13 Field Testing and Instrumentation of Railway Vehicles

Julian Stow and Evert Andersson

CONTENTS

I. INTRODUCTION

An understanding of testing and instrumentation methods is essential to the accurate construction and validation of railway vehicle dynamic models. The dynamics engineer may need to produce specifications for test work, understand the applicability and limitations of data produced, and manipulate test results to provide comparisons with modelling work. This chapter provides an overview of the situations in which the engineer may require test data, together with an introduction to common techniques and equipment used, both in the laboratory and for conducting vehicle testing on-track. The examples given largely relate to vehicle testing which forms the most relevant body of work for the vehicle dynamics engineer. However, dynamic simulation is increasingly used in rail/track related investigations where many of the same techniques may be applied.

A. REASONS FOR TESTING

During the development of a new vehicle or modification of an existing one, requirements for test work may arise for a number of different reasons:

Component characterisation — tests may be required to establish the properties of the various components that make up the suspension in order to allow the initial construction of a model. Such tests are normally carried out in the laboratory using small to medium sized test machines or dedicated test rigs.

Determination of parasitic or secondary effects — once assembled vehicles (particularly modern passenger vehicles) can exhibit behaviour that is difficult to predetermine from the individual suspension components. These parasitic effects typically arise from the summation of a number of small stiffness contributions from components such as anti-roll bars, traction centres, and lateral and yaw dampers in directions other than those in which they are mainly designed to operate. Other effects, which may need to be quantified arise from flexibilities in mounting brackets or similar, as well as internal flexibility in dampers. Such tests are normally carried out statically or quasi-statically on a complete vehicle in the laboratory.

Structural testing — the testing of vehicle body structures and bogie frames for strength, fatigue life, and crashworthiness is a complete subject in itself and beyond the scope of this chapter. However, the dynamicist may need to obtain parameters to enhance models, particularly with respect to simulation of ride and passenger comfort. Typical examples include the vertical and lateral bending modes of vehicle bodies and the torsional stiffness of bogie frames. Tests are most often carried out in the lab using bare body shells or bogie frames mounted in dedicated structural test rigs.

Validation testing — it is generally necessary to increase confidence in the correct operation of models by comparing the results with those from a series of tests. Such tests may be on bogies or complete vehicles. At a basic level, these may be carried out quasi-statically in the laboratory, but any extensive validation is likely to require on-track tests under a range of conditions to fully understand the dynamic behaviour of the vehicle. The level of validation required will ultimately depend upon the intended use of the models.

Acceptance tests — all railway administrations require new or modified vehicles to undergo a series of tests to demonstrate safe operation for various conditions. Such tests may be specific to an individual company or country or, as in the case of European Standards,[1,2] may allow a vehicle to operate across a number of countries. The exact requirements for these can vary widely but will usually comprise of a mixture of lab and field tests. Many administrations now allow some of these requirements to be met by simulation of the test procedure using a suitably validated vehicle dynamics model. In any case, simulation of these tests forms a common part of vehicle development to ensure that proposed designs meet the required standards. As such tests will be carried out on all vehicles accepted for service, they may also provide a useful source of information to validate models of existing vehicles.

In addition, the dynamics engineers may also be involved with testing to assess performance against specified criteria such as passenger comfort or to investigate problems with existing rolling stock.

Reproducing track geometry — many simulation tasks will require the use of "real" track geometry measured by a high-speed recording vehicle or hand operated trolleys. Although such data is generally presented as "ready to use," experience has shown that an appreciation of the measuring systems and instrumentation used is vital to ensure that an accurate reconstruction of the track geometry can be obtained.

Measuring wheel and rail profiles — accurate representations of worn wheel and rail profiles are vital to understanding vehicle (and track) behaviour. A number of proprietary devices are available to measure profiles, however, as with track geometry, accurate results will be aided by an understanding of the principles behind their operation.

II. COMMON TRANSDUCERS

This section provides a brief overview of the range of transducers commonly encountered to measure displacement, acceleration, and force.

A. DISPLACEMENT TRANSDUCERS

These are used for measuring linear or rotational displacements. The most common type of transducer is the linear variable differential transformer (LVDT). This comprises a transformer with a single primary coil and two secondary coils wound onto a hollow cylindrical tube as shown in Figure 13.1. Within this tube, a ferromagnetic core can move up and down. The primary coil at the centre of the tube is excited with an AC signal and this induces a voltage in the secondary coils. The secondary coils are normally connected as shown in Figure 13.2. This arrangement, known as "series opposition,"[3] has the effect of producing zero output voltage with the core in its central or zero position. As the core is moved, the coupling between the primary and one of the secondary coils increases whilst the coupling with the other secondary coil decreases in direct proportion. With correct arrangement of the coils and core, the resulting output voltage will be linear over the majority of the stroke. It should be noted that as the core moves past the zero position (central on the primary coil), the output voltage undergoes a 180° phase shift.

In practice, a transducer that requires AC input and produces AC output is inconvenient, so a signal processing module is used in conjunction with the LVDT. This senses the zero-passing phase shift described above and uses this to distinguish between AC signals of equal amplitude either side of the zero position. The resulting conditioned output is therefore a positive or negative DC voltage either side of the zero position. The signal conditioning module usually also converts a DC supply

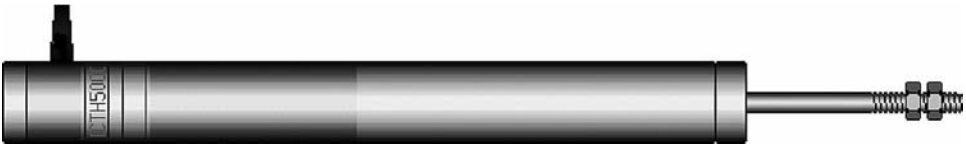


FIGURE 13.1 LVDT (courtesy of RDP Electronics). *Source*: From RDP Electronics Ltd. — Catalogue. With permission.

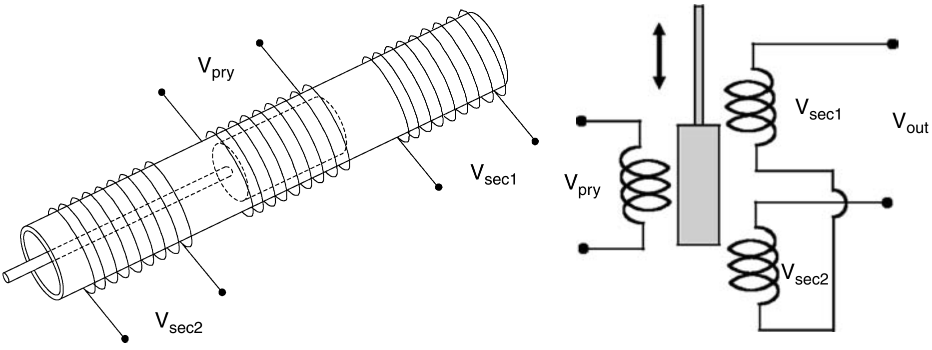


FIGURE 13.2 Schematic of primary and secondary coils in an LVDT.

voltage into the required AC excitation for the primary coil. The signal conditioning may be in a separate module but is often incorporated within the transducer casing itself.

LVDTs have the advantage of being inherently non-contact devices and therefore have no wearing parts. They typically achieve better than ± 1% linearity over their specified range and are available commercially in measuring ranges from a few millimetres up to approximately 0.5 m. LVDTs generally operate on input voltages up to 24 V DC and may be obtained with floating cores or with a sprung loaded plunger.

B. ACCELEROMETERS

Accelerometers are electromechanical transducers that convert vibration into an electrical signal. Unlike displacement and velocity, acceleration can be measured as an absolute, rather than relative, quantity. This factor combined with the accuracy, robustness, and good frequency response/sensitivity of modern accelerometers makes them ideal for use in vehicle dynamics test applications.

Figure 13.3 shows a simplified accelerometer. A mass (the seismic mass) is mounted within a rigid casing on a spring and damper. Accelerometers are designed such that the natural frequency of the seismic mass is high compared to the desired measuring frequency range. In such an

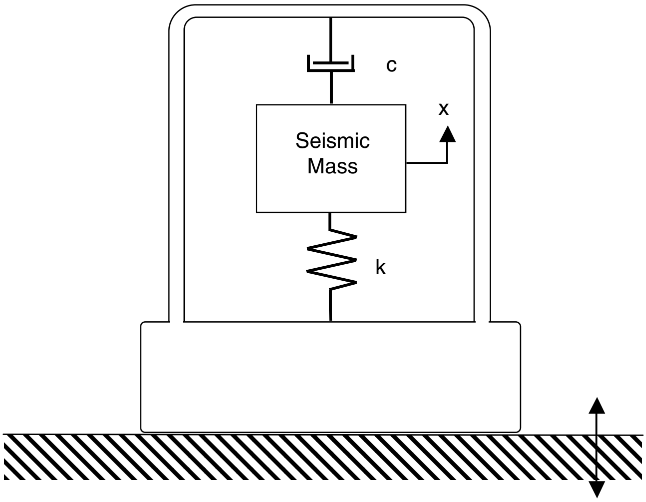


FIGURE 13.3 Simplified accelerometer.

arrangement, the amplitude of displacement of the seismic mass will be directly proportional acceleration exciting the transducer. It follows, therefore, that accelerometers work by sensing the relative displacement of the seismic mass with respect to the transducer casing. It can be shown, mathematically,[3] that the maximum useful frequency range of an accelerometer, around 20–30% of the transducers natural frequency, is achieved with a damping ratio of 0.7. This damping ratio also provides almost zero phase distortion.

1. Piezoelectric Accelerometers

The most commonly used type of accelerometer is the piezoelectric accelerometer. The sensing element in such devices is a slice or disc of piezoelectric material. Such materials develop an electrical charge when they are subjected to mechanical stress. A number of naturally occurring materials exhibit this effect (e.g., quartz), but transducers typically employed man-made materials of a family known as "ferroelectric ceramics."[4]

Practical accelerometer designs typically employ a seismic mass resting upon, or suspended from, a number of slices of the piezoelectric material. The vibration of the seismic mass within the accelerometer exerts a force on the piezoelectric material and a charge is developed that is proportional to the force exerted. Three common designs of accelerometer are illustrated in Figure 13.4 below.

The centre mounted compression design is a relatively simple arrangement where the mass is mounted on a centre pillar with a spring to provide the preloading. The mass acts in compression on the piezoelectric element. These designs have the advantage of good useable bandwidth. However, as the base and centre pillar act as a stiffness in parallel with the piezoelectric element, any bending of the base or thermal expansion can cause erroneous readings.

Planar shear designs feature two slices of piezoelectric material either side of the centre post, each having a seismic mass attached to it. The masses are held in place by a clamping ring which preloads the piezoelectric elements and results in a high degree of linearity. The charge induced by the shear forces acting on the piezoelectric elements is collected between the housing and the clamping ring. In this design, the sensing elements are effectively isolated from the base and these designs therefore have good resistance to base strains and temperature variations.

The delta shear design is similar to the planar shear version described above. In this case, three masses and piezoelectric slices are mounted radially to the centre pillar at 120° to each other. Once again, a clamping ring preloads the elements. In addition to good resistance to base strain and temperature changes, these designs also have high resonant frequency and sensitivity.

An understanding of the useable bandwidth of a device is vital when selecting the correct accelerometer for a vehicle test application. The typical frequency response of a piezoelectric accelerometer is shown in Figure 13.5. As described above, the upper frequency limit for the device

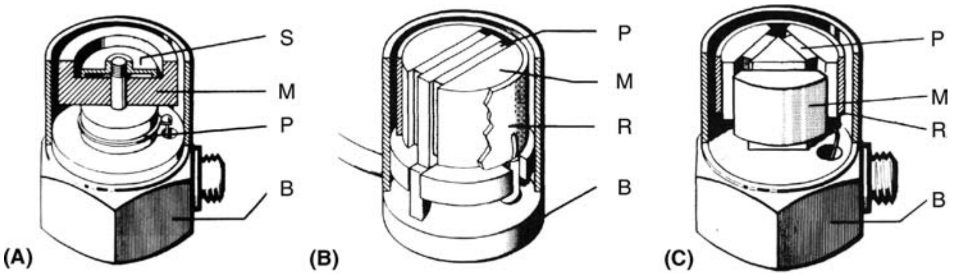


FIGURE 13.4 Common accelerometer designs, (a) centre mounted compression, (b) planar shear and (c) delta shear® (courtesy of Bruel and Kjaer). *Source*: From Serridge, M. and Licht, T. R., *Piezoelectric Accelerometers and Vibration Preamplifier Handbook Bruel and Kjaer*, Revised November 1987. With permission.

