From track switch to inductive wheel sensor using a variety of technologies

Josef Frauscher

Rail contacts that respond to the wheel flanges of train wheels occupy anundisputed place in railway safety technology in the form of switching, detection and counting devices.
In their simplest application, rail contacts detect an approaching railway vehicle precisely on the spot where the first wheel or the first axle of the vehicle is exactly above the rail contact. Depending on speed and kick-down delay time, one switching operation is output per axle or per train. The operation of level crossing protection systems or warning systems for workmen gangs in the danger area exemplify a number of applications.
Two rail contacts, placed a short distance from one another, whose single pulses overlap when traversed, afford a reliable driving direction detection that is independent of speed. These rail contacts, also known as double track switches, are the basis for direction-dependent axle counting in the form of track vacancy detection systems, which have found increasing acceptance over track circuits due to their higher availability.
Within a four-year research and development project, based on 25 years of experience in the field of inductive sensor technology, Frauscher GmbH has developed a wheel sensor with outstanding properties. The operating mode of the product with type desig nation RSR123, which will shortly be ready for certification, is based on a variety of known inductive mechanisms. Following a short description of the various operating principles, the article focuses on the complex effects that are always present and which need to be coped with as tractive efforts increase.

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1 Operating principle of the rail contacts

The history of railway signalling technology has known a large variety of operating principles, only a few of which have stood the test of time and been implemented.
Probably the oldest operating principle is based on mechanically operated contacts, where the wheel flange operates a spring-loaded actuator connected to one or several electrical contacts. Such track switches are still available as double track switches and are used for signalling contacts and for warning system for workmen gangs, e.g. in the SNCF network and in several Maghreb countries.
In the middle of the last century the first contactless switching devices were employed. The rail contacts, known as magnetic wheel contacts (MK) or pulse generators, feature a permanent magnet system, to which magnet-operated electrical contacts are exposed. The effect of the iron of the wheel flange changes the magnetic field and triggers the contact. Magnetic switches are still being used in large numbers as detection devices for level crossing protection systems and as counting heads for track vacancy detection systems.
Over the same period, contactless switches based on the transformer principle came to be known [1]. A primary coil generated an AC magnetic field in an iron core with at least one air-gap in the direction of the head of rail. A wheel flange passing over the air-gap would change the magnetic flux and consequently the induction in a secondary coil, preferably designed as a differential coil. This operating principle was subsequently improved by using ferrite magnets and increasing operating frequencies [2, 3].
In the seventies, electronics strongly influenced the operating principle of rail contacts. Simultaneously with an enormous advance in development in the area of industrial electronics, the operating principle of the inductive proximity switch took its first steps. At first, so-called head of rail contacts were mounted into a vertical bore of the head of rail in order to allow detection of the wheel treads. Subsequently, a model prevailed which was mounted laterally on the inside face of a rail and whose upward placed coils detected the impact of the wheel flange. At the time, the NA-MUR interface (NAMUR = Normenausschuss Messen und Regeln), which defined two-wire switches with standard voltage

and current levels (EN50227/DIN19234), was used quite frequently.
At about the same time, devices were designed that used the magnetodynamic principle [4]. The operating principle of the rail contacts designated at magnetic pulse generators is based on a permanent magnet system with a soft iron yoke. The flux changes caused by the passing wheel flanges induce measurable voltages in the coils placed in the area of the magnetic flux. This operating principle requires a certain speed, which, however, by means of continuous improvement of the circuits, was reduced to practically zero.
To conclude this list of wheel flange based operating principles – which does not claim to be exhaustive – the microwave method should be mentioned.
At no time was there a lack of methods using other trigger criteria. For instance, pneumatically triggered contacts were used to a certain extent. They take advantage of the bending of the rail at the point of impact of the wheel, which, in turn, affects a membrane cylinder, which triggers the switch contacts by means of a pressure pulse. A related method is the application of force sensors, which measure the material stress in the area of the web of rail when traversed by a wheel [5, 6].
Widely used are rail contacts with a transmitter coil on one side of the rail and a receiver coil on the other. The wheel or tyre affects the inductive coupling between transmitter and receiver. The devices are mostly designed as double sensors and are often used as counting heads for axle counters.

