Condition Monitoring of Audio Frequency Track Circuits

P. F. Weston, J. Chen, E. Stewart and C. Roberts
The Birmingham Centre for Rail Research and Education, Department of Electronic, Electrical and Computer Engineering, The University of Birmingham, Birmingham, UK

Abstract

Railways are expected to operate with ever increasing levels of availability, reliability, safety and security. One way in which high levels of dependability can be ensured is through the use of condition monitoring systems. This paper presents the initial results from operational trials of track circuit condition monitoring equipment installed at two TI21 audio frequency track circuits in the UK.

Introduction

A track circuit is a safety-critical asset. It is designed to be fail safe. A failure resulting in a section being indicated as occupied when it is not causes delays either while the fault is identified and corrected, or whilst it is worked around by talking drivers through the faulty section.

There is little published work on monitoring of track circuits in the field. One system available in the UK is described in [1, 2]. There is a move to introduce self-diagnostic features into track circuit systems in order to identify fault conditions or potentially incipient failures (failures that grow over time and can be detected before a fault occurs).

There are nearly 50,000 track circuits in operation on the mainline railway network within the UK. A number of different types of track circuit exist, including DC, AC and audio frequency jointless track circuits, such as TI21 and FS2550. Table 1 shows the number of track circuits installed in Network Rail’s Southern Zone together with typical failure statistics. From the table the average failure rate is around 45% per year per installation. Any track circuit failure can cause significant disruption to rail services and be a safety risk. Over 12,000 track circuit failures were reported in the UK during 2004–2005, resulting in 1.5 million minutes of delay. Typically, the infrastructure operators are penalised by £20–£60 per delay minute arising from infrastructure failure. Therefore, the ability to detect and diagnose track circuit failures in order to provide a fast response to failures/incidents has significant economic benefits.

<table>
<thead>
<tr>
<th>Track Circuit Type</th>
<th>Number</th>
<th>Failure reports per year</th>
<th>Failure Rate per year</th>
<th>Impact Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-TC</td>
<td>3,643</td>
<td>1264</td>
<td>0.347</td>
<td>158,000</td>
</tr>
<tr>
<td>TI21</td>
<td>1,326</td>
<td>524</td>
<td>0.395</td>
<td>65,500</td>
</tr>
<tr>
<td>FS2600</td>
<td>528</td>
<td>241</td>
<td>0.456</td>
<td>30,125</td>
</tr>
<tr>
<td>HVI TC</td>
<td>952</td>
<td>390</td>
<td>0.410</td>
<td>48,750</td>
</tr>
<tr>
<td>Reed TC</td>
<td>1,895</td>
<td>1304</td>
<td>0.688</td>
<td>163,000</td>
</tr>
<tr>
<td>Overall</td>
<td>8,344</td>
<td>3723</td>
<td>0.446</td>
<td>465,375</td>
</tr>
</tbody>
</table>

Table 1. Typical track circuit failure statistics

Audio track circuit operation

The principle of a track circuit is to detect the presence of a train by its wheelsets shorting out a signal transmitted along the rails to a distant receiver [7]. In TI21 jointless audio frequency track circuits, a carrier frequency $f_0$ is coupled into the track and detected at the receiver. In fact, the carrier frequency is modulated between $f_0 - 17$ Hz and $f_0 + 17$ Hz at a rate of 4.8 Hz as detailed in [4]. The receiver only accepts the received signal when the received current is high enough and the correct modulation pattern is observed. The frequencies along a track are assigned in pairs that are used alternately along the railway track. Transmitters and receivers are connected to the track via tuning units that incorporate an isolating transformer and other passive components designed to achieve two objectives. Firstly, to form a resonant circuit in combination with around 20 m of track, at the track...
circuit frequency, and secondly, to appear as a short circuit at the alternate frequency. The receiver observes the signal at its set frequency and only holds in signalling relay when the received current exceeds a certain level (and also subject to other conditions linked to the modulation pattern). The wheelsets of a passing vehicle divert the current from the receiver, causing the signalling relay to drop out. Different track circuit lengths are accommodated by changing the receiver gain.