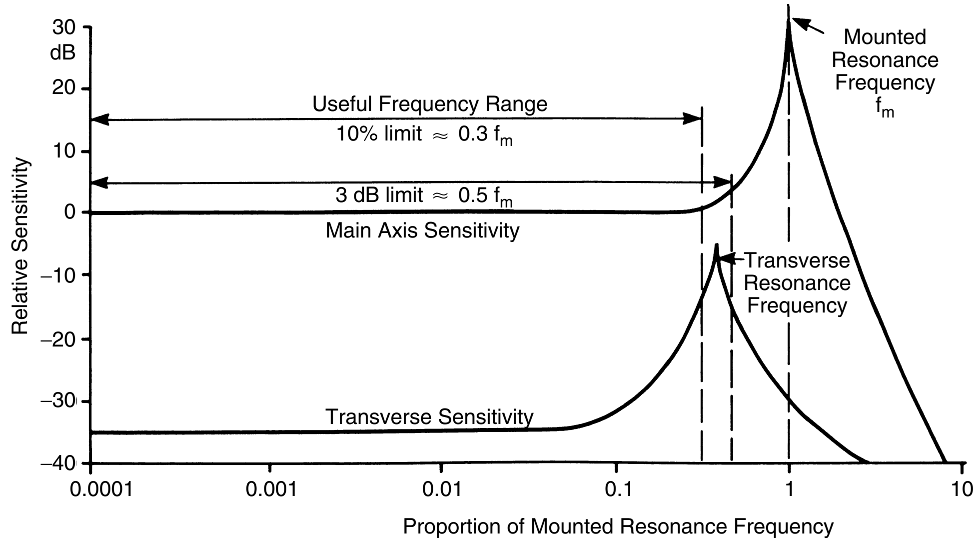


FIGURE 13.5 Frequency response of an accelerometer (courtesy of Bruel and Kjaer). *Source*: From Serridge, M. and Licht, T. R., *Piezoelectric Accelerometers and Vibration Preamplifier Handbook Bruel and Kjaer*, Revised November 1987. With permission.

will be dictated by the resonant frequency of the accelerometer. A commonly used rule of thumb is that the upper frequency limit should be no more than one third of the resonant frequency. For general purpose piezoelectric accelerometers, the resonant frequency may be of the order of 20 kHz, putting their upper useable limit way above anything likely to be required for a vehicle dynamics application. Piezoelectric accelerometers have one very important limitation with regard to vehicle dynamics test applications. The lower frequency limit is determined not by the accelerometer itself but by the RC time constant of the charge amplifier used to condition the signal from the transducer. Whilst it is possible to sense very low frequencies using preamplifiers with very high impedance, general purpose equipment may limit the lower useable frequency limit to 1–3 Hz. Clearly, this has important implications for the vehicle dynamics engineer. A general purpose piezoelectric accelerometer may be quite acceptable for mounting on unsprung masses such as the axle box, but may be operating near its lower limit when mounted on a bogie frame. Vehicle body modes may occur at 0.5 Hz or less and therefore would be below the lower limit of a general purpose piezoelectric accelerometer. Piezoelectric accelerometers are generally not capable of measuring the quasi-static accelerations due to curving. In the case of bogie and body measurements, the capacitive accelerometer, described in Section II.B.2 below, will provide a solution to this problem.

An ideal accelerometer design would only respond to vibrations applied to the main sensing axis. However, in practice, most accelerometers will exhibit some sensitivity to excitations at 90° to the main axis, known as the transverse sensitivity. These are caused by small irregularities in the piezoelectric material causing the axis of maximum sensitivity to be slightly misaligned with the operating axis of the accelerometer. It can be imagined, therefore, that the transverse sensitivity will not be constant and subsequently there will be directions of maximum and minimum sensitivity at 90° to each other. Some accelerometer designs will indicate the direction of minimum transverse sensitivity on the accelerometer body to aid correct mounting of the device. It is generally found that the transverse resonant frequency is lower than the main resonant frequency and therefore falls within the useable bandwidth of the accelerometer. However, at the relatively low frequencies of interest to the vehicle dynamics engineer, the maximum transverse sensitivity is usually less than 4% of the main axis sensitivity.[4]

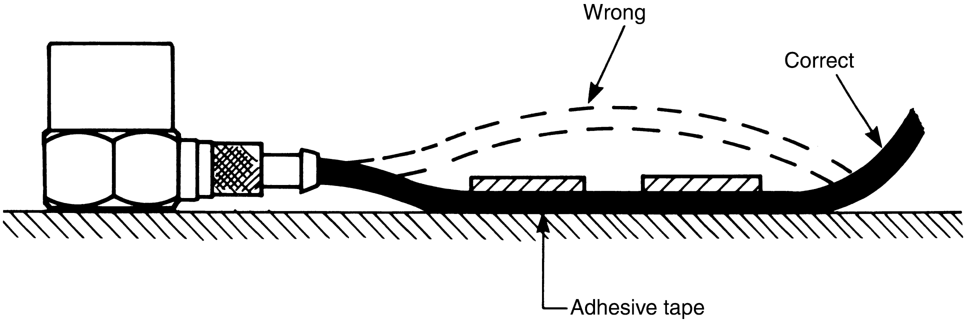


FIGURE 13.6 Accelerometer mountings and cabling (courtesy of Bruel and Kjaer). *Source*: From Serridge, M. and Licht, T. R., *Piezoelectric Accelerometers and Vibration Preamplifier Handbook Bruel and Kjaer*, Revised November 1987. With permission.

To achieve reliable results, care should be taken when mounting and cabling piezoelectric accelerometers. The device may be mounted using either a stud screwing into a hole tapped directly into the test component or by gluing it in place onto a clean flat surface. However, in many railway vehicle applications the accelerometer will be mounted on its stud to a bracket which will in turn be bolted or clamped to the vehicle. In this case, the mounting bracket and clamping arrangement should be as rigid as possible to ensure that the measured data is not degraded by vibrations or deflection of the mounting itself. A thin mica washer is often placed between the base of the accelerometer and the mounting which, when used in conjunction with an insulated stud, increases the electrical isolation of the accelerometer from the test piece. It should be noted that dropping an accelerometer onto a hard surface, such as a workshop floor, can cause a shock load that exceeds the maximum design limit and damages the device permanently.

A described above, the piezoelectric sensor generates a small charge when subjected to mechanical stress. Any noise generated between the accelerometer and the signal conditioning/charge amplifier module can therefore adversely affect the accuracy of the results obtained. Flexing of the accelerometer cables can induce a charge as a result of the separation of the layers within the co-axial cable, known as the triboelectric effect. These charges can be sufficiently large to induce significant "noise" when measuring low levels of vibration. It therefore follows that accelerometer cables should be securely clamped or taped in position to prevent flexing of the cables that induce such charges (see Figure 13.6). In addition, cable runs between accelerometers and charge amplifiers should be as short as possible as the signal conditioning unit will generally output a strong DC voltage which will be less sensitive to noise than the incoming signal from the transducer. An alternative (which may be preferable in many vehicle test applications) is to use an accelerometer with an in-built preamplifier that performs some or all of the required signal conditioning. For piezo-electric accelerometers, this is usually in the form of a miniature "charge amplifier" which produces an output voltage proportional to the charge generated by the accelerometer. As with all test equipment, cabling runs should avoid sharp bends and be routed away from sources of electrical and magnetic interference, such as traction equipment and current collectors (third rail shoes/pantographs).

2. Capacitive Accelerometers

Although piezoelectric accelerometers have very high frequency upper useable limits, they can be limited to around 1 Hz at the lower end of their frequency range (dependent on the charge amplifier employed), as described in Section II.B.1. In contrast, capacitive accelerometers have no lower limit on their useable frequency range as they are capable of giving a DC or static response. They also have a number of other attributes that make them attractive for railway vehicle test

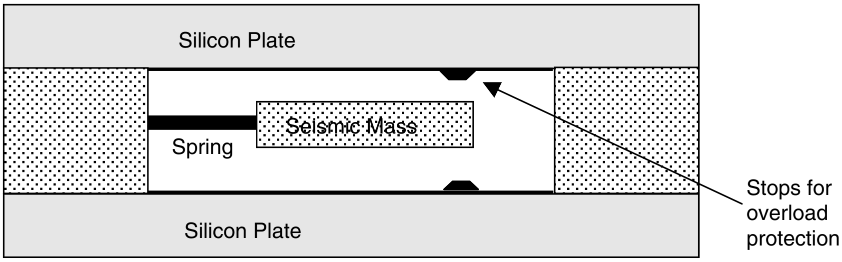


FIGURE 13.7 Schematic arrangement of a typical capacitive accelerometer.

applications. They generally exhibit no phase shift at low frequencies, are insensitive to thermal effects and electro-magnetic interference, have a high signal to noise ratio and a low transverse sensitivity, typically around 1%.

The sensor comprises a tiny seismic mass etched onto a slice of silicon which is interposed between two further silicon plates which act as electrodes. The plates are arranged as a capacitive half-bridge, and the small space between the plates is filled with a gas which provides the necessary damping to the seismic mass.[5] The arrangement is shown in schematic form in Figure 13.7. A useful feature of the design is that the plates provide a mechanical stop for the seismic mass, preventing damage by shock loadings. When the accelerometer is stationary, the mass is central between the plates. Applying an acceleration causes the mass to move towards one of the plates and unbalances the capacitive half-bridge. This results in a charge which is proportional to the applied acceleration. Devices of this type normally include the signal processing within the accelerometer package. Therefore, although the half-bridge is excited by a high frequency AC voltage, the accelerometer requires only a low current (few milliamps) DC input and provides a DC output that can be fed directly to a data logger.

Due to the modest upper frequency limit, mounting methods are less critical than for piezoelectric accelerometers, with the device being glued or bolted to the test components. Once again, however, it is essential to avoid any additional vibrations that may result from insufficiently stiff mounting brackets. Typical capacitive accelerometers suitable for body or bogie mounting may have accelerations of ±2 g with a frequency response of 0–300 Hz, or ±10 g with a frequency response of 0–180 Hz. It should be noted that, in general, increasing the acceleration range is achieved at the expense of lower sensitivity. As static devices, capacitive accelerometers also measure acceleration due to gravity. The output from the accelerometer will therefore be the sum of the vibration being measured and the component of the acceleration due to gravity acting on the main sensing axis.

C. STRAIN GAUGES

The science of force and strain measurement is a complex one and it is not possible to provide more than an introduction to the subject in this context. Strain gauges operate on the principle of measuring the change of resistance of a conductor when it is subjected to a strain. This change of resistance is generally measured using a bridge circuit as described below. The most common form of strain gauge is the foil gauge in which the required pattern is etched onto a thin metal foil, a simple example of which is shown in Figure 13.8 below. A good strain gauge will have two apparently conflicting requirements. It must have a short "gauge length" in order to provide a point measurement of strain on the test specimen, whilst having the longest possible conductor to give the maximum change in resistance per unit strain. It is for this reason that most foil gauges use a folded or "concertina" pattern, as illustrated in Figure 13.8.

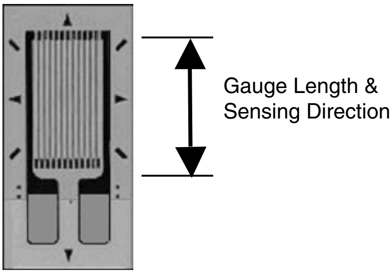


FIGURE 13.8 Foil strain gauge (courtesy of Micro Measurements Inc.). *Source*: From Micro Measurements Catalogue. With permission.

The change in resistance of the gauge is related to the strain (i.e., the change in length of the gauge) by a constant known as the gauge factor.

$$k = \frac{\Delta R/R}{\Delta L/L}$$

since strain is defined as $\varepsilon = \Delta L/L$

$$k = \frac{\Delta R/R}{\varepsilon}$$

where k = gauge factor; ΔR = change of resistance; R = unstrained resistance; ΔL = change in gauge length; L = unstrained gauge length; and ε = strain (normally quoted in terms of micro-strain).

The higher the gauge factor, the higher the sensitivity of the gauge. Good linearity is also a key requirement for accurate measurement; foil strain gauges typically have gauge factors around $k = 2$ and linearity varying from $\pm 0.1\%$ at 4000 $\mu\varepsilon$ to $\pm 1\%$ at 10,000 $\mu\varepsilon$. Many configurations of foil strain gauges are available for a variety of strain measuring applications, a selection of which are shown in Figure 13.9. Less commonly used are thick-film and semi-conductor strain gauges. These have considerably higher sensitivity than foil gauges with $k = 10$ to 20 and $k \approx 50$, respectively.