2 Track switches and wheel sensors using the inductive operating principle

Increasingly, the operating principle of the inductive track switch/wheel sensor is being used (*Figure 1*). The advantage for the user lies in its simple design, little mounting work and the fact that no electronics are needed at the rail itself.
To be noted is that the AC magnetic field starting from the coil necessarily covers part of the head of rail, because it is necessary to detect not only wheel flanges that run close to the head of rail, but also wheel flanges with less contact and those traversing heads of rail with considerable wear and tear. This factor is decisive for the considerations that follow.
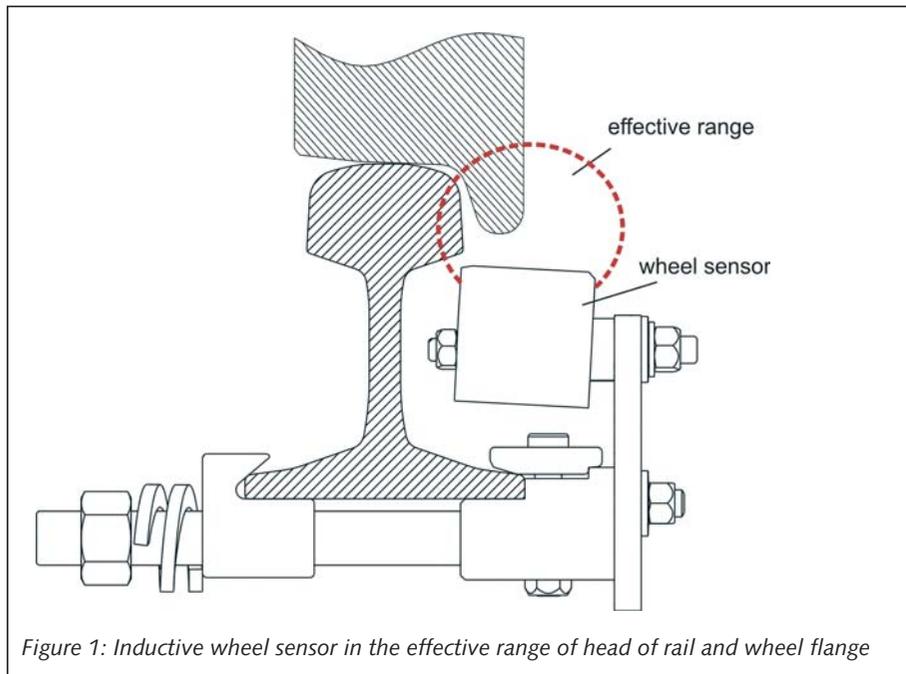
Figure 1: Inductive wheel sensor in the effective range of head of rail and wheel flange

In order to give a serious description of this technology, one cannot ignore the well-known methods included under the main concept of "inductive sensor". Although in all cases at least one coil, through which AC current passes, acts as the core element, it is necessary to differentiate between the following methods:

2.1 Eddy-current method and hysteresis method

The AC magnetic field starting from the sensor coil causes eddy-current and hysteresis losses in ferromagnetic materials (here: wheel flange) that are exposed to it. These losses reflect on the sensor coil and absorb power, that is, they reduce the quality of the oscillating circuit.

2.2 Field deflection method

The magnetic field generated by a coil supplied with alternating current is deflected by existing ferromagnetic materials in such a way that induction in a close-by receiver coil changes.[7] This deflection can increase or decrease.

2.3 Inductivity method

The inductivity of a sensor coil changes due to the influence of ferromagnetic materials in its vicinity. The influence of the material depends on the operating frequency.

3 Complex effects on wheel sensors

An inductive wheel sensor must reliably detect the wheel flange of a railway vehicle and simultaneously be immune to the following interferences:

3.1 Ambient temperature between -40 and +85 °C (in northern countries up to 60 °C)

This extreme temperature range is fairly well dominated as far as electronic components are concerned, however, the development of coils that are frequency-stable and quality-stable is still quite a headache. The fact that coils are still made of some sort of copper conductors which need to be embedded into a sealing compound in order to be protected against humidity results in the following problems: increased temperature implies higher copper resistance and reduces coil quality, which is also influenced by the dielectric loss factor of the sealing compound between the coil windings. The relationship between dielectric loss factor and temperature is not linear and normally increases distinctly after 60 °C.