**Instrumentation**

Track circuit voltages and currents can be directly measured using portable equipment, as used for installation and maintenance. The currents flowing in the tuned zones can be determined using equipment separated from the track by a small distance, either from the lineside [6, 2], or from a probe attached to a moving vehicle [5]. However, to understand the behaviour of real track circuits in the field, and to obtain long term data on two particular track circuit a more comprehensive fixed system is required. Based on the fault-detection requirements described in [3], two sequential track circuits have been instrumented in the UK, operating on two frequencies labelled ‘A’ and ‘B’. The transmitter voltages are measured as are the currents flowing between each tuning unit and the track, using clamp-on current probes. In addition, the state of the associated track circuit relays is also monitored, as well as the outside temperature. Rainfall is also monitored using local meteorological data. The monitored currents and voltage are spread out over a distance approaching 1 km, so some means of collecting and transmitting data is required. A CAN (controlled area network) bus with a 50 kbit/s data rate was used to network the measurement nodes. A cable carrying both power and differential data pairs was laid in the existing cable troughing along one side of the track. Fig. 1 shows the layout of the CAN nodes.

Several CAN node variants were constructed to form the monitoring system; all featuring a common microprocessor and CAN interface section. The simplest node measures temperature, consisting of a digital temperature measuring semiconductor linked directly to a microcontroller. Another type of node measures the CAN system supply voltage and current, using simple analogue to digital conversion on the microcontroller. More complicated nodes were developed to collect data over a range of
frequencies, as shown in fig. 2. In this type of node, the sensor signal is passed through a switched-capacitor bandpass filter with a Q of around 30. The actual centre frequency of the bandpass filter is under microcontroller control. The clocking frequency is fed back to the microcontroller for frequency measurement. When the centre frequency is changed, the microcontroller measures the clocking frequency while the signals in the bandpass filter, rms converter, and analogue to digital converter are allowed to reach steady state. The analogue signal path could be implemented using a digital signal processor, but the analogue electronics solution allows a simple microcontroller to be used in each node.

![Diagram of a variable frequency instrumentation node block diagram.](image)

A current CAN node takes in a voltage proportional to the current measured by a non-contact current sensor. The current sensor is clamped around a cable connecting a tuning unit to one of the rails. A voltage node sensor is made up of a galvanically isolated sensor connected to the transmitter terminals within a lineside cabinet. The output of this sensor is connected to a frequency-variable CAN node. The relay controlled by the receiver is monitored via spare relay contacts that are connected to a CAN node via an opto-isolation stage.

Two sequential track circuits have been instrumented, one operating at frequency ‘A’ and the other at frequency ‘B’. The ‘A’ and ‘B’ channel transmitter voltages are measured at their nominal frequencies, plus or minus 100 Hz. All currents are measured around both the ‘A’ and ‘B’ frequencies to obtain a picture of the current flows for both ‘A’ and ‘B’ channels at all locations. The outdoor temperature and rainfall are measured. Data captured by the nodes are transmitted on the CAN bus to a host CAN interface attached to a PC located in a lineside cabinet. For the initial instrumentation exercise, all the raw data collected by the nodes is saved. This raw data is being used to develop processing algorithms that will, at some later date, be incorporated into the nodes so that the amount of data generated will be much reduced.

**Data collection**

Voltage and current measurements are collected in two different ways depending on whether a railway vehicle is present on either of the two consecutive monitored track circuits. For the majority of time, the two track circuits are unoccupied (the two track circuit relays are held closed) and the centre frequency of the band pass filter is swept over the ‘A’ and ‘B’ frequency ranges for current nodes. For voltage nodes, either the ‘A’ or ‘B’ frequency range is covered, depending on the transmitter frequency. Whenever one or both of the track circuit relays is released, indicating the presence of a train in one or both track circuit sections, data are collected at one spot frequency for voltage nodes and at two spot frequencies for current nodes. This provides a more rapid sequence of data as a railway vehicle moves over the two track circuit sections.

**Data processing**

Data at each frequency are taken in approximately 40 ms. With approximately 150 readings being taken, covering a frequency range of the nominal centre frequency plus or minus 100 Hz, taking around six seconds and the signal being modulated at 4.8 Hz, the source frequency actually changes around 20 times during the frequency sweep. Some readings are taken while the transmitted frequency is constant, while others are taken as the signal frequency is changing. This results in the
rms signal measurement changing between two envelopes. This is shown in fig. 3, where there are plainly two bell shaped curves corresponding to the frequency response of the band-pass filter. The measurement data fall either on one curve or the other when the source signal remains on one frequency for the duration of the reading. Some points lie in between the two curves, indicating that the source signal changed frequency during the reading.