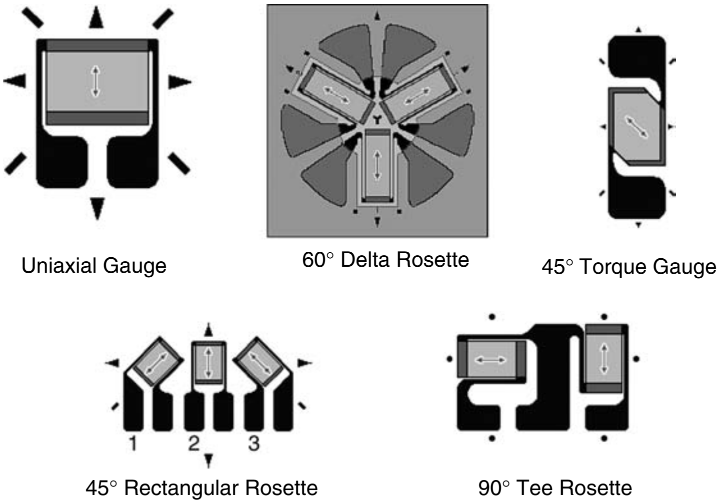


FIGURE 13.9 Examples of various strain gauge configurations (courtesy of Micro Measurements Inc.). *Source*: From Micro Measurements Catalogue. With permission.

Foil gauges are particularly delicate items, and considerable care is required when mounting them on a test component if accurate and reliable measurements are to be achieved. Mounting surfaces must be polished to a good surface finish and then cleaned with specialist solvents and cleaning agents to remove any oil contamination and oxides and ensure that the surface is at the optimum pH for bonding. An adhesive will then be applied to the surface of the part and the gauge, complete with its backing tape, will be pressed onto the surface. Finally, the backing tape is peeled away leaving the gauge bonded to the test specimen. Gauges may be supplied with leads already attached to them, or the leads may be soldered in place once the gauge is mounted. In either case it is good practice to bond a terminal in place adjacent to the gauges from which the main leads can be led away to the bridge circuit. Once the installation is complete, the gauges should be tested before being finally encapsulated in a protective coating to prevent ingress of water and other contaminants. Strain gauges are now available with various mounting systems including weldable gauges that are fixed to the component using a small spot welder.

Strain gauges have a number of applications in the fields of rail vehicle testing. They are commonly the basis of force-measuring devices such as load cells and force-measuring wheels. Strain gauges may also be attached directly to components that are being tested under laboratory conditions. In both these instances the load cell or component can be mounted in a test machine and the resulting strain can be calibrated against a known force input. Strain gauges are also widely used in structural test applications such as determining the strain regimes present in bogie frames or vehicle bodies for testing performed either in the laboratory or on track. The data generated may be used to provide validation for finite element models or as the basis of fatigue calculations. However, as gauges measure strain at singular point(s), considerable care and skill is required to ensure that the critical elements of a structures behaviour are captured.

1. Bridge Circuits

The change of resistance generated by strain gauges is very small, typically of the order of a few hundredths of an ohm. The most convenient means of measuring such changes is with a Wheatstone bridge. This comprises of four resistances connected to a DC power supply as shown in Figure 13.10. If $R_1 = R_2 = R_3 = R_4$, the bridge is said to be balanced and a voltmeter connected across the bridge as shown will read 0 V. It can be shown[3] that:

$$R_1/R_3 = R_2/R_4$$

This equation highlights two important factors about the Wheatstone bridge. If more than one strain gauge is connected in the measuring circuit, the sensitivity of the bridge can be increased. It is also apparent that changes in resistance on one half of the bridge may "balance" by changing the resistance of the other half. As described below, this provides a useful method of compensating for the temperature sensitivity of strain gauges.

In order to measure strains, the resistors shown in Figure 13.10 are replaced by one or more strain gauges (which are of course variable resistors whose resistance changes with applied strain). At the start of the test, the balancing potentiometer is used to balance the bridge, giving 0 V at the voltmeter. Applying the test load will then cause the resistance of the strain gauge to change and unbalance the bridge again, producing a voltage output that is proportional to the applied strain. The actual strain can then be calculated. It is not uncommon to find situations where it is not possible to calibrate the strain measurement system using a known test load, for example, when gauging a large structure such as a vehicle body. In these cases it is possible to undertake an electrical calibration by placing a high resistance in parallel to the active arm(s) of the bridge. This method is known as shunt calibration and assumes that the surface strain in the test component is fully transmitted to the strain gauge in which it produces a linear response. The fact that the active gauge itself is not a part of the calibration is clearly a drawback, however, providing sufficient care

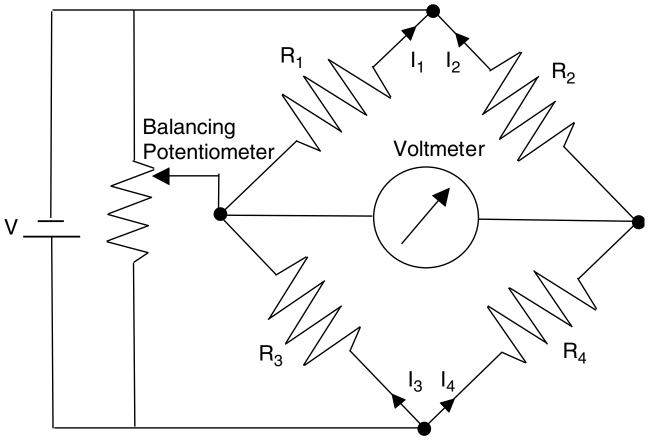


FIGURE 13.10 Wheatstone bridge (with balancing potentiometer).

is exercised, results from such set-ups may be used with a reasonable degree of confidence. Where long cable runs are used, it is essential that the shunt resistance is applied across the gauge with the cable in place to ensure that the effects of cable resistance are accounted for in the calibration.

A bridge may contain one, two, or four strain gauges in the arrangements shown in Figure 13.11, and these are known as a $\frac{1}{4}$-bridge, $\frac{1}{2}$-bridge and full bridge, respectively. A $\frac{1}{4}$-bridge will have the lowest sensitivity of these three arrangements. If no precautions are taken it may also produce errors if the gauges used are sensitive to thermal effects. In order to prevent this, one of the resistors adjacent to the active gauge may be replaced with a "dummy" gauge. This will be an identical strain gauge to the active one that is subject to the same environmental conditions but is not subject to loading, achieved, for example, by mounting it on an unstressed part of the test component. Both gauges will be exposed to any temperature changes and the effect is to cancel out any resulting unbalance on the bridge due to thermal effects. A $\frac{1}{2}$-bridge will have a higher sensitivity than a $\frac{1}{4}$-bridge as the additional strain gauge will produce a larger unbalanced voltage across the Wheatstone bridge. The presence of two active gauges will also cancel out any thermal effects as described above. A full bridge will have the greatest sensitivity of the three arrangements and will similarly be self-compensating for temperature changes (Figure 13.11).

Strain gauges are available that are self-compensating for temperature changes and the need for dummy gauges is therefore eliminated. However, changes in temperature can also affect the resistance of the lead wires and connectors and, if no dummy is present, such changes may unbalance the bridge resulting in errors in the strain measurement. Such errors can be minimised by the use of a "three-wire" arrangement such as that described in.[6]

It should be noted that the output voltage changes from strain bridges are usually very small and therefore should be amplified as close to the bridge as possible. Once again, cabling should be fully screened and carefully installed to prevent unwanted noise from interfering with the test data. It may be advisable to include dummy gauges in the system that are subject to the same environmental conditions, wiring and connection arrangements as the active gauges but are not subjected to strain. These can be used to assist in determining the level of noise present.

D. FORCE-MEASURING WHEELSETS

Recently proposed European standards[1,2] call for the assessment of wheel–rail forces — track forces — in newly developed or essentially modified main line rail vehicles, particularly for those operating at higher speeds. National standards and practices often call for track force assessment

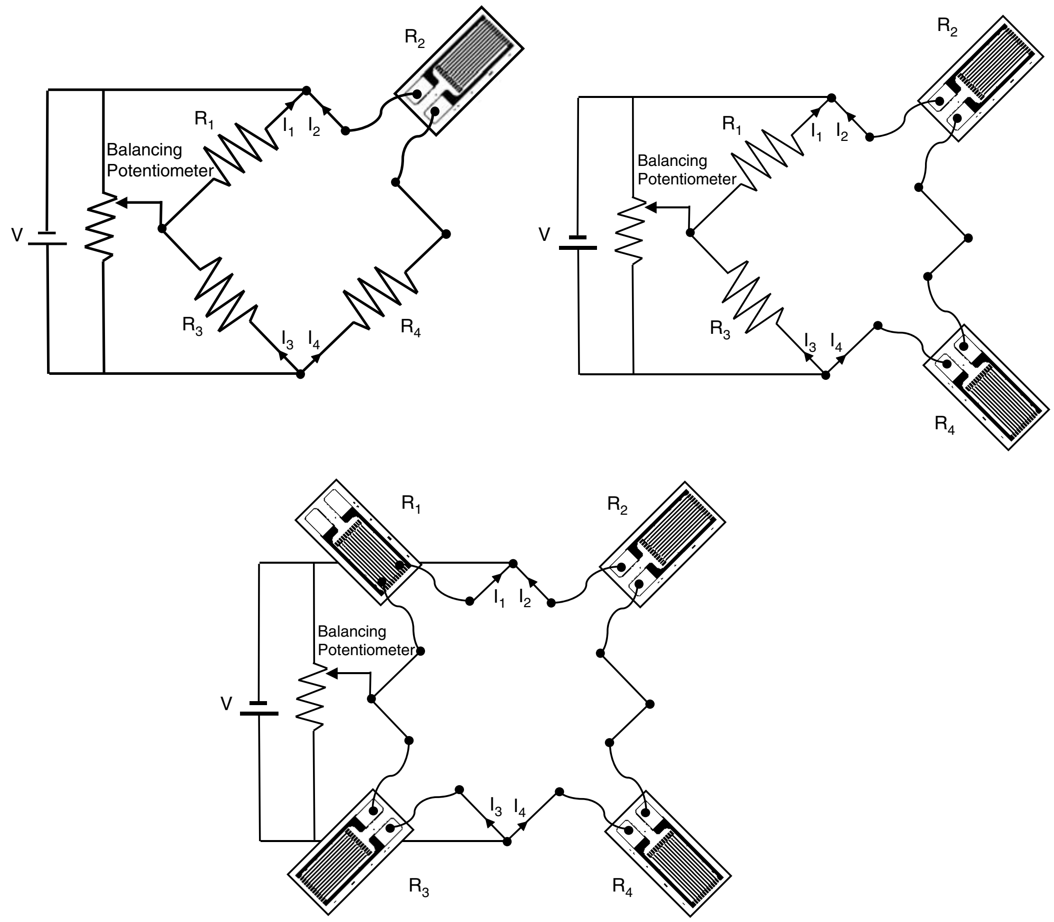


FIGURE 13.11 $\frac{1}{4}$, $\frac{1}{2}$, and full bridge arrangements.

for acceptance testing. The data generated by force-measuring wheelsets is, obviously, also useful for direct validation of vehicle dynamics simulations. With force-measuring wheelsets, run over appropriate sections of track, it is possible to evaluate the vehicle–track interaction continuously under different operating conditions. Force-measuring wheelsets are often called instrumented wheelsets.

With the more advanced wheelsets it is possible to measure lateral and vertical, and sometimes even longitudinal wheel–rail forces, continuously during “on-track” tests. With correct wheelset design and instrumentation, measuring precision can be good (of the order of 5–10%). However, the instrumentation processes, as well as the procedures during the tests, are sometimes tedious and time consuming.

The sort of measuring device to be used is partly regulated in the current European standard proposals. For low-speed vehicles with conventional running gear, modest axle load and modest cant deficiency it is not mandatory to measure Y and Q forces. In such cases a simplified method with instrumented wheelsets measuring just the lateral forces between wheelsets and the axle boxes are considered as sufficient. In some cases (for example, freight wagons with standard running gear at ordinary speed) instrumented wheelsets are not required. However, above a certain speed (usually >160 km/h or >120 km/h for freight wagons), Y and Q forces must be assessed. This is also the case for higher axle load or cant deficiency. In the European standard assessment of Y and Q

forces this is referred to as the "normal measuring method." This requires a more advanced technique for the instrumented wheelsets than for the simplified method described above.

It should be pointed out that there is no known technique available for measuring the forces at the wheel–rail interface directly. Instead, reactions such as strains or accelerations must be measured in structures affected by the wheel–rail forces, i.e., in wheels, axles, or axle boxes. A brief overview of each of the techniques available is given below, whilst a detailed description of the different methods available can be found in.[7] Historically, strains in the track structure have also been measured, but such techniques are outside the scope of this chapter.

1. Measuring Lateral Forces between Wheelset and Axle Box

The simplest form of a force-measuring wheelset is to install strain–force-measuring devices between axle journals and the axle boxes. The lateral force can then be estimated by the calibrated strain–force relationships. The operating principle of the device is shown in Figure 13.12. In this case, the lateral axle force is referred to as the *H*-force. It is similar, but not identical, to the track shifting force *S*. The difference is due to the wheelset mass force.

