems (size of the complete PCB is

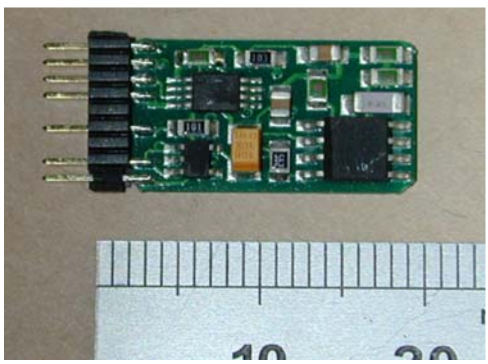

Figure 6: Miniature FM telemetry transmitter.

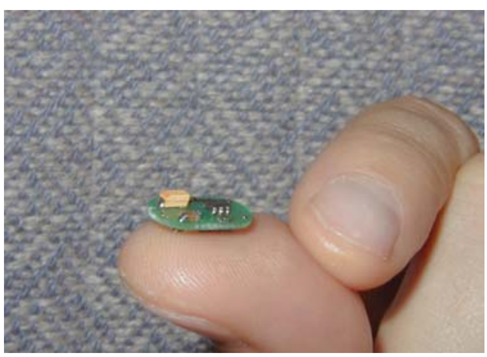

Figure 7: Miniature strain gauge amplifier.

similar to the size of the average strain gauge) allows a very compact and integral installation. A typical application of a short range telemetry system installed on a rail axle is shown in Fig. 8.

Transmission Dynamics (JR Dynamics Ltd) has developed a comprehensive range of miniature data loggers which are equipped with multiple options for long-term data logging, including Rainflow Count for fatigue life evaluation, Time at Level and Level Crossing. A unique and very useful feature of these data loggers is that they also record short bursts of time domain signal before and after high stress or acceleration events and store the 100 highest stress/acceleration events in a rolling stock which can be downloaded with the other logged data. In the simplest mode of operation these data loggers can operate as basic telemetry systems.

In a typical application the data loggers are programmed using a PC and are set to operate unattended for periods up to 4 years of continuous operation. Over recent years the size of the loggers has been significantly reduced, while their capabilities have increased. The overall size of today's data logger is 27 × 22 × 6 mm, which makes it ideal for application in restricted places and on rotating machinery. An example of an uncased current Radio Microlog with Rainflow and Time at Level analysis capability, and 100 × 4 s of highest signal time domain data storage (4 Mb on board memory capacity) with infra-red telemetry system for data downloading is shown in Fig. 9a and the system with radio communication is shown in Fig. 9b.

The data loggers are now so small that in practice the size of the final installation is governed entirely by the size of power supply. When the space is not critical and access is not restricted a battery operated system will offer a robust and practical solution. An example of such a system installed on a propeller shaft of a commercial vehicle is shown in Fig. 10.

When batteries cannot be easily changed or the system requires permanent power, an inductive power supply is recommended. A typical application showing a data logger powered by an inductive loop is shown in Fig. 11. This photo shows long-term data logger installation on a main torque tube of a 6 MW Gas Turbine powered generator, where the shaft runs at 1500 RPM.

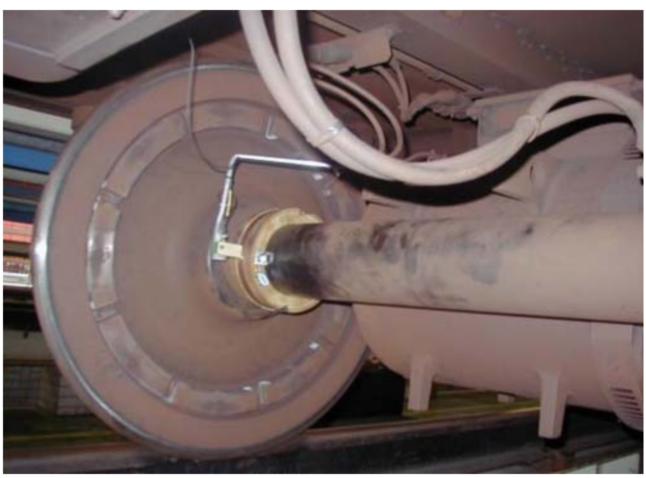

Figure 8: Short range FM telemetry installed on a motorised axle – Singapore.