3.2 Rail temperature between - 40 and + 100 °C (additional heating of rail due to linear eddy-current brake)

As already mentioned, the head of rail is very much exposed to the sensor coils. Permeability and conductivity of the iron change with temperature. This leads to a drift in the sensor coil and causes, as temperature rises, an increase of eddy-current losses and, simultaneously, a decrease in hysteresis losses due to declining permeability of the material. Neither process is linear in regard to the given operating frequency.

3.3 Permeability changes in the rail material due to track currents

Track return currents generate a magnetic field, which also magnetizes the surface of the rail material. This reduces the permeability of the head of rail material and leads to decreasing hysteresis losses that are detected by the sensor coil. Furthermore, the effects of AC traction differ from those of DC traction. Short-circuits up to 40 kA in the overhead contact line or transients due to discharge into the atmosphere can cause magnetic saturation of the rail material and thereby suppress hysteresis losses altogether.

3.4 Magnetic field generated by track return currents

Track return currents generate a magnetic field that is disposed concentrically around the rail, and hence the sensor coil is fully exposed to the field. If the sensor coil has a ferrite core, the magnetic field may cause its saturation. Short-circuits in the overhead contact line and currents from discharges into the atmosphere entail similar effects.

3.5 Traction current commutation

The sparks which can often be seen at quite a distance around the pantographs of the vehicles, or contact problems between rail and wheels, cause changes in the return current across a broad range of frequencies. The resulting magnetic fields induce voltages in the sensor coil, which have to be coped with.

3.6 Humidity, snow, frost

The magnetic field generated in practice by inductive sensors and ranging from a few kHz up to several MHz does not as a rule cause interference in case of humidity, snow and frost. However, high operating frequencies also generate electrical fields, which respond to the capacitive influence of water or similar conditions. It is therefore necessary to compensate sensor coils against the propagation of electrical fields. This concludes a summary of the effects and interferences generated directly at the rail or starting from there, irrespective of whether any vehicle is traversing the sensor or not. Far more dramatic for the sensor are usually interferences generated by vehicles when traversing the sensor:

3.7 Interfering magnetic fields generated by inverters, coils, transformers

Low-loss performance inverters require high switching frequencies and steep switching flanks. Therefore, interfering magnetic fields with large bandwidth and fre-

quencies ranging up to several MHz are to be expected under the vehicles. Where an interfering magnetic field collides directly with the operating frequency of the sensor, effects are especially drastic.

3.8 Beacons, continuous train control (LZB)

The data exchange between vehicles and fixed trackside equipment is based on pre-set frequencies and magnetic fields, which must not cause any interference. As these values are known, its interferences can already be considered when designing the sensor.

3.9 Electro-magnetic rail brake, eddy-current brake

These braking elements have several effects on wheel sensors. On one hand, the metal and coil volume of the brake, which reaches laterally over the head of rail into the effective range of the sensor, causes a partial damping of the sensor system, which must not trigger the sensor as if it were a wheel flange. On the other hand, both types of brakes, especially the eddy-current brake, generate an enormous magnetic field, which in turn has two different effects. The magnetic field permeating the steel of the head of rail will cause its magnetic saturation. Effects are similar to those described in item 3.3. The leakage magnetic field reaches the sensor, which has to cope with it without being disturbed. Effects are similar to those described in item 3.4.

3.10 Parasite resonant circuits

The WHEEL-AXLE-RAIL-SLEEPER geometry can be looked at as a conductor loop, which is exposed to part of the magnetic field generated by the sensor. If the resonant frequency range of the loop is similar to the operating frequency of the sensor, the sensor system may be affected.

3.11 Mechanical shock, vibrations

Shocks are mainly caused by flats on the running surface of the wheels, while vibrations are mainly caused by short pitch corrugation of the rail surface. EN 50125-3 defines the values for mechanical shock and vibrations. In practice, significantly higher strains may apply.

4 Switch or sensor

The demands on rail contacts vary depending on whether they are used as single systems for direction-independent pulses or as double systems with direction detection for axle-counting applications. For in-

stance, an "axle counter" may very well be affected by the interferences described in items 3.7 – 3.10 without the system being negatively affected.

In the field of axle counting quality, the evaluation criteria of the sensor properties described here are always defined by the specifications of the network operators. As soon as a sensor features the desired properties, its application as track switch (pedal) for axles is included anyway.