This simple *H*-force method can be further developed by attaching an accelerometer to the wheelset, measuring the lateral wheelset acceleration. This makes it possible to calculate and compensate for the lateral mass force of the wheelset. With this technique it is possible to achieve a fairly good idea of the total lateral track shift force *S* between the wheelset and the track. However, with this method it is only possible to measure the total lateral force on the wheelset or on the track; it is not possible to separate the lateral force between the two wheels, i.e., the *Y*-forces, or to measure vertical *Q*-forces.

2. Measuring Lateral and Vertical Wheel–Rail Forces — The Axle Method

Through the measurement of bending moments in the axle, on four cross sections, it is possible to estimate approximate vertical and lateral forces on the wheels, if mass forces generated by the wheelset are neglected. By additionally measuring two torques, approximate longitudinal forces can be calculated. Thus, with six measured moments and torques it is possible to determine six forces (two longitudinal, two lateral, and two vertical) "on-line." The principle is shown in Figure 13.13. Moments and torques are measured by strain gauge bridges. Signals are transmitted to and from the axle through slip-ring devices, inserted at one of the axle journals, or by radio transmission.

This principle of measuring axle moments and torques seems, at first sight, to be fairly simple, efficient, and accurate. A further advantage is that wheels can be changed on the instrumented axle. However, this method has two major disadvantages:

- Forces on the wheels may be applied at various positions. For example, the lateral position of the contact area may change as much as ±35 mm over the wheel tread, thus

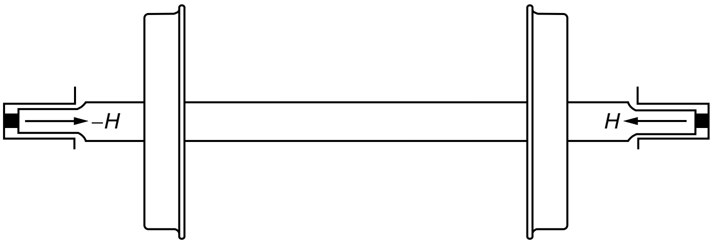


FIGURE 13.12 Lateral force *H*, measured between axle journal and axle box.

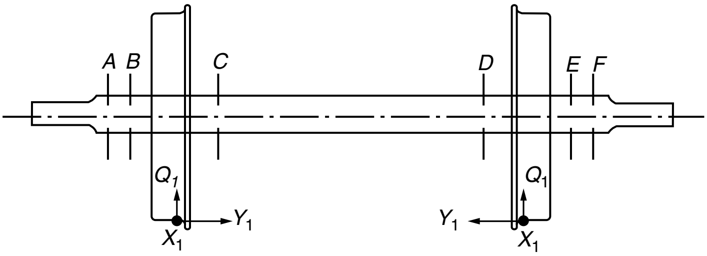


FIGURE 13.13 By measuring six bending moments and torques, approximate measures of forces x, y, q on the wheels can be determined.

the position of the vertical force application will also change. The changing positions will also change the moments measured in the axle, thus introducing errors that cannot be compensated because the actual position at which the force is applied is not known.

- Moments in the axle are dependent, to a small degree, on the vertical mass forces, due to the unsprung mass of the axle and other unsuspended parts of the wheelset. Thus, it is not possible to fully assess the effects of the unsprung mass on the vertical dynamic forces.

Due to the deficiencies described above, this method has been further developed. By applying strain gauges on the wheel webs, the effects of varying positions are reported to be compensated. However, this makes the method more complicated and approaches the "wheel methods" described in the next section.

3. Measuring Lateral and Vertical Wheel–Rail Forces — Wheel Methods

"Wheel methods" can be divided into two different techniques, either measuring strains in the spokes of spoked wheels, or measuring strains in the wheel web of ordinary railway wheels, i.e., in the web between the axle and the outer wheel rim.

The "spoked wheel method" is not frequently used nowadays, mainly due to the need to design and manufacture special wheels. In addition, the calibration procedures are tedious and time consuming. However, with properly designed and calibrated instrumented spoked wheels, this method is reported to produce a good accuracy. The mass forces of the unsprung mass are, to a large extent, included in the measured quantities.

The most frequently used method today — besides the simplified "axle box method" described in Section II.D.1 also is the wheel web method. Within this method a number of different technologies are used. The basic principle is that strains are measured at various locations on the wheel web as a result of the applied forces on the wheel as shown in Figure 13.14. A number of strain gauges are applied on the same web, usually in the radial direction on the inside as well as on the outside of the wheel. However, these locations must be carefully selected.

Figure 13.15 shows an example of measured strains in single strain gauges of one wheel web as the wheel rotates and the wheel is loaded by lateral forces Y or vertical forces Q. In order to achieve signals proportional to the applied load, the strain gauges must be combined in Wheatstone bridges in an intelligent and precise way. Separate bridges are required for the lateral Y forces and the vertical Q forces. Sometimes, two bridges are used for the same force on the same wheel, installed at different wheel angles. In this case, additional data processing is needed to combine the two bridge signals. In a few cases, forces are measured in all the three directions: longitudinal, lateral, and vertical. Signals are usually transferred to and from the wheels via slip rings, although radio transmission may also be used.

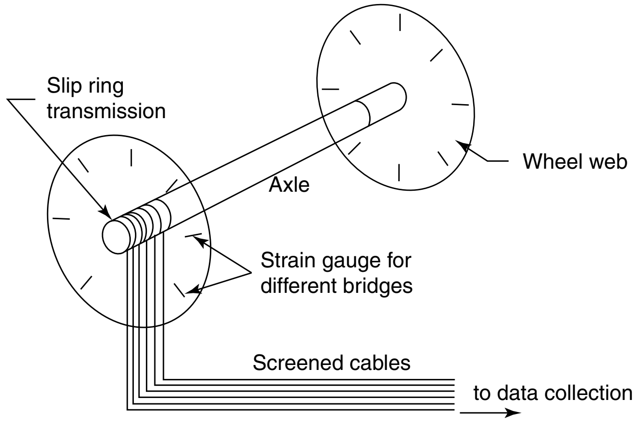


FIGURE 13.14 Schematic arrangement of force-measuring wheelset using the wheel web method.

4. Compensation for Undesired Parasitic Effects

An important issue for force-measuring wheelsets is how to compensate for "parasitic" effects and possible cross talk between forces in the longitudinal, lateral, and vertical directions. The parasitic effects include the influence of wheel rotation, temperature, and temperature distribution and, finally, the location of the forces on the wheels. As described in the previous section, the lateral position of the vertical force application will change by as much as ± 35 mm over the wheel tread, which may generate errors in the output signal. Also, electro-magnetic noise must be carefully considered as very strong currents (1000–2000 A) will sometimes pass just some 50–100 mm away from the wheels and the cabling. Effects of water and humidity, temperature and mechanical impact must also be considered.

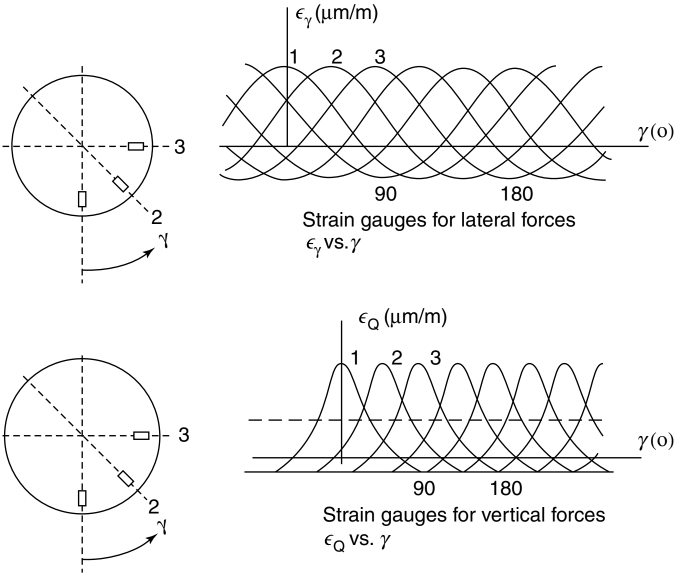


FIGURE 13.15 Example of measured strains in single strain gauges of one wheel web as the wheel rotates — y and q applied at the lowest part of the wheel.

The overall goal is to achieve output signals proportional to the applied loads with a minimum of cross talk and parasitic effects. Several techniques are used for this purpose, for example, in France, Germany, Sweden, U.S.A., and China. The selection of locations for the strain gauges, their connection in bridges and the additional data processing, may vary considerably from one laboratory to another. The design, calibration, and operation of this type of equipment is a highly specialised subject and a detailed description is beyond the scope of this chapter.

The principle advantage of the "wheel web method" is that it is possible to measure the *Y* and *Q* forces continuously quite close to the wheel–rail interface and hence most of the dynamic effect from the unsprung mass is included in the measured data. It is possible to measure quite high-frequency forces (up to at least 100 Hz). The measuring accuracy may be good or at least acceptable (within 5–10% under normal conditions) if wheels and the whole system are properly designed and calibrated. The major drawback is the volume of work required for system design and calibration, requiring specialised knowledge which generally makes the technique very expensive. A further drawback is that the instrumented wheelsets must very often be specifically designed for the type of vehicle to be tested.

E. VEHICLE SPEED AND POSITION MEASUREMENT

A prerequisite of almost all on-track testing applications will be the ability to determine vehicle speed and position. This section discusses the most commonly used approaches to this problem.

1. The AC Tachogenerator

The most commonly encountered means of generating a vehicle speed signal is the AC tachogenerator. This is, effectively, a two-phase induction motor, comprising a rotating magnet with a pair of stator coils arranged at 90° to each other and to the axis of rotation as shown in Figure 13.16. One coil is excited with a constant frequency AC signal. The resulting eddy currents in the core induce an AC voltage in the sensing coil which is proportional to the rotational velocity of the core. The direction of rotation can also be determined from the device as the output voltage phase will change by 180° when the rotation direction is reversed. AC tachometers are generally used as they are less susceptible to noise and "ripple" of the signal than their DC equivalents. They can also be fairly robust, an important consideration as axle box mounted equipment may be exposed to very high accelerations.

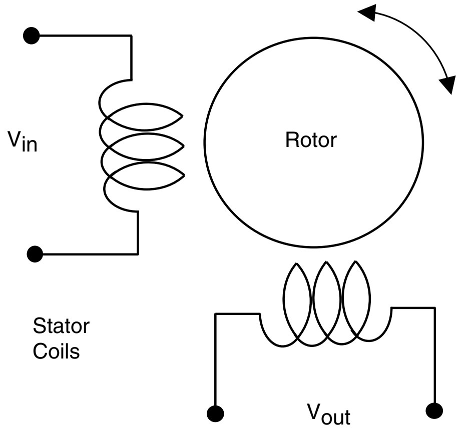


FIGURE 13.16 AC tachogenerator.

In order to determine actual vehicle speed and distance travelled from devices of this sort, the vehicle's wheel diameter at the nominal rolling position must be measured. Inevitably, the accuracy is limited by the lateral movement of the wheel from the nominal rolling position. If measurements are carried out over extended periods, the wheel diameter must be remeasured to compensate for the effects of wheel wear.

2. Hall Effect Probes

An alternative means of measuring wheel rotational speed is with a Hall Effect probe. If a conductor with a current flowing through it is placed in a magnetic field whose direction is normal to the direction of the current, a voltage (the Hall voltage) will be induced across the width of the conductor. This is due to the magnetic field causing the electrons to take a curved path through the conductor. The effect is found most strongly in semiconductors and these are therefore the basis of commercially available Hall Effect probes.[8] Rotational speed measurement is achieved by combining the probe with a ferrous toothed wheel, as shown in Figure 13.17. As the ferrous tooth passes the probe, it causes the reluctance of the probes internal magnetic circuit to change and this change produces a varying Hall voltage where the frequency is proportional to the rotation speed. Once again, if the resulting speed signal is used to estimate distance travelled, the wheel diameter must be known and appropriate corrections made for wear.

3. Ground Speed Radar

This is a noncontact device that relies upon the Doppler effect to measure the vehicle speed. The Doppler effect is based upon the frequency shift that occurs when energy waves radiate from, or are reflected off, a moving object. A familiar example is the change in pitch in the noise from a train passing at speed. Due to the Doppler effect, the pitch increases as the train approaches and then lowers as it departs. For a ground speed radar device, a high, known, frequency signal is transmitted from the radar, aimed at a point on the track beneath the vehicle. The reflected signal will be detected by the sensor and the phase shift from the original transmitted signal will be calculated allowing the velocity of the vehicle relative to the stationary target (the track) to be determined. The Doppler frequency shift is given by:

$$F_{\mathrm{d}} = 2V(F_0/c) \times \cos\theta$$

where F_{d} = Doppler shift Hz; V = velocity; F_0 = transmitter frequency Hz (typically 25–35 GHz); c = speed light; and θ = offset angle.