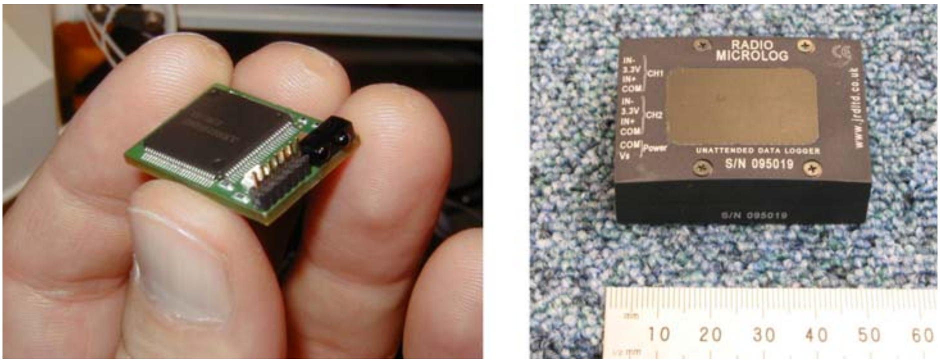

Figure 9: (a) Miniature data logger with infra-red communication. (b) Radio Microlog with digital radio communication.

Figure 10: An example of battery powered data logger fitted on a propeller shaft (shaft speed 4200 RPM, battery life 3 months, temperature range −30°C to +60°C) – China.

Inductive power supplies of this type have been used successfully at shaft speeds up to 25,000 RPM.

The miniature data loggers have been further developed with a fast integral digital communication link (Bluetooth) so that up to six loggers can be monitored and controlled from a CPU, which has GPS and GSM capability. This allows for the simultaneous recording of time domain data on all loggers when an extreme signal is detected by any one. With the GPS facility, the location of each extreme event (which is recorded as time domain data) is also

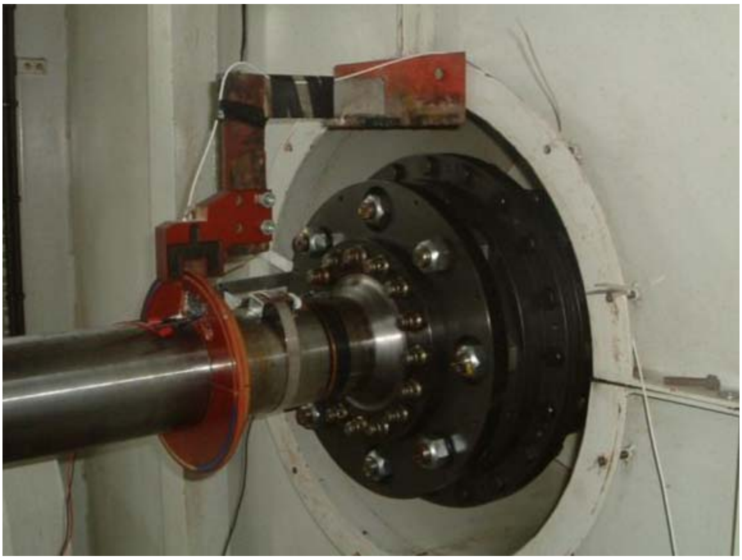

Figure 11: An example of inductively powered data logger fitted on a 6 MW generator torque tube – Bangladesh.

recorded. Finally, all these systems are re-programmable by radio communication making them extremely flexible in case of future software updates.

The use of these data loggers on railway applications is not only to acquire axle stress data but also to correlate this data with axle box acceleration, axle load, vehicle speed and train location on the track. A comprehensive Rail Axle Stress Monitoring (RASM) system typically consists of:

- Two axle stress data loggers fitted on one axle, measuring bending stress in two planes, and torsional axle stress (3-channel data logging).
- Four 2-axis acceleration data loggers fitted on each axle box on one bogie.
- Radio transceiver unit fitted centrally on a bogie, synchronising operation of six data loggers and the Central Processing Unit (CPU).
- CPU fitted in a convenient location within a vehicle, equipped with memory storage device (128 Mb MMC card), on board GPS system to accurately locate 'high' events (optional 2 m or 15 m positional accuracy) and GSM engine for continuous mobile network link (SMS messaging, uploading critical data, emergency calls, etc.).