25 years of experience in the development of inductive sensors, starting in 1980 with inductive position decoders and first implementations of wheel sensors for the measurement of wheel diameters in 1986 [7] have shown that it is practically impossible to perform such tasks without an analog output signal measuring distance. Contrary to a switch limited to "ON" and "OFF" or "High" and "Low" status detection, an analog sensor affords a number of further items of information that can be used, for example, for diagnostics and early detection of failures.

Wheel sensor type RSR122, which has been manufactured by Frauscher GmbH for the past 6 years and 12,000 units of which are in operation covering safety liabilities, exemplifies this (*Figure 2*).

The figure shows the signal curve of a sensor system when traversed by a wheel. The overall signal range available is divided into the following zones:

Range 1:
<5,25 mA >4,75 mA: Sensor correctly mounted on rail, no interference
from wheel
Range 2:
>5,5 mA: Sensor dropped off from rail (signal rises, because the head of rail is outside the effective range).
Range 3:
<3,8 mA > 0,5 mA: Sensor damped by wheel

Range 4:
<0,5 mA: Wire break or component defective
Intermediate ranges:
Sensor system still able to detect damping, but requiring maintenance (adjustment)
These signal values are made available at the wheel sensor in form of injected current values and can be easily evaluated via cable by an intelligent board in the indoor installation. The supply of the analog signal values affords a number of further evaluations besides the status outputs mentioned above. Calculation of wheeldiameter, output of wheel centre via sensor or detection of an electro-magnetic rail brake are but a few examples. Furthermore, the analog sensor signal allows triggering of the output of the rectangular signal used for counting purposes at freely preselectable signal levels, thereby affording detection of wheel running surfaces without wheel flanges or wheel flanges applying less contact on the head of rail.

Wheel sensor RSR 122 complies with the requirements set forth in the specification of Deutsche Bahn AG, and was developed in compliance with Mü 8004 and approved by the German Federal Railway Authority (EBA) (EBA Approval No. 207016.2/9) [8], as well as in other countries.

5 Wheel sensor type RSR 123

Wheel sensor type RSR 122 uses the "eddy-current method and hysteresis method", while another series product from Frauscher GmbH with type designation RSR180, in series production since 1992, uses a combination of "field deflection method" and "inductivity method".
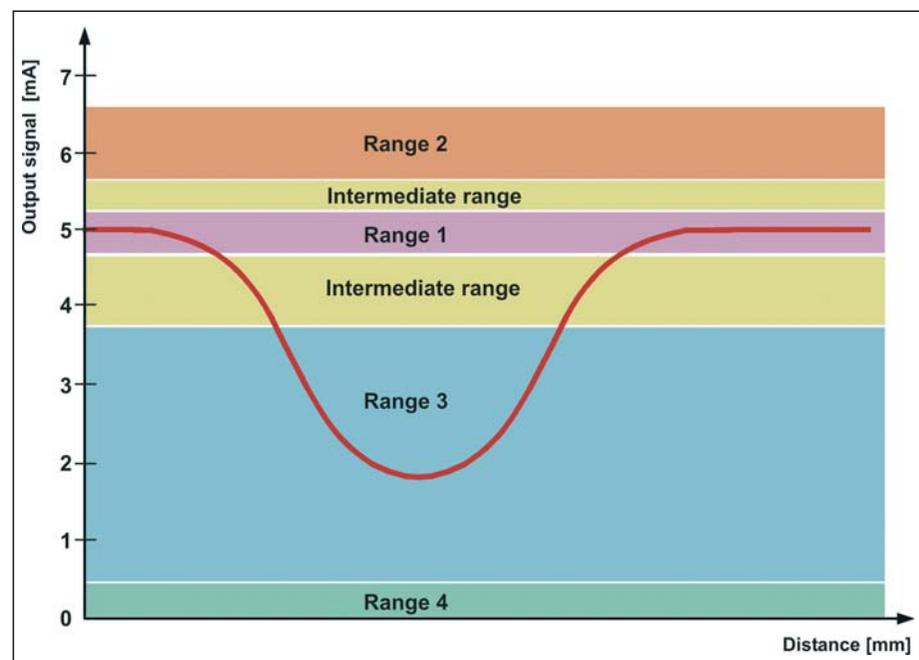Favoured by the large number of units of