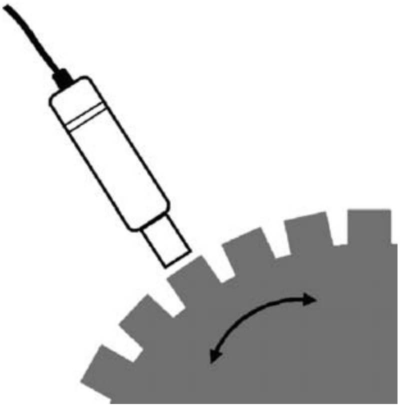


FIGURE 13.17 Hall Effect rotational speed sensor.

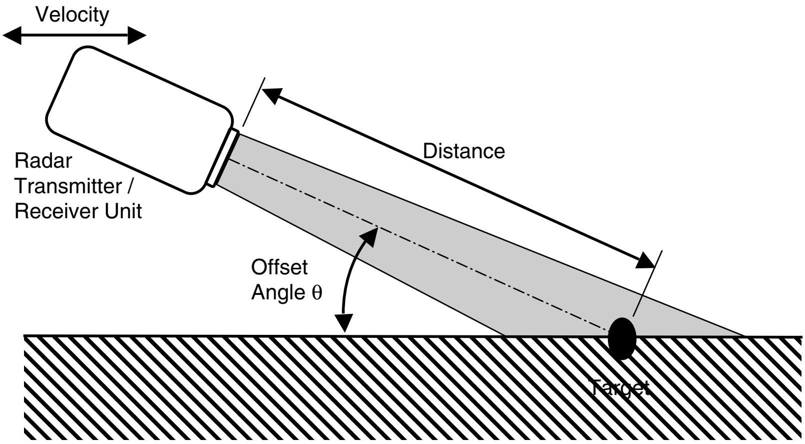


FIGURE 13.18 Simple Doppler effect speed sensor.

A simplified arrangement of a Doppler effect speed sensor is shown in Figure 13.18. It should be noted that the sensor is usually mounted at an angle as shown. This represents a compromise between the strength of the return signal, which is greatest with the sensor vertical and reducing the sensitivity to vertical motion due to the vehicle/bogie bouncing and pitching on its suspension. Larger offset angles can introduce a "cosine error"[9] as targets at the edge of the conical beam will be at a slightly different angle to those in the centre of the beam. Commercially available ground speed radar devices may have two sensors, one of which faces forwards while the other faces backwards. This arrangement can be used to automatically correct mounting or vehicle pitch errors. Devices of this type are typically mounted between 0.3 and 1.2 m from the ground and have an accuracy for speed measurement of better than 1% above 50 km/h. Below this speed the accuracy reduces somewhat (say within 0.5 km/h below 50 km/h) and as such these devices are less suitable when accurate low speed measurements are required.

4. Determining Vehicle Position

Before the advent of global positioning systems (GPS), a vehicle's position was recorded in the test data by means of marking events such as mile/km posts in a separate data channel on the logger. This could be carried out manually by observations from the test coach, or alternatively a known position at the start of the route could be synchronised with a data file containing a list of features and their locations for the chosen test route (known in the U.K. as a "route setting file"). These would then be written to the test data based on the distance calculated from the vehicle speed. When such a method is used, it is normally necessary to resynchronise against an observed position to remove the effects of measurement errors from the speed/distance measurement device.

Modern GPS systems make establishing the location of a vehicle relatively straightforward, provided an asset register is available to relate the logged GPS position to the location of stations and other infrastructure features. GPS is based upon a network of 24 satellites orbiting around 12,000 miles above the Earth. They are arranged so that a GPS receiver should be able to see signals from four of these satellites at any given time. Each satellite transmits low power radio signals which can be detected by a GPS receiver on Earth. The signals contain information which allow the GPS receiver to determine the location of each satellite it is tracking and how far it is from the receiver. Knowing this information for three satellites allows the receiver to calculate a two-dimensional position (latitude and longitude) whilst adding the position of a fourth satellite produces a 3-D position (latitude, longitude, altitude). A more detailed description of the system may be found in Ref.10. Typical accuracies for GPS systems are in the order of 6–12 m. A system known as Differential GPS (DGPS) uses Earth based "reference stations" at known locations to determine corrections to the satellites transmitted positions. Using DGPS, accuracies of 1–5 m or better may be achieved.

For railway test applications, the GPS antenna is mounted on the roof of the vehicle to ensure that the maximum number of satellites is visible. However, since GPS is a "line-of-sight" system, deep cuttings, tunnels, high buildings, and other obstructions will prevent the system from working. In addition, it may be considered advisable to confirm the logged location by "marking" the logged data, either by a manually activated signal against known locations (mileposts, etc.) or automatically by recording signals from trackside balises or signalling devices (e.g., AWS/TPWS loops in the U.K.).

III. TEST EQUIPMENT CONFIGURATION AND ENVIRONMENT

The elements of a typical test arrangement are shown in Figure 13.19. The example shown might be appropriate for gathering data on the suspension behaviour or ride comfort of a vehicle, but the principles apply equally to many on-vehicle or lab test tasks.

Data from the selected transducers is passed through the appropriate conditioning electronics and transmitted to the analogue side of a data logger. Such signals are usually in the form of DC voltages although some devices utilise AC voltage or varying current with a steady DC voltage. The signals are passed through an analogue to digital converter and stored in digital format in the data logger memory. Many systems allow real-time display of the incoming data and this is very useful for checking that the measurement system is performing correctly and that sensitivity settings for different channels are correctly configured. It is essential when vehicle acceptance or safety tests are being undertaken.

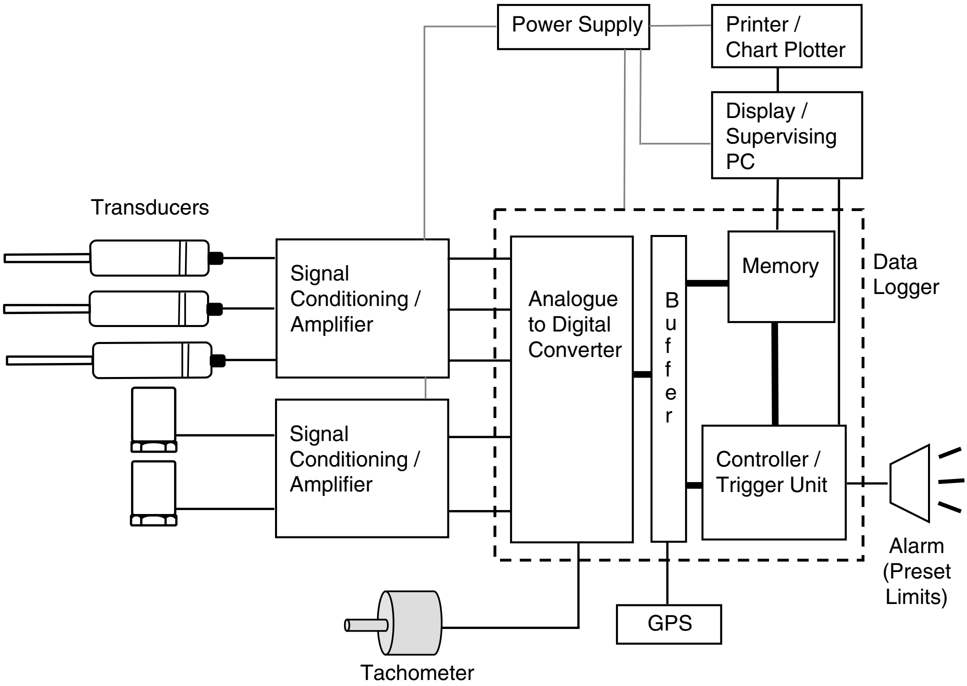


FIGURE 13.19 Typical test equipment configuration.

The railway represents an aggressive environment in which to perform test measurements, and careful attention to detail is required if reliable test set-ups on vehicles or track are to be implemented. Transducers and cabling may be subject to high levels of transient vibrations, particularly if mounted on unsprung components (e.g., axle boxes or rails). Acceleration levels of the order of 30–50 g are not uncommon on axle boxes, and peaks of up to 100 g have been recorded. Extremes of temperature and weather must be catered for and all externally mounted components should resist the ingress of moisture and dirt. The test data must not be affected by electrical noise from a wide variety of source including high voltage AC or DC traction systems. Conversely, the test set-up must preclude the possibility of generating electro-magnetic interference that could adversely affect train control or signalling systems. Fortunately, most commonly used transducers are low voltage, low power devices and hence the problem does not arise.

The following list highlights typical requirements for a reliable installation:

- All brackets should be rigid and robust and should prevent unwanted backlash between the bracket and transducer.
- Cabling should be secured to prevent (insofar as possible) movement. This is particularly important in the case of connections to transducers or joints between cables.
- Cables should be routed to avoid sources of electrical noise (traction motors, pantographs/collector shoes, wiring looms, generators etc.).
- Where possible, signal conditioning should be carried out within the transducers. Where this is not possible (for example, with some types of accelerometer requiring a separate charge amplifier), the distance between the device and the conditioning unit should be as short as possible as very low power signals may be rendered useless by even modest amounts of electrical interference.
- Cables and connectors should be shielded to the highest available standards.
- All transducers, cables, and enclosures should be sealed to a recognised standard such as IP66/IP67.
- Transducers should be selected to prevent the likely peak vibration transients exceeding the "shock loading" specification for the device.
- Cabling lengths should be minimised and be routed inside vehicles at the earliest opportunity. Cables should be arranged tidily and long coils of spare cable should be avoided at the end of cable runs.
- Care should be taken to ensure that expensive transducers and data loggers cannot be exposed to damaging voltage "spikes."

Sources of power are an important consideration when conducting field testing. It is generally recommended that when using power other than from the mains (for example, from generators or vehicle sources), suitable voltage stabilisation and surge protection devices are used. In many cases, field power supplies cannot be guaranteed and an alternative battery backup should be arranged to guard against the loss of important test data.

A. TRANSDUCER POSITIONS ON VEHICLES

One of the most common instrumentation applications that the vehicle dynamics engineer will encounter is the fitting of accelerometers and displacement transducers to the body, bogies and suspension, for ride test, passenger comfort, or dynamic response track tests. When choosing the locations for instrumentation, it is important to clearly understand the vibration modes that each transducer will "see" to ensure that the correct data is gathered and that the desired information can be derived from it.

It is evident from Figure 13.20 that a vertical accelerometer mounted on the vehicle floor in line with the vehicle centre of gravity ($A1v$) will largely sense to the bounce mode responses to the track

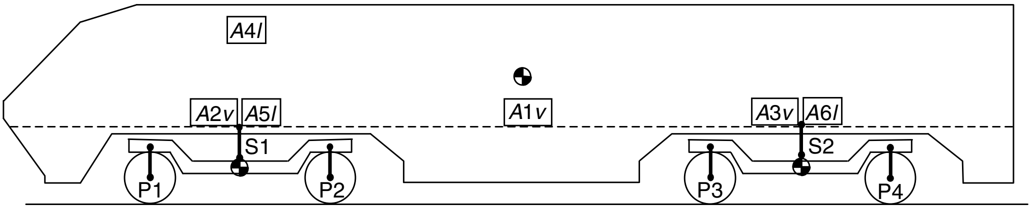


FIGURE 13.20 Simple transducer layout. Key: *Axv*–vertical accelerometers, *Axl*–lateral accelerometers, Px–primary suspension LVDTs, Sx–secondary suspension LVDTs.

input. As it is not practical to actually mount the accelerometer at the centre of gravity, some accelerations due to the change in floor height as the vehicle rolls will also be detected. Vertical accelerometers mounted on the vehicle floor above the bogie centre pivots (*A2v* and *A3v*) will sense both the bounce and pitch mode responses. However, whilst accelerations due to body bounce will be in phase at both transducers, the accelerations due to pitching will be 180° out of phase. Assuming that the carbody is perfectly stiff, i.e., that no flexible modes occur, the pitch and bounce components of the signal at accelerometer *A2v* can therefore be separated thus:

$$A2_{\text{bounce}} = (A2v + A3v)/2$$

$$A2_{\text{pitch}} = (A2v - A3v)/2$$

Similarly, accelerometers *A5l* and *A6l* will sense body lateral and yaw responses in and out of phase, respectively. *A4l* will likewise sense a combination of body yaw, lateral, and roll modes. Providing that sufficient transducers have been provided, and their locations chosen carefully, it should be possible to reliably establish the natural frequencies of the various modes of vibration of the vehicle body. The sensed accelerations on the body will also include the effects of flexible body modes. These may also be of interest to the dynamics engineer (for example, when considering the effect of the first body bending mode on passenger comfort). Accelerometers will also detect inputs from body mounted mechanical equipment such as internal combustion engines and compressors. However, these will often occur at constant frequencies, somewhat higher than the frequencies of interest to the dynamics engineer and may, if desired, be easily removed by filtering.

