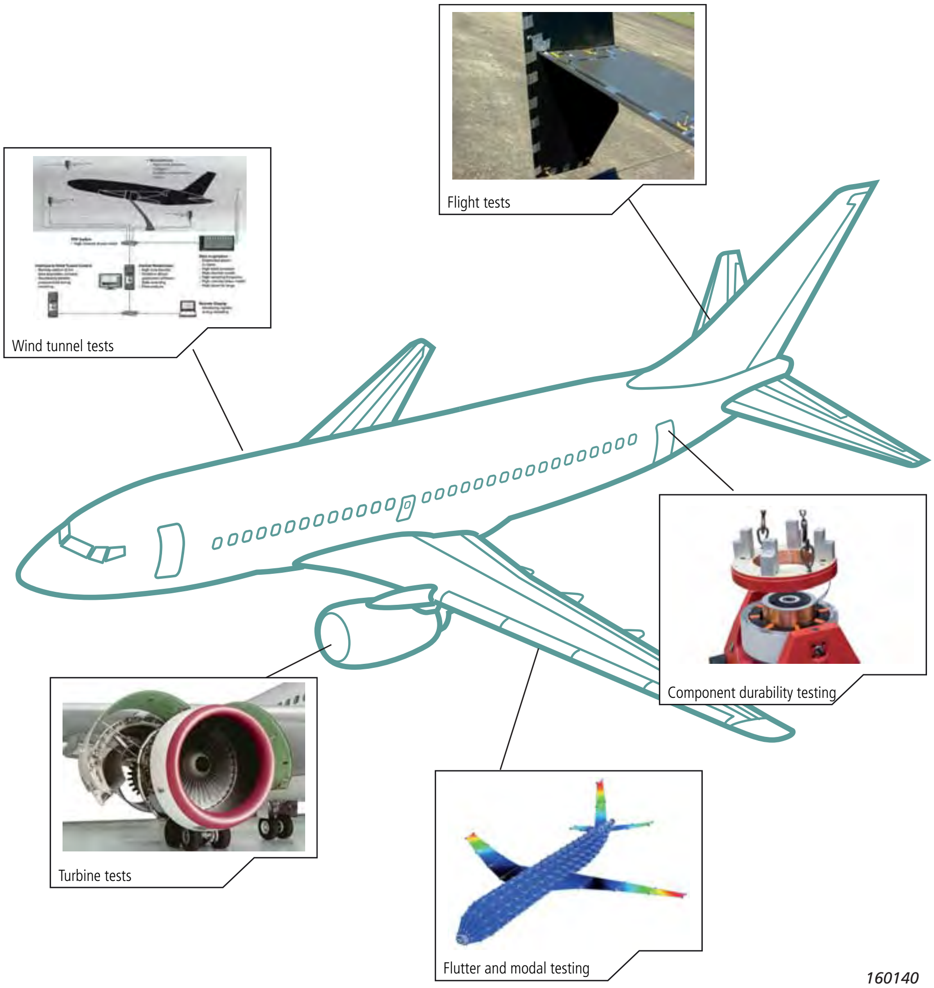
APPLICATION NOTE

Brüel & Kjær

Performing Bridge Measurements with LAN-XI

The basic principles behind the hardware



Bridge Module Type 3057* is a three-channel 102.4 kHz LAN-XI module intended primarily for dynamic measurements using bridge-type transducers and pressure sensors. The module supports strain gauge bridges and has built-in half-bridge and quarter-bridge completion and shunt calibration. Additionally, the module supports the dynamic strain gauge configuration for AC strain measurements with minimum mounting and cabling effort.

Type 3057 contains a built-in bridge excitation supply that can be configured either as a 0 – 10 V constant voltage source with optional remote sensing, or as a 0 – 25 mA constant current source.

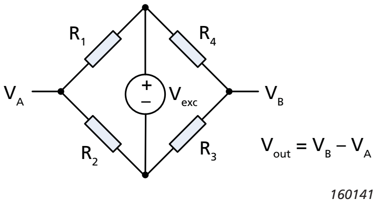
This application note contains a presentation of the common terms and most basic principles used in bridge measurements, seen in relation to Type 3057.

Description of a Bridge Transducer

A bridge transducer is any transducer that is electrically configured as a Wheatstone bridge, which is the circuit arrangement shown in Fig. 1. Examples include strain gauge bridges, bridge accelerometers, pressure sensors, and load cells.