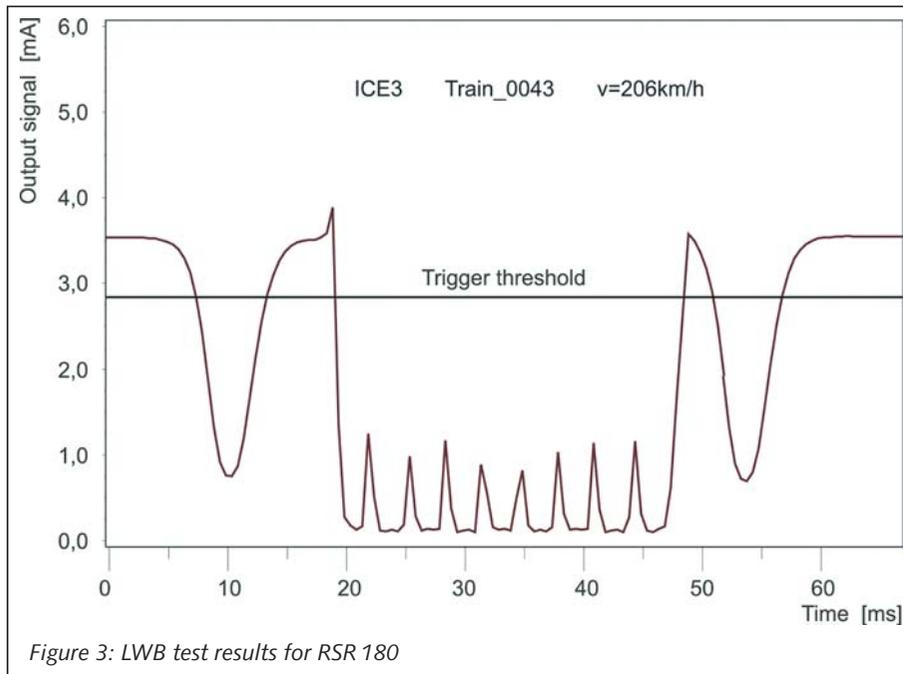*Figure 2: Analog signal value of a sensor system when traversed by a wheel*
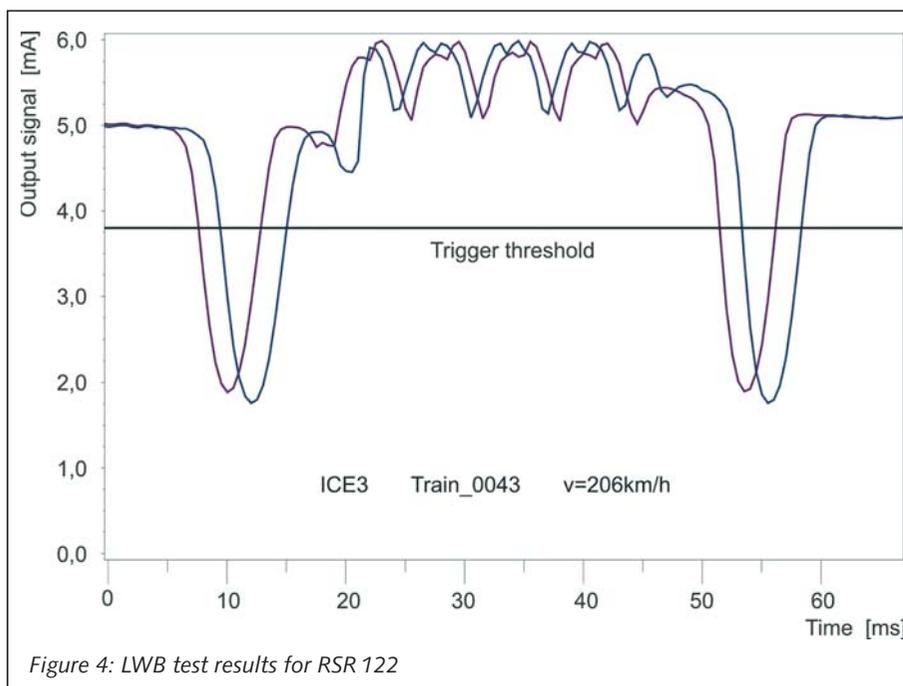
Figure 3: LWB test results for RSR 180

Figure 4: LWB test results for RSR 122

both wheel sensors which are in operation all over the world (approx. 23,000 units), continuous observation and customer service have revealed special strong points as well as weaknesses of the different methods. This was reason enough for the research department of Frauscher GmbH to design a new circuit that would combine the advantages of the different operating methods and eliminate their disadvantages. From the very start, one decisive item in the requirement specification was absolute compatibility with product RSR 122, and thus the type designation RSR 123 is the logical progression of the product family.