Similar considerations to those described above will also apply to accelerometers mounted on the bogie frame or displacement transducers fitted across the primary or secondary suspension. Accurate records should be made of the mounting positions of all transducers on the vehicle to allow for later correction of geometric effects.

IV. DATA ACQUISITION

Test data must be collected and store in a suitable form for later analysis. In the past this was often carried out using magnetic media such as tape recorders to allow large volumes of data to be stored. However, modern computer systems are able to directly store such large volumes of data, making tape storage largely redundant. Modern data loggers are usually either in the form of a PC with suitable additional hardware cards and software, or a standalone device with a PC compatible up-link. In either case the analogue signals from the test devices must be converted to digital form to allow the data logger to store them. In addition to logging varying voltage or current signals from transducers, loggers may also have additional hardware inputs for digital signals and serial data (for example an RS232 connection to a GPS).

As computers/data loggers store information in digital format, and most transducers provide an analogue signal, an analogue-to-digital converter (ADC) is required to convert the signal.

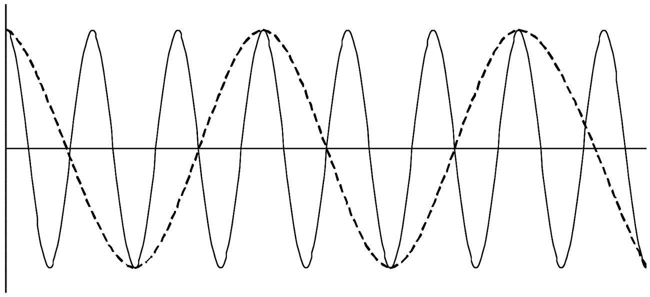


FIGURE 13.21 Aliasing due to insufficient sampling rate.

The process of sampling and converting the signal leads to the possibility of two forms of inaccuracy in the digitised signal, known as aliasing and quantisation errors.

A key decision when setting up a data logging system is the sampling rate. This is the time interval at which the logger takes a “snapshot” (sample) of the incoming analogue signal. If the sampling rate is too low, a high frequency signal may appear incorrectly as a lower one, as illustrated in Figure 13.21. Although the aliased frequency shown here is one third the actual signal frequency, a whole series of aliases are possible depending upon the sampling frequency chosen. Theoretically, the chosen sampling rate should be at least twice the highest frequency (of interest) in the sampled signal. However, in practice, it is normal to sample at between five and ten times the highest frequency required in order to ensure good representation of amplitude as well as frequency.

An additional aliasing problem can arise if the sampled signal is degraded by an unknown, high frequency, noise component. A sampling rate of, say, ten times the highest frequency of interest, could cause this noise to be aliased into the measurement frequency range giving incorrect results. The solution in this case is to low pass filter the signal using an analogue filter prior to sampling to remove the unwanted component. This precaution is known as anti-alias filtering.

Quantisation errors are introduced by the ADC forcing a continuous analogue signal into a limited number of discrete levels (binary digits or “bits”). The error will be present in all digitised signals and has the effect of restricting the dynamic range of the signal. The magnitude of the error will be proportional to the resolution of the ADC. Quantisation errors are not generally a serious restriction for modern data loggers. However, care should be taken to ensure that the full range of the ADC is used. For example, consider an ADC using an 8-bit conversion, which allows 256 discrete states of the converted signal. If the ADC range is set to ± 1 V and a ± 1 V signal is converted, the digitised signal will consist of 256 discrete values and will give a good representation of the original analogue signal. However, if the same signal is passed through with the ADC range set to ± 10 V, the ± 1 V signal may only have 256/10 discrete values and a significant quantisation error results. It also follows, therefore, that the potential for quantisation errors are larger when a signal has a wide dynamic range.

Once the signal has been converted to digital format, further operations can be performed easily, such as filtering, bias or offset removal, amplification, etc. Detailed discussion of digital signal processing techniques is beyond the scope of this chapter, but numerous texts exist to guide the interested reader.

Important considerations when selecting a data logger include:

- The number of transducers to be used in the test, and hence the number of channels required by the data logger.
- The rate at which each transducer is to be sampled. Modern data loggers are generally capable of sampling at very high frequencies (of the order of kHz), many times higher than required for most railway vehicle dynamics applications. Many loggers allow

different sample rates to be set for different channels, though these must generally be divisible by the highest sample rate chosen.
- The duration of the test and hence the volume of data to be stored. Assuming each sample for one transducer represents one byte, this can be easily calculated by multiplying the sample rate, the number of channels sampled and the required test duration to give the storage volume needed.
- The resolution of the analogue-to-digital converter. This must be high enough to allow the transducer data to be collected to the required precision.
- The construction of the data logger. A PC may be appropriate for lab test work, but on-train applications may require a more rugged construction. This will depend partly upon whether the logger is to work in a test vehicle on a temporary basis or to remain in a service vehicle over extended periods. It should be noted that traditional computer hard disk drives are not reliable when subjected to substantial or prolonged vibration and, for on-train systems, consideration should be given to using more rugged components (such as flash memory).
- The method of sampling employed. Most high-end data loggers sample all the required channels simultaneously ensuring that the data is perfectly synchronised. However, modern logging devices are available very cheaply that, whilst only sampling each channel sequentially, can do so at high frequencies. Where a small number of channels is only required to be sampled at low frequency, these loggers may be adequate.
- The interface required during the tests. A logger may be required to record data unattended, in which case no interface is required. Alternatively, a real-time display of all the data being logged may be needed allowing, for example, alarm thresholds set to give warnings if predetermined levels are exceeded on any channel. Logging tasks which also require extensive real-time calculations to be performed on the logged data may require the development of dedicated software.

It is always advisable to have the ability to view measured data on-line when conducting on-track testing work where the ability to repeat tests is limited. This is particularly important on the first day of an extended test programme in order to ensure that all data is as expected and to ensure that errors do not occur in the complete measuring system due to faulty scaling factors, electrical noise, etc.

V. MEASUREMENT OF WHEEL AND RAIL PROFILES

The accurate measurement of wheel and rail profiles is critical to many vehicle dynamics simulation tasks. Early measuring devices for such tasks relied on moving a stylus over the profile, the shape being transferred via a linkage with a pen attached to a piece of tracing paper. An alternative mechanical measuring method used an indexing plate to allow a dial-test-indicator to be moved to a number of known positions around the wheel or rail, a reading being taken at each. Such devices tended to be labourious to use and required the data to be manually entered into a computer for use in dynamics simulations. Several proprietary devices are available for making such measurements. These devices either use a mechanical linkage or a laser beam to electronically record the cross sectional rail or wheel profile in terms of Cartesian coordinates. Vehicle dynamicists will usually require a high degree of accuracy to be maintained when taking profile measurements as wheel/rail forces may be significantly affected by variations in shape of a few tenths of a millimetre. In general, measuring systems to provide this level of accuracy rely on readings being carried out manually during track walks or depot visits. Caution should be exercised if using data from automated in-track or on-train inspection systems as the need to carry out measurements at speed may limit the accuracy of the recorded profile.

The device must be capable of measuring not only the profile, but also its correct orientation in the lateral-vertical plane. Small errors causing rotations of a wheel or rail cross sectional profile will

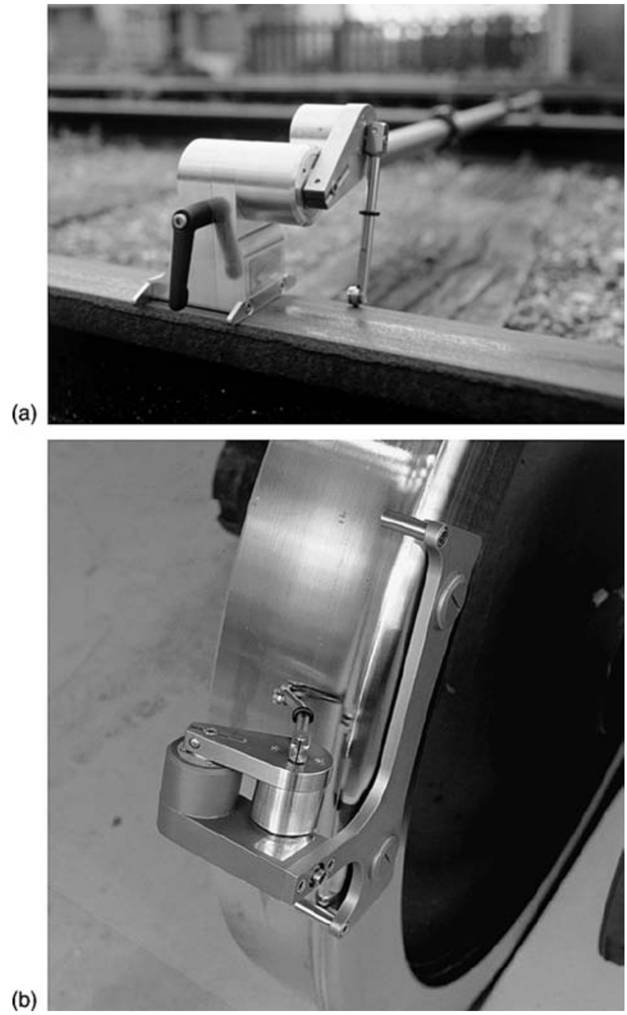
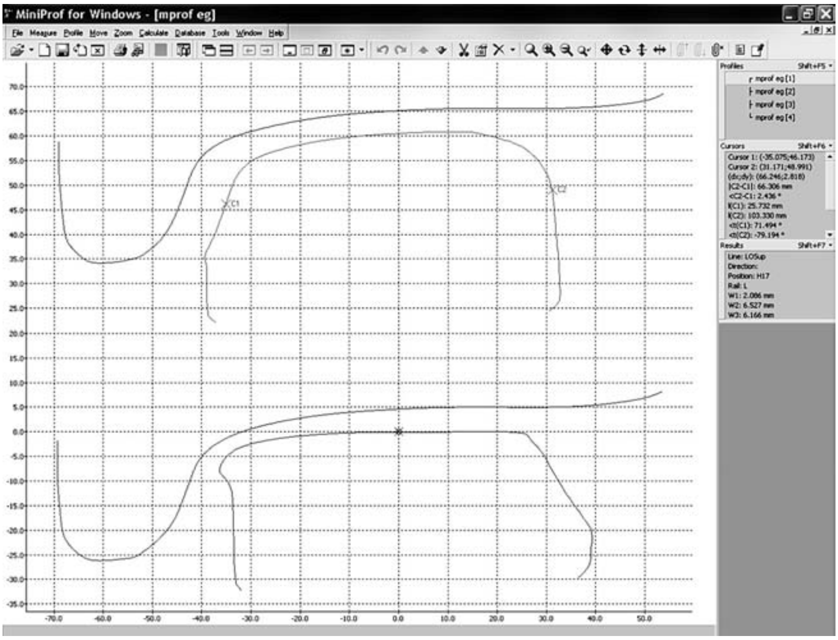


FIGURE 13.22 MiniProf rail and MiniProf wheel measuring instruments (courtesy of Greenwood Engineering). *Source*: Catalogue — Courtesy of Greenwood Engineering.

appreciably alter the resultant contact conditions and the resulting equivalent conicity and must be avoided for realistic simulations. Several devices use the flangeback as the datum position for wheel profile measurements. This simple approach may generate significant errors when measuring profiles where the flangeback is worn, for example, by contact with check rails. Experience shows that this simple approach therefore has limitations. For measurement of both wheel and rail profiles, the device should have an outrigger which bears on the opposite wheel or rail to ensure that the measuring head remains in plane of the track/wheelset. Such equipment is not generally available for measuring wheels. In all cases, however, a system using two measurement heads capable of recording a pair of wheel or rail profiles and their relative orientation simultaneously will provide superior results.

As the requirement is generally to gather profiles which are representative of a given location or situation, the exact position at which profiles are measured should be chosen with some care to avoid localised pits or defects. Profiles should always be cleaned prior to taking the measurement as contamination on the wheel or rails (e.g., dirt, wear debris, or grease) may prevent accurate recording of the profile shape. Similarly, it is particularly critical that the measuring head of contacting devices is also kept clean.



mprof eg [1]
mprof eg [2]
mprof eg [3]
mprof eg [4]

Cursor 1: (-35.075;46.173)
Cursor 2: (31.171;48.991)
(dx;dy): (66.246;2.818)
|C2-C1|: 66.306 mm
<C2-C1: 2.436 °
l(C1): 25.732 mm
l(C2): 103.330 mm
<t(C1): 71.494 °
<t(C2): -79.194 °

Line: LOSup
Direction:
Position: H17
Rail: L
W1: 2.086 mm
W2: 6.527 mm
W3: 6.166 mm

FIGURE 13.23 Viewing measured profiles using MiniProf software (courtesy of Greenwood Engineering). *Source*: Catalogue — Courtesy of Greenwood Engineering.