![Figure 3: Typical set of frequency/current data points.](image)

The shape of the bell curve is determined by the band pass filter built into the CAN nodes. The peaks of the two curves correspond to the centre frequency plus or minus 17 Hz. Hence the only parameters are the centre frequency and the heights of the two curves. The heights of the two bell curves are proportional to the rms level of the source signal at each of the two frequencies. While it is easy for the human eye to see two curves in fig. 3 and ignore the intermediate points, an algorithm is required to automate this process.

The way that curves were initially fitted is to assume that they have the form

\[ y_1 = \frac{a_1}{1 + \alpha(f - f_1)^2} \]  

\[ y_2 = \frac{a_2}{1 + \alpha(f - f_2)^2} \]

(1) (2)

where \( y_1 \) and \( y_2 \) represent the two curves as functions of frequency. The two frequencies \( f_1 \) and \( f_2 \) are assumed to be plus or minus 17 Hz from a central frequency \( f_0 \), which is to be estimated. Parameter \( \alpha \) determines the width of the bell curves and is determined by the Q-factor (quality factor) of the bandpass filter on the measuring node. This parameter is well known, the quality factor being set to \( Q=30 \). Hence, there are essentially 3 parameters to be estimated: \( a_1 \), \( a_2 \), and \( f_0 \). These 3 parameters are estimated by minimising a cost function that is the weighted sum of two parts. The first part is a measure of how well each point fits the two curves; either on the curves or between the curves is acceptable. No cost is associated with a point between the two curves, but a quadratic cost is associated with points lying outside of the curves. This is not, however, a sufficient definition of the
cost. If it were, then it would be possible for one curve to have a very large amplitude and the other to have a small amplitude such that all data points lie between the two curves and the cost is zero. The second part of the cost function is proportional to the square of the area between the two curves, the idea being to find a pair of curves that tightly contain the data points. A suitable weighting between the two components of the cost function has been found by trial and error. The cost function is given by:

$$J = w_1 \sum_i d_i (y_i - y_{i,j})^2 + w_2 \sum_i (y_{1,j} - y_{2,j})^2$$

(3)

Quantity $d_i$ is set to zero when the data point $y_i$ lies between the two curves and is set to 1 when the point lies outside of the two curves, the square of the distance to the nearest curve ($j=1$ or $j=2$) being used in the cost. The second part of the cost function is based on the distance between the two curves. The obtained curves for the data of fig. 3 are shown together with the original data in fig. 4.

![Figure 4: Data points from fig. 3 with fitted curves.](image)

In this example, the amplitudes of the two curves are nearly equal. However, if the two carrier frequencies are somewhat offset from the resonant frequency at the transmitter or receiver ends, then the amplitude of one curve will be increased while the other is decreased. The ratio of the two amplitudes is used later to indicate the extent of any mismatch between the transmitter frequency and the resonant parts of a track circuit.

The data points lying between the two curves arise when the transmitter frequency jumps by 34 Hz during the rms measurement, resulting in an rms level somewhere between the two curves depending on when the frequency switch occurred.

The remainder of the paper shows the results from data collected in the first few months of operation.
Initial results

The system has been returning data since 19 October 2007. At the time of writing (Jan 2008), only some of the data have been examined to ensure that the system is working, and to determine if any changes have occurred since the system was installed. The system was installed on track circuits that are well behaved and where installation was relatively simple. It is anticipated that another system will be installed at a location where problems are observed with the track circuits. The results shown below are taken from node 34 (0x22), the current sensor located on the lead connecting the track to one receiver tuning unit. This tuning unit acts as a short circuit to the 'A' frequency and as a receiver for the 'B' frequency. The effects of rainfall and temperature are of particular interest, as well as any long-term changes.

The first result is how rainfall affects the received ‘B’ frequency current. This is the current that falls dramatically when a railway vehicle enters a track circuit, diverting the current from the receiver. Fig. 5 shows the received current against time and also the hourly rainfall (divided by 2 to fit more conveniently on the diagram). Note that the rainfall information comes from a weather station located some miles from the test site. It is intended that local rainfall will be measured using a tipping rain gauge at a future date. The data are only shown when no vehicle is in the vicinity of the track circuit and 6 outliers (out of 6280 data) have been edited out.

![Figure 5: Average current amplitude against time and hourly rainfall against time.](image)

The current falls by about 10% when it rains, except when only 0.2 mm of rain falls in one hour. The quantity of rain does not seem to affect the current reduction. Following rainfall, the current recovers to the normal level over a period of between a few hours to nearly one day. It is just possible to make out a diurnal variation (7 cycles in each week) assumed to be related to temperature fluctuations.