The bridge consists of four variable or fixed resistances $R_1 – R_4$ and requires a supply voltage V_{exc} or a supply current I_{exc} applied to it in order to produce an output signal. The supply voltage or current is known as the bridge excitation. Without a physical input, the four resistances are pair-wise equal in value ($R_1 = R_2$, $R_3 = R_4$) and the bridge produces zero output. In this case it is said to be balanced.

Fig. 1 *Electrical configuration of the Wheatstone bridge*



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* The module's full type number is 3057-B-030.

A bridge transducer works by translating the physical input into a change in one or more of the resistances $R_1 – R_4$. When this happens, the bridge comes out of balance and produces a differential output between points V_A and V_B. This output can be sensed with LAN-XI Module Type 3057, which is capable of measuring differential signals. Since the midpoint voltages V_A and V_B are proportional to the bridge excitation level, the same will apply to V_{out} and to the sensitivity of the transducer. For semiconductor strain gauges and transducers, the dependency is near-proportional.

The advantage of using a bridge configuration instead of simply measuring a single resistance is the differential output, which partly makes noise suppression possible and partly makes it easier to measure small resistance changes due to the initial balanced condition. Furthermore, the bridge topology makes temperature compensation possible and, in the case of strain gauges, strain components can be added or subtracted depending on how the strain gauges are mounted on the physical test object and connected to the bridge. In accelerometers, the resistive bridge topology makes it possible to achieve DC response.

Maximum sensitivity is obtained when all four resistors in the bridge circuit are active, that is, they respond to the physical input. In some cases it is preferred to use only one or two active sensors. Since the bridge requires four resistors to be operational, the remaining positions are replaced with passive completion resistors. This is explained under Supported Bridge Configurations.

Because of tolerance in the static values of $R_1 – R_4$, any bridge transducer will exhibit some amount of initial unbalance. This means that the transducer will produce an output (usually small) even though no physical input is present. Initial unbalance can also be caused by static preloading of the specimen under test. Either way, this static offset can be removed in the analyzer display by activating the nulling function in Type 3057 before making the measurement.

Supported Bridge Configurations

Bridge transducers always consist of four resistances arranged in a bridge circuit. Depending on how many of these are active sensors, the bridge is referred to as a full, half or quarter bridge.

Full Bridge

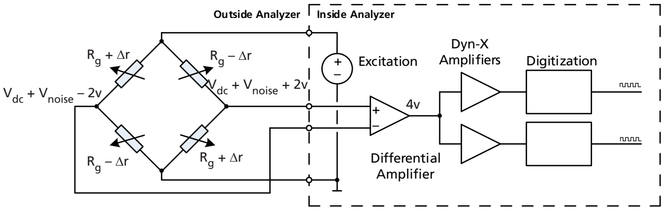
In a full-bridge transducer, all four bridge arms are active. In Fig. 2, this is indicated by an arrow on all four resistors.

Fig. 2 shows the transducer to the left and Type 3057 to the right with a dashed line around it. As shown, to perform its basic function, the full-bridge setup requires no other conditioning than bridge excitation and a differential input.

Please note: When selecting the bridge type in the analysis software, bridge completion is automatically deselected if a full bridge is chosen.

The full bridge has the highest sensitivity of the bridge configurations, obtaining a maximum bridge factor of 4. The bridge factor is a proportionality factor that helps describe the overall sensitivity of the measurement chain. It is not given by the choice of bridge in itself, but by the bridge type and the given application in combination. The bridge factor and other parameters affecting the sensitivity of the bridge are described under Strain Gauge Measurements.

Fig. 2 *Full-bridge circuit connected to LAN-XI Module Type 3057*



The full-bridge setup is often used in prefabricated transducers, such as bridge accelerometers or pressure sensors, and is also applied in strain gauge measurements.

Half Bridge

In some cases, it is preferred to omit two of the active sensors and replace them with passive resistors. This may be done for various reasons, for example to save space or mounting time in the measurement setup, to save conductors in the wire harness, or because the full bridge does not make sense from an application point of view. The resulting bridge configuration is called a half bridge, and the passive resistors used to complete the bridge are referred to as completion resistors, or in this case, half-bridge completion.

Because of the reduced number of active sensors, the half bridge has half the maximum sensitivity of the full bridge. Maximum bridge factor is 2.