An example of a widely used device is the MiniProf (Figure 13.22). The measuring head in this case (which is common to both wheel and rail devices) consists of two arms and two rotary optical encoders. These are used to determine the position of a magnetic measuring wheel. As the operator moves the measuring wheel around the profile, the signals from the encoders are logged by a laptop computer. The profile of the wheel or rail being measured is then calculated from the position of the two arms as obtained from the encoders, with suitable correction being applied to allow for the varying contact position on the measuring wheel itself. The use of a wheel rather than a stylus has a filtering effect upon the measured profile, as the wheel cannot follow very small surface irregularities. However, providing that the radius of the measuring wheel remains significantly smaller than the smallest wheel or rail profile radius, this effect is of little importance. Software supplied with the MiniProf allows profiles to be viewed and provides the facility to undertake various geometric wear calculations against "reference" profiles (Figure 13.23).

Although less widely used, other profile measuring devices exist, only some of which are suitable for use in vehicle dynamics simulations or for a detailed study of wheel–rail contact conditions. The general requirement is for a high degree of measuring accuracy, probably better than 0.02 mm. Some devices using scanning lasers are suitable for this application, although other displacement or rotation measuring transducers are also likely to be suitable. In the past, systems designed to give "real time" measurements of wheel profiles, either track based automated systems in depots or train based systems, have not achieved sufficiently high accuracy levels. This is because some of the accuracy is sacrificed for speed of measurement. However, with advances in scanning laser technology, this may well change in the future.

VI. TRACK GEOMETRY RECORDING

The vehicle dynamics engineer frequently requires data describing real, representative track geometry as a basis for simulating vehicle behaviour. It is convenient, for both maintenance engineers and vehicle dynamicists, to separate the long wavelength features that represent the design layout of the track from the short wavelength features that form the variation from the design (i.e., the track irregularities). This usually results in a description based on the following five geometrical terms:

Curvature — the lateral design layout of the track radii (long wavelength). Curvature is defined as the inverse of the curve radius in units of rad/km. However curvature may also be quoted as a "versine" measurement in mm, this being the distance from the centre of a chord of known length to the rail.

Cant — the vertical difference in height of the left and right rails, (long wavelength).

Lateral alignment — the short wavelength lateral track irregularities.

Vertical alignment — the short wavelength vertical track irregularities.

Gauge — the distance between the rails measured at a specified distance below the crown of the rail. This is typically 14 mm in the U.K. and Europe and 5/8 in. in North America. Gauge may be given as an absolute value or a variation from a nominal gauge (e.g., 1435 mm European standard gauge).

The geometry of railway track may be recorded using one of several techniques.

A. MANUAL SURVEY

The surveyor establishes a datum (or several datums) position on the site to be surveyed, usually by placing a marker in the ground. A theodolite is then used to record the position of the left and right rail with reference to the datum position. Considerable care is required to produce accurate results from these techniques. Good results have been achieved by using a high accuracy "autotracking" theodolite measuring to a target placed on the fixed end of a cant and gauge stick above the rail gauge corner. The theodolite is then used to measure the position of one rail, and the position of the adjacent rail is determined from the cant and gauge measurements displayed on the stick (see Figure 13.24).

In the absence of other methods, useful results may be obtained for track design curvature by conducting a versine survey. In this case, a chord (wire) of fixed length is stretched along the high rail of the curve and the distance between the centre of the chord and the gauge corner is measured. Chord lengths of 10, 20, or 30 m are common depending on the curve radii to be measured. The chord length is normally chosen so that the measured versine does not exceed 150 mm on the tightest curve to be surveyed. Successive versine measurements are taken at frequent intervals, with the maximum recommended interval being half the chord length. Increasing the measurement frequency will increase the detail contained in the survey results. The radius of curvature at any mid-chord position can then be calculated as follows:

$$R = \frac{C^2}{8V}$$

where: R = curve radius (m); C = chord length (m); and V = versine (mm).

FIGURE 13.24 Cant and gauge stick (courtesy of Abtus Ltd.). *Source*: Abtus Ltd. — Catalogue. With permission.

However, the ability of such techniques to "see" short wavelength lateral irregularities is inherently limited as the position of the datum (the wire itself) depends upon the track irregularities at either end of the wire. This survey method is simple and cheap to carry out and requires limited equipment, but has the disadvantage of needing three people to undertake the survey.

Manual surveys are generally fairly slow to carry out and are therefore limited to short sections of track.

B. TRACK GEOMETRY TROLLEY

A number of proprietary recording trolleys are available. These carry instrumentation and a data logging system to allow track irregularities to be measured. They commonly measure vertical irregularities cross-level and gauge and (less commonly) lateral irregularities and curvature. An electronic record of the geometry is stored in the on-board data logger for later retrieval, and many trolleys also provide a paper-trace of the stored data. Some feature on-line calculations allowing alarms to be set for exceedances in, for example, track twist over a given distance. Trolleys are generally pushed at walking pace by an operator, though some are self-propelled at low speed. The length of line that can be surveyed by this method is generally greater than for manual surveys, but is limited by the slow recording speed and the capacity of the on-board data logger and power supplies (Figure 13.25).

C. TRACK RECORDING VEHICLES

Most railway administrations operate dedicated track geometry recording vehicles. These vehicles are equipped with measuring systems, often based upon the inertial principle described below, which allow data to be gathered at high speeds (typically up to 185 km/h). Such specialist vehicles have extensive data storage and analysis capabilities which allow regular surveys of entire routes to be undertaken at normal running speeds. These vehicles provide the most commonly used source of data for vehicle dynamics engineers.

The following description of the inertial measurement is based upon the track recording systems used in the U.K. and described in Refs 11–13. The general principles are, however, common to all systems of this type. The signal from an accelerometer mounted on the vehicle body is double integrated to provide a displacement measurement. This is then low-pass filtered to

FIGURE 13.25 Track geometry recording trolley (courtesy of Abtus Ltd.). *Source*: Abtus Ltd. — Catalogue. With permission.

remove the long wavelength design information, effectively creating a moving average datum for the measurement of the shorter wavelength features.

Vertical (track top) measurements are made using one wheelset on the vehicle as the sensor. Displacement transducers are fitted across the primary and secondary suspension as shown in Figure 13.26, with an accelerometer mounted directly above them. Subtracting the suspension displacements from the body displacement (double integrated from the acceleration) gives the track top profile. As the suspension movements are removed from the final answer, the system is effective regardless of suspension type.

Noncontact measurement of the track gauge at high speed presents a considerable challenge. Early systems projected a narrow beam of light onto the railhead and used cameras to measure the intensity of the reflected light and thus determine the location of the gauge face. Recent developments include using a laser beam is guided onto a point 14 mm below the crown of the rail, the normal gauge measuring point, by a mirror. This mirror is “steered” by a galvanometer, responding to suspension displacement measurements. Alternatively, a fanned array of laser beams may be projected directly onto the railhead. In either case the reflected laser light is then used to measure the position of left and right rails, and these are combined to obtain the gauge (Figure 13.27).

The lateral irregularity of the track is obtained by subtracting the rail position, measured by the laser displacement sensors described above from the inertial datum produced by a body mounted lateral accelerometer.

The cross-level is determined by subtracting the difference in the vertical suspension displacements from the body roll angle obtained from an on-board gyroscope. The gyroscope also provides the plan view rate of turn of the body and this, together with the vehicle velocity, allows the curvature to be calculated.

The foregoing description is, of necessity, a somewhat simplified version of what is a sophisticated and complex measuring system. It is worth noting that the lateral irregularity and curvature channels are effectively short and long wavelength parts of the same signal. Track geometry data is normally supplied at 0.2–0.25 m intervals in the U.K. and will not therefore adequately capture very short wavelength features, less than 1.5 m, such as dipped joints. The system also does not capture wavelength greater than 70 m, and being inertially based will only provide data above 30 km/h. Other systems are now becoming available, capable of measuring

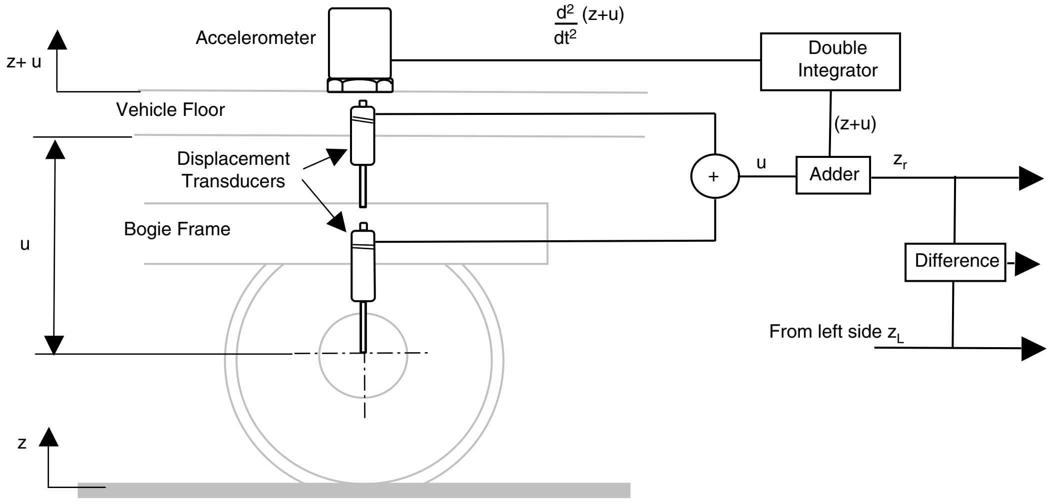


FIGURE 13.26 Vertical measuring system schematic.

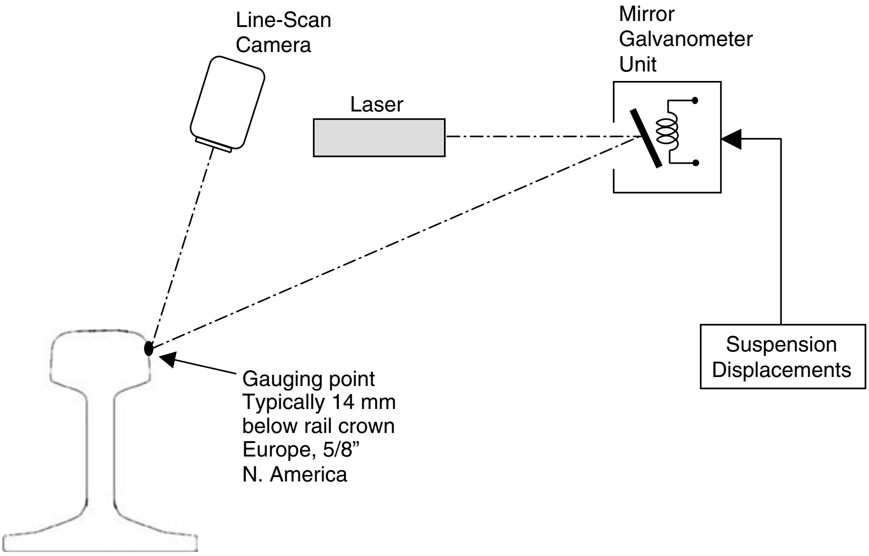


FIGURE 13.27 Noncontact measurement of rail position.

longer wavelengths up to at least 100 m, for example the Swedish STRIX system, developed by Banverket Production.

It can be seen that all the data required by the dynamics engineer to reconstruct the track geometry is available from this type of track geometry vehicle. However, several operations must be carried out to ensure it is suitable:

- As transducers are mounted on different parts of the vehicle, there will be an offset or lag in the some raw data channels depending upon the position of the transducers used to obtain them. This offset may also vary depending upon the direction in which the vehicle is running. These offsets are normally removed from the data at source, but this should be confirmed.
- Filtering data introduces both phase and amplitude distortion in the filtered signal compared with the original. As the cross-level and gauge channels are not filtered, the filtering will also introduce an offset between channels. Clearly, this offset is not a realistic representation of the real track geometry and, as it can significantly affect simulation results, it must be corrected. This is done by re-passing (backfiltering) the data through a filter of the same design as that originally used. This restores both the phase and amplitude distortions caused by filtering.

Track recording vehicles may also record a range of other parameters such gradient and cant deficiency and may derive other measures, for example, track twist or cyclic top from the raw data.

D. CHORD OFFSET MEASURING SYSTEMS

Vehicle based chord offset measuring systems rely on the same three-point measurement of versines described in Section VI.A above. In this case however, the chord is the vehicle wheelbase and a third wheelset or bogie is placed in the centre of the vehicle to provide the measurement at the 1/2-chord position. As discussed above, versine measurements have the distinct disadvantage that they have an inherent geometric filtering effect that prevents them from “seeing” particular wavelength ranges. Attempts have been made to improve this problem including fitting a number of measuring wheels so that a better reference line can be used. However, this offsets the essential benefit of this method, namely its simplicity.

Chord offset based measuring vehicles are no longer in common usage and data measured by such systems should be treated with some caution by the dynamics engineer for the reasons discussed.