Research for wheel sensor RSR 123 was difficult and protracted. It suffered a number of setbacks and presented continuous-

ly new challenges to developers. Complementing the "College electronics" in certain areas, where the knowledge transmitted was not deep enough for the task at hand, was as important as conceiving unconventional test devices: for instance, a device to generate up to 18 kA of track current and a magnetic field generator for field strength up to 1 Tesla (T) at the top of rail (SOK).

After approximately two years of research, a satisfactory basic circuit operating with a mix of the inductive methods described in items 2.1 - 2.3 had been designed (variety of technologies). The development process initiated in compliance with CENELEC revealed several other items requiring improvement. After exhaustive testing, measuring and test runs the properties already

proven can now be summarized as follows shortly before the certification process is concluded:
- No disturbing interference by track currents up to 40 kA (from DC...50 Hz)
- No disturbing interference by magnetic fields in the frequency range up to 1 T (height of top of rail)
- No disturbing interference by magnetic fields in the operating frequency range of the sensor systems (approx. 1 MHz) up to 3,0 µT
- No disturbance by parasite resonant circuits due to neutralization of the distant field
- No interference due to temperature changes in the rail material

It would exceed the scope of this article to present all hitherto existing measurement results graphically. As an example, the measurement data under the linear eddy-current brake (LWB) on the high-speed , Frankfurt-Cologne track may suffice (Figures 3-5). For the purpose of comparison with the values of the RSR 123, the figure shows the signals of wheel sensors RSR180 and RSR 122, which had been mounted along with the test subject on the same rail and registered during one train run. The behaviour of the different operating principles is very insightful, because one can presume that each sensor was subject to the same influences and interferences. Measurements recorded under the active influence of the linear eddy-current brake (LWB) are especially meaningful, because not only are there strong magnetic fields that act upon the wheel sensors, but there is also a magnetic saturation of the head of rail and, additionally, a partial damping of the sensor systems by the metal surface of the brake (see item 3.9).

LWB test results for RSR 180 (Figure 3)
The sensor current of approx. 3,5 mA applied to the sensor system is at first influenced by the first axle of the bogie. This is followed by the influence of the magnetic field of the linear eddy-current brake (LWB), which causes saturation of the transmitter ferrite coil in the sensor. The failure of transmission due to magnetic interference is detected by the sensor coils and displayed in the lowered sensor signal. This wheel sensor is, therefore, not suitable for applications with eddy-current brakes.

LWB test results for RSR 122 (Figure 4)
The sensor current of 5 mA applied to both sensor systems is at first influenced by the first axle of the bogie. Then the effect of the linear eddy-current brake after the first axle of the bogie becomes visible, expressed as a strong modulated rise of the signal. This is due to the irregular magnetic saturation of the head of rail by the iron yokes of the linear eddy-current brake (LWB). In this condition, the head of rail suppresses the damping of the sensor systems. The eddy-current losses, which damp the sensor, are still effective, but in this condition the head of rail practically

acts like stainless anti-magnetic steel as far as its magnetic properties are concerned. As the signal rise under the eddy-current brake is suppressed by the evaluation board, this sensor type is suitable without restriction to be used as counting head in combination with the eddy-current brake.