The result is perhaps expected. Wet conditions could reduce the ballast resistance (the resistance between the rails), allowing more of the transmitted current to leak from one rail to the other and not reach the receiver end of the track circuit. The magnitude of the reduction on a different site, for example where concrete sleepers are in poor condition, may be different. The recovery to dry operation presumably occurs as the sleepers and ballast dry out. The invariance to the quantity of rain
may be because the site drainage is good and only water soaking into the surface of sleepers and on the surface of the ballast is important.

However, a more careful examination of the data shows that explanation in terms of a reduction in ballast shunt resistance is insufficient. Fig. 6 shows the received current and rainfall as in fig. 5, but with the transmitted current added.

![Graph showing transmitted current added to fig. 5.](image)

The figure shows that the transmitted current decreases during wet periods in a similar way to the received current. While the received current falls by approximately 10% during and following rainfall, the transmitted current falls only by 5%. The mechanism for the reduction in transmitted current has not yet been identified, but it is possible that the tuned zone has a more damped response caused by a reduction in shunt resistance when it is wet, causing a reduction in Q of the tuned circuit. A similar reduction in Q is possible in the tuned zone at the receiver end of the track circuit, further reducing the received current. Hence, a reduction in shunt resistance along the length of the track circuit may not be required to explain the observed current changes. An examination of an electrical model of the track circuit is needed to test this hypothesis.

The transmitted frequency continually switches between 17 Hz above and below the nominal centre frequency. The current measuring equipment measures the amplitudes of both of these components. If the centre frequency aligns with the tuned zone frequency, and the transmitter generates equal levels of each frequency, then the amplitude ratio should be 1. The ratio between the amplitudes as seen at the transmitter and receiver tuning units are plotted against time in fig. 7, with rainfall (divided by 10) also shown where available. There are minor daily variations proportional to the temperature (determined by a close inspection on a different scale) and small variations with rainfall. However, the transmitter and receiver ratios show different long term behaviours. While the transmitter ratio remains close to 1.02 over two months, the receiver current ratio drifts from 0.96 to 0.93 in the same time. This cannot be explained in terms of temperature or rainfall. Observations are ongoing to establish if this trend continues.
Figure 7: Transmitter and receiver frequency amplitude ratios, and rainfall.

Fig. 8 shows the measured (lower) ‘B’ frequency against time and also the temperature (in Celsius, divided by -10 and offset by 2290).

Figure 8: Received B (lower) frequency and scaled and shifted temperature (dotted).
At the beginning of the data the frequency variation matches the temperature variation. In the rest of the data, the change in frequency is sometimes larger than the corresponding change in temperature. Note that the temperature is measured outside, while the transmitter unit is inside a lineside cabinet and may see somewhat different temperature changes. The frequency shows some long-term drift unrelated to temperature. This changing frequency, although modest, may partly explain the changing amplitude ratio observed in fig. 7. As the frequency drifts upwards, assuming that the tuning unit remains unaffected, the ratio of the amplitudes should drift downwards, as seen in fig. 7. The properties of the tuning unit may also be temperature dependent.

Conclusions

A system has been developed to allow the long-term study of in-service audio-frequency track circuits. Frequency-dependent currents and voltages are being measured continually, as well as the signalling relay states. The data allow the rms amplitude of both modulation frequencies to be determined, from which long-term changes in track circuit behaviour can be monitored. At the time of writing, the monitoring system has not been operating for long enough to show long-term trends. However, some initial results have been shown. Algorithms have been developed to reduce the collected data to sets of three parameters that provide the important information required for long-term monitoring.

Changes in the received current have been shown to be affected by rainfall, but also found to be largely independent of the amount of rainfall. The situation with other track circuits may be different, or more change may occur in the event of flooding, for example.

The continual switching between two carrier frequencies allows information to be obtained about mismatch in the tuning of the track circuit by comparing the amplitudes of the two frequencies. Some variation with temperature has been observed. The operating frequency varies slightly with temperature and this affects the received amplitudes very slightly and is sufficient to explain most of the daily variation observed. However, there appears to be a gradual drift in the track circuit operating frequency that will continue to be monitored to assess whether it is a trend. There remains a great deal of data from other nodes that has yet to be analysed. This analysis is ongoing.

Data collection will continue for at least one calendar year to allow analysis of data from all seasons. In addition, it is intended that the equipment, having been proved to be reliable, will be duplicated on a track circuit that is more susceptible to failures.

Acknowledgements

The authors acknowledge the support of Network Rail (UK) and Bombardier (UK).

References