A schematic view of the complete system is shown in Fig. 12.

Each of the six data loggers is programmed not only to perform Rainflow Count (counting fatigue or acceleration cycles) but also to acquire 100 highest events in the time domain, synchronised on all channels. By logging synchronised data from axle stress and axle box acceleration it is possible to correlate high axle stress events with vehicle operation and to study dynamic wheel–rail interaction.

With the rail axle data logging systems fitted on routinely operating trains it is possible to monitor critical sections of the track and to effectively determine track deterioration. Such data will greatly improve our understanding of axle stressing, and how this correlates with

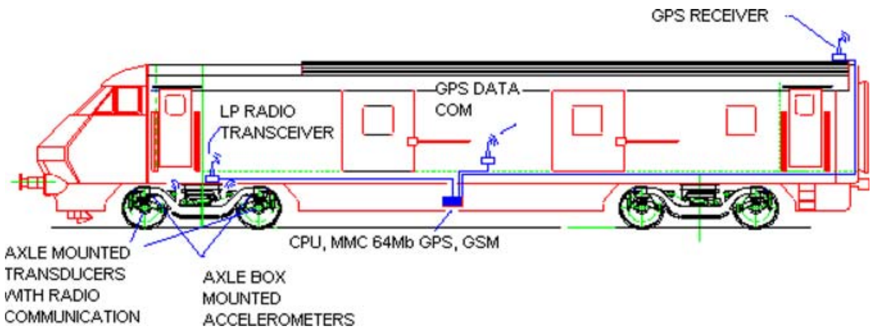

Figure 12: Rail axle stress monitoring system designed for application on routinely operating trains.

axle acceleration and track features. It provides useful data for both basic academic work, such as wheel–rail interface modelling, and also facilitates the development of more rational track maintenance criteria based on axle stress and wheel set acceleration limits.

4 PANTOGRAPH DAMAGE MONITORING

The background and state-of-the-art in pantograph monitoring is discussed in [10]. To ensure seamless collection of power, pantographs must maintain good contact with Overhead Line under all running conditions. The unstable current collection condition on overhead line caused by contact force fluctuation has been studied in [11]. This study confirms that the contact force amplitude has a correlation with conditions of the height profile of contact wires and the contact wire mechanical faults.

Due to the nature of the environment in which the Pantograph operates, it is very difficult to put any monitoring in place. Figure 13 show the role of the pantograph in connecting the supply from the overhead line to the train.

In Fig. 14, the close-up view of the pantograph is shown at the resting position. When the power is needed, the mechanism is raised until the carbon strips get closer to the overhead line making contact.

Taking measurements of the interaction between train pantograph and the overhead line catenary has long been a challenge to overcome the hostile environment and the problems of isolation. Such measurements require a telemetry system to transmit information from pantograph-mounted transducers, at a potential of 25 kV, to recording equipment located in the vehicle body.

Transmission Dynamics in conjunction with Serco Rail has developed and successfully implemented a Pantograph Monitoring System which is now deployed on routinely operating trains in the UK. The following section deals with the details of the components involved and typical signals used in on-line monitoring.

The Monitoring System uses two subcomponents. The first subcomponent is the Digital Processing Module (DPM) which is directly clamped on the live 25 kV pantograph structure as shown in Fig. 15. The DPM is interfaced with the accelerometers attached in vicinity of the carbon strip. The DPM houses integrated battery primary cells and is equipped with an array of three solar panels. Intelligent power management ensures that batteries are replaced only twice per full year of operation.

Figure 13: Pantograph connecting overhead to the train.

Figure 14: Close-up view of the pantograph.

Figure 15: Digital processing module.

The second subcomponent is the Receiving Signal and Relay Unit (RSRU) which is installed in a secure location inside the carriage. The DPM uses Bluetooth communication to report any unexpected events to the RSRU.