LWB test results for RSR 123 (Figure 5)
Basically only the metal surface of the brake acts upon the sensor systems and the signal drop thus caused is still distant enough from the trigger threshold "wheel". Neither the strong magnetic field permeating the sensor nor the magnetically saturated head of rail generate disturbing signal interferences.
In the course of the development of wheel sensor RSR 123 further findings from the present sensor applications were analyzed. Thus, besides its excellent EMC values, wheel sensor RSR 123 offers the following additional improvements:
- Micro-controller controlled adjustment at the rail: After mounting to the rail, which only takes a few minutes thanks to the rail claw, the automatic adjustment of the wheel sensor via connecting cable can be started by simple command. This precludes handling errors and allows adjustment to be performed at a safe distance from the track.
- Connectors: The provision of a suitable connector at the wheel sensor meets the wish of many signalling technicians who prefer short handling times when dismounting sensors due to track work or replacement.
- Large effective range: Due to a special coil geometry the effective range is 20 % greater compared to wheel sensor RSR 122. This affords much better filtering of transmission interferences that may occur in unsymmetrical cables.
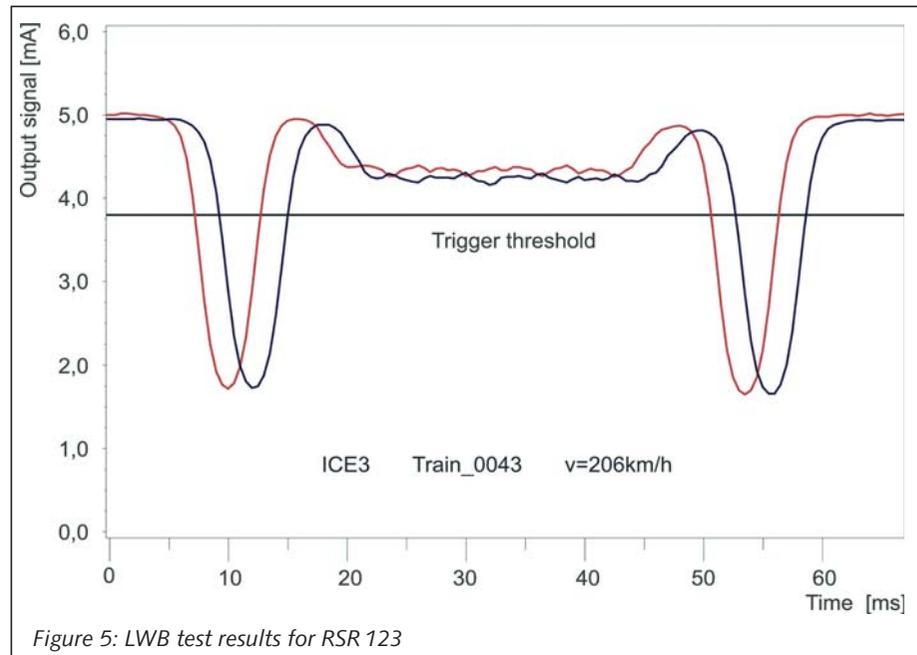

Figure 5: LWB test results for RSR 123

Figure 6: RSR 123 prototype

6 Summary

Worldwide, Frauscher GmbH has large numbers of wheel sensors in operation based on the inductive operating principle, but using different operating methods. The experience gained was the basis for a research project lasting several years, which not only lifted the last veils off the complex effects of wheel sensors, but also provided the development of a basic sensor circuit boasting unprecedented electromagnetic compatibility. Research results were converted into a new wheel sensor with type designation RSR 123 (*Figure 6*), developed in compliance with the CENELEC procedure. The operating mode of RSR 123 is based on a variety of technologies using known inductive mechanisms. Sensor properties mark a new state-of-the-art and afford users a further increase in equipment availability and a reduction in mounting, adjustment and maintenance cost.

ZUSAMMENFASSUNG

Vom Schienenschalter zum induktiven Radsensor mit Verfahrensmix

Die Frauscher GmbH hat weltweit hohe Stückzahlen an Radsensoren im Einsatz, die nach dem induktiven Wirkprinzip, aber nach unterschiedlichen Verfahren arbeiten. Die daraus gewonnenen Erfahrungen waren Grundlage für ein mehrjähriges Forschungsprojekt, das nicht nur die letzten Schleier in Bezug auf die komplexen Einwirkungen auf Radsensoren lüftete, sondern auch die Entwicklung einer Sensorbasisschaltung mit bisher kaum erreichter elektromagnetischer Verträglichkeit ermöglichte. Die Forschungsergebnisse wurden in einem nach dem CENELEC Prozess entwickelten neuen Radsensor mit der Typenbezeichnung RSR123 (*Bild 6*) umgesetzt. Die Wirkweise des RSR123 besteht aus einem Verfahrensmix aus bisher bekannten induktiven Verfahren. Die Eigenschaften des Sensors markieren einen neuen Stand der Technik und ermöglichen dem Anwender eine weitere Steigerung der Anlagenverfügbarkeit und eine Reduzierung des Montage-, Einstell- und Wartungsaufwandes.