VII. EXAMPLES OF VEHICLE LABORATORY AND FIELD TESTS

This section provide examples of laboratory and field tests that may be commonly encountered by, or provide useful information for, the vehicle dynamics engineer. Whilst they are based specifically on U.K. practice, similar tests are employed by many railway administrations worldwide.

A. STATIC/QUASI-STATIC TESTS

These tests are normally carried out on a vehicle in a specialist laboratory. The results may be used to gain confidence in the general behaviour of a vehicle model and also to estimate the additional (parasitic) stiffness present in the completed vehicle. However, as the dynamic behaviour can vary considerably from the static behaviour, some comparisons against dynamics tests (such as ride tests) are required to enable a vehicle model to be fully validated.

1. Wheel Unloading Test

This test is detailed in Appendix A of Ref. 14. Packings are placed under the wheels on one side of the vehicle to reproduce the track twist feature shown in Figure 13.28. The resulting wheel loads are measured using a load cell and expressed in terms of the change from the static load $\Delta Q/Q$. The test is repeated to place each corner of the vehicle in turn at the bottom of the dip. The limiting $\Delta Q/Q$ value is normally specified as 0.6 (Figure 13.29).

2. Bogie Rotational Resistance Test

This test is detailed in Appendix B of Ref. 14. One bogie is placed on a turntable and rotated both clockwise and anticlockwise to an angle that represents the minimum operating curve radius for the

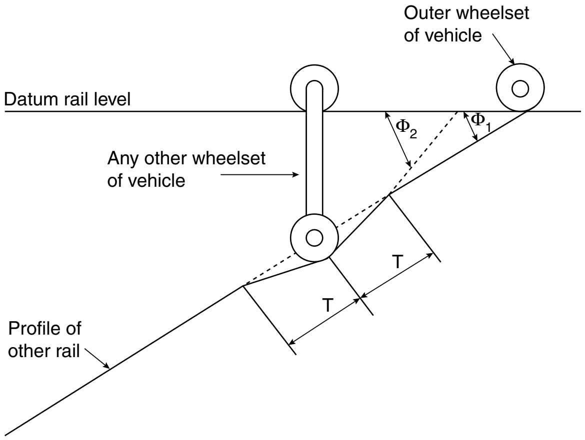


FIGURE 13.28 GM/RT2141 Appendix A, track twist geometry for $\Delta Q/Q$ tests. *Source*: RSSB — GM/RT 2141 Railway Group Standard.

FIGURE 13.29 Wheel unloading test.

vehicle. The test is usually performed at 0.2 and 1°/sec rotation speeds and the torque required to rotate the bogie is measured (Figure 13.30). Where yaw dampers are fitted, they may or may not be disconnected during the test depending on the test requirements. If yaw dampers with positional control (i.e., designed to blow-off at a particular bogie rotation angle) are included, the results from the test will reflect both the velocity and displacement dependent nature of such an arrangement. It follows that the vehicle model must be simulated in the same condition if comparable results are to be achieved. The resulting *X*-factor is calculated as follows:

$$X = \frac{\text{Body to bogie yaw torque}}{\text{Wheelbase } x \text{ axleload}}$$

The limiting value is 0.1 except for freight vehicles < 8 tonnes axle load.

The measured bogie rotation torques are particularly useful when confirming the behaviour of a vehicle model with friction sidebearers or airspring secondary suspensions. Typical examples of results from such tests for various vehicles are shown in Figure 13.31.

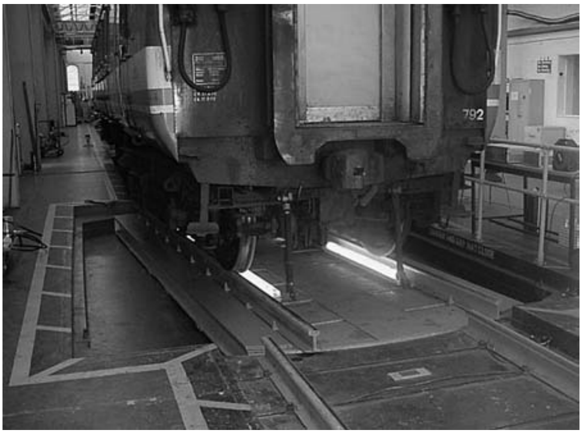
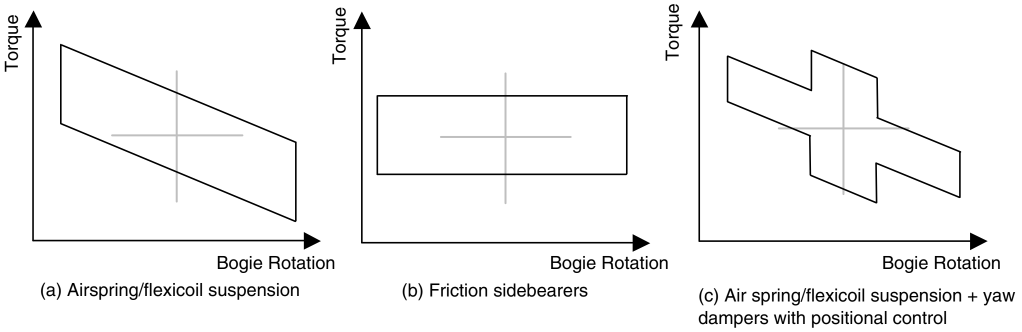


FIGURE 13.30 Bogie rotation test.



(a) Airspring/flexicoil suspension (b) Friction sidebearers (c) Air spring/flexicoil suspension + yaw dampers with positional control

FIGURE 13.31 Typical bogie rotation test results for common suspension types.

Before a bogie rotation test is carried out, the bogie is normally moved slowly to it maximum rotation position to check clearances between all body and bogie mounted equipment.

3. Sway Test

Such tests are normally carried out to generate the input data for the kinematic gauging process or to verify that the vehicle will remain within a predetermined static envelope. Their usefulness to the dynamics engineer is in enabling a reasonable estimate of the parasitic stiffnesses (particularly in roll and lateral directions) to be made. A number of targets are fixed to the end of the vehicle at cantrail, waistrail, and solebar level. One side of the vehicle is raised in stages to approximately 10° of cant. A theodolite placed some distance from the end of the vehicle is used to measure the displacement of the targets as the vehicle is raised. Additional measurements of vertical and lateral suspension movement may prove useful when comparing test and model results (Figure 13.32).

FIGURE 13.32 Sway test. *Source*: Photo — courtesy of Serco Railtest Ltd.

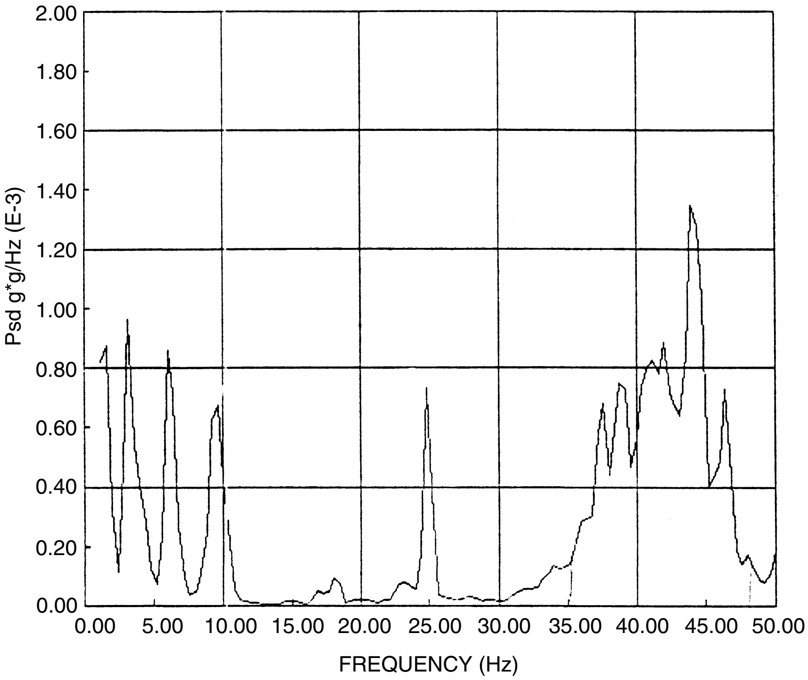


FIGURE 13.33 PSD of body vertical acceleration, mainline diesel locomotive.

4. Body Modes Tests

Such tests are generally commissioned to provide the dynamics engineer with confirmation of the fundamental vibration modes of various parts of the vehicle. They are useful for comparison with the eigenvalue analysis used at the model checking stage as they will include the effects of all the parasitic stiffnesses. Tests are usually performed by disconnecting the vehicle dampers and then applying a sine sweep displacement signal in the direction of interest via an electric or hydraulic actuator. The response of the vehicle body is measured using both vertical and lateral accelerometers mounted at various positions along the length of the vehicle. These tests may also be used to confirm the first body bending mode.

B. DYNAMIC TESTS

Vehicle ride tests provide the means to validate the dynamic behaviour of a model. The vehicle will typically be instrumented with accelerometers at various positions on the body, bogie frame, and axle boxes, and this may be complemented with displacement transducers to measure primary and secondary suspension displacements. To be of maximum value for model validation purposes, the data should also include the vehicle speed and location and be accompanied by recent track recording coach data for the test route and measured wheel profiles from the vehicle at the time of the test.

Raw acceleration data from ride tests is normally expressed in terms of the power spectral density (p.s.d.) of the signal vs. its frequency range, as shown in the example in Figure 13.33. The test data p.s.d. plots are likely to include peaks representing the rigid body modes, flexible modes, and rail length passing frequencies. They may also include peaks associated with the traction unit, originating from vibration of the engine or driveline. The results may be further sorted into speed banded p.s.d. to assist in identifying speed dependent effects such as excitation of various body/bogie modes and response to cyclic track geometry. Additionally, the test data may be analysed in sections according to track type to determine the vehicle's response to changes in track construction (welded, jointed etc.) and track quality. Care should be taken to ensure that a full understanding of the vehicle behaviour is reached under a range of conditions including any evidence of hunting or of body modes being driven by other modes such as bogie pitch.

The measured wheel profiles, track geometry, and speed data can be used to set up a time stepping integration (transient analysis) for the model in question, simulating the test run and outputs. The outputs from this simulation will be accelerations (and displacements) from specified positions on the vehicle such that they replicate the signals seen by the real instrumentation. Test data and model results can then be compared both in terms of time histories and power spectral densities. It is important to note that if the test data is filtered, the characteristics of the filter must be known to allow the simulated data to be treated in the same way.

Wheel–rail forces themselves can also be validated if test data is available from force–measuring wheelsets. However, their use may be restricted due to their high cost and the difficulties of acceptance.

REFERENCES

1. CEN. *Railway Applications — Testing for the Acceptance of Running Characteristics of Railway Vehicles — Testing of Running Behaviour and Stationary Tests*. prEN14363, December 2004.
2. UIC: *Testing and Approval of Railway Vehicles from the Point of View of their Running Behaviour — Safety — Track Fatigue — Ride Quality*. Code 518 OR, Draft September 2003.
3. Turner, J. and Hill, M., *Instrumentation for Scientists and Engineers*, Oxford University Press, Oxford, 1999.
4. Serridge, M. and Licht, T. R., *Piezoelectric Accelerometers and Vibration Preamplifier Handbook*. Bruel and Kjaer, Revised November 1987.
5. Berther, T., Gautschi, G. H., and Kubler, J., Capacitive accelerometers for static and low-frequency measurements, *Sound Vib.*, June, 1996.
6. Window, A. L. and Holister, G. S., Eds., *Strain Gauge Technology*, Applied Science Publishers, Barking, 1982.
7. Gabrielsson, O., Analysis of a New Method for Measuring Wheel–Rail Forces, Report 1996, 24, KTH Railway Technology, 1006.
8. Sinclair, I., *Sensors and Transducers*, 3rd ed., Butterworth Heinemann, London, 2001.
9. Anon: Fundamentals of Non-Contact Speed Measurement Using Doppler Radar. *Application Note 1000 Rev 1.1*, GMH Engineering, 2003. (Available from http://www.gmheng.com).
10. Anon: GPS Guide for Beginners. *Garmin Corporation Part no 190-00224-00* Revision A, 2000. (Available from http://www.garmin.com).
11. Lewis, R. B., Track recording techniques used on British rail, *IEE Proc.*, 131(3), Part B, May 1984, .
12. Lewis, R. B. and Richards, A. N., A compensated accelerometer for the measurement of railway track crosslevel, *IEEE Trans. Veh. Technol.*, 37(3), August 1988.
13. Track Recording Handbook. *Railtrack Line Code of Practice RT/CE/C/038*, Issue 1, Rev B, February 1996.
14. Resistance of Railway Vehicles to Derailment and Rollover. *Railway Group Standard GM/RT2141*, Issue 2, October 2000.