The DPM has an on-board GPS module and acquires and stores time domain data corresponding to 100 highest events captured during daily train operation. The data are downloaded to the RSRU on a daily basis. Any high alarm events are instantaneously transferred to the train to warn the operator and the control centre about potentially harmful events which require immediate attention.

The data collection showed that the signals were free from any electromagnetic interference. The typical signal from the two accelerometers on the carbon strip is shown in Fig. 16. It shows the acceleration caused by the impact load on the pantograph.

The instantaneous monitoring enables the 'hot spots' caused by overhead line to be mapped and trended to allow successful implementation of predictive maintenance of the Over-Heal Line (OHL) (Fig. 17).

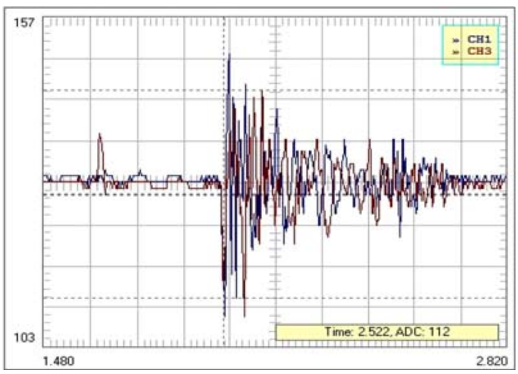

Figure 16: Signal from the accelerometer.

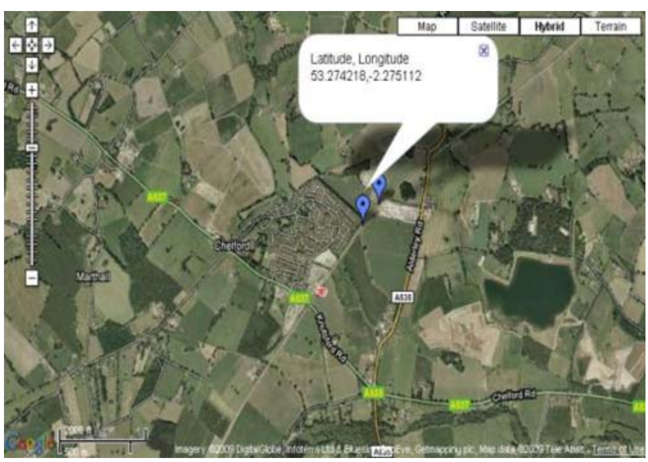

Figure 17: OHL fault location stamp.

The above described Pantograph Damage Monitoring System (PANDAS) has been extensively tested by independent laboratories to comply with Rail requirements and obtained both EMC and Vibration compliance approvals. Following more than 1 year of operation on routinely operating passenger trains the system is now approved by Network Rail for deployment on trains across the UK.

5 CONCLUSIONS

A computer model is presented for the traction system. It includes the interaction of the gearbox with the chassis as well as the interaction between the rail and the wheel. The model would enable the investigators to determine the response of each component for excitation from different sources.

The development of strain gauge instrumentation, telemetry systems and data loggers for demanding transport applications is illustrated by multiple examples showing implementation of miniature data loggers and strain gauge instrumentation on a wide range of components on the train. Based on this experience a modern Rail Axle Stress Monitoring system has been developed for application on the routinely operating trains. The system is now in regular service on the routinely operating Pendolino tilting trains operating in the UK. The system obtained Network Rail acceptance and is being deployed across the UK.

The Pantograph Damage Assessment System (PANDAS) described in this paper represents the newest developments in pantograph monitoring and it is now in routine operation. Its features are:

- Directly mounted on a 25 kV life pantograph;
- Bluetooth radio communication with train;
- On Board GPS for accurate event location stamp;
- Battery/Soar Panel Powered – long operation life;
- On board data storage and signal processing;
- Using two accelerometers and two ‘dummy’ channels;
- Overnight download of all events to train mounted SD memory card;
- Connected to GPRS mobile network for immediate access and interrogation;
- Remotely re-programmable via mobile network;
- Robust design – Proven in Service;
- EMI certified for operation in the demanding Rail Environment.

This innovative monitoring system reduces the maintenance costs not only for the pantograph but also for the overhead line electrical equipment.

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