Internal vs External Bridge Completion

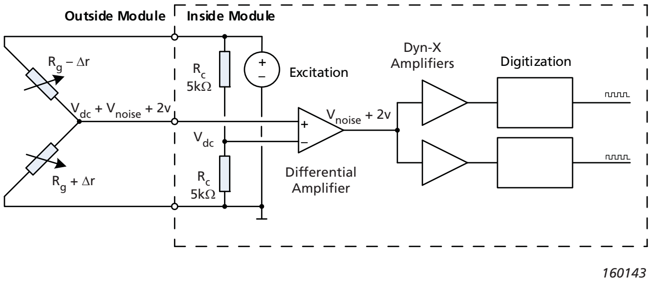
The half bridge is used both for prefabricated bridge transducers and for strain gauge measurements. Prefabricated half-bridge transducers usually require bridge completion to be done in the analyzer module (internal completion), but certain types have built-in completion resistors (external, remote completion).

If internal bridge completion is used, the noise suppression obtained with the full bridge due to its differential output will be lost because the external part of the bridge in this case has a single-ended output. If the transducer uses remote bridge completion (that is, completion resistors mounted at the transducer end), noise properties are comparable to those of a full bridge.

Fig. 3 shows the internal half-bridge completion in Type 3057 that is activated by the user during analysis setup. The two half-bridge completion resistors, R_c, shown are 5 kΩ each.

If external completion is applied, half-bridge completion in Type 3057 must be disabled.

Fig. 3 *Half-bridge circuit connected to LAN-XI Module Type 3057. Bridge completion is done inside the module*

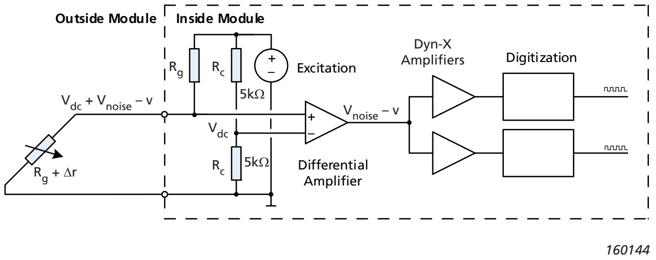


Quarter Bridge

A quarter bridge uses three passive resistors and only one active element. This configuration is often used in experimental stress analysis. The half-bridge completion resistors are used to create one half of the bridge, and a third resistor is added to complete it. Together, the three resistors are referred to as quarter-bridge completion.

The value of the third resistor must be of roughly the same value as the resistance of the sensor element, as the bridge would otherwise come too far out of balance. The user can select the proper value during analysis setup. Type 3057 supports 120 Ω, 350 Ω and 1 kΩ quarter-bridge completion.

Fig. 4 *Quarter-bridge circuit connected to LAN-XI Module Type 3057. Bridge completion is done inside the module*



The quarter bridge has one fourth the obtainable sensitivity of the full bridge. Maximum bridge factor is 1.

In addition to the lower sensitivity, a limitation using the quarter bridge is that because it has no complementary sensor in the arm opposite the active gauge to balance temperature drift, the temperature compensation inherent in the full and half bridge topologies do not exist unless using remote bridge completion at the transducer. Furthermore, the quarter bridge has a non-linear characteristic. This is further described under Linearity Errors. For many applications using metal foil strain gauges, the non-linearity is small enough that it can be neglected.

In regards to measurement noise, the same considerations apply as for half-bridge completion.

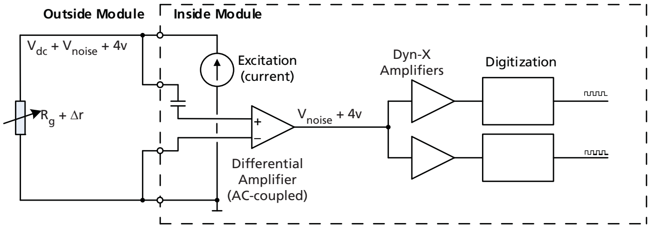
Single Constant-current-fed Strain Gauge ("Dynamic Strain Gauge") vs Quarter Bridge

The single constant-current-fed strain gauge is a special application of the strain gauge in which only one active sensor is used. Since this configuration is not a bridge, rather a simple resistance measurement, it differs from the quarter-bridge circuit by not using any bridge completion. Instead, the strain gauge is fed with a constant current, and the voltage developed across it is sensed directly with the input of Type 3057.

As shown in Fig. 5, the voltage sensing is done by connecting the measurement inputs to the excitation outputs on the plug of Type 3057's front panel. Like the quarter bridge, this setup takes up little physical space and allows for very simple cabling, which has practical advantages.

This strain gauge configuration is used, for example, in the aerospace industry when testing for resonances in the turbine blades of jet engines. Here, the simple cabling is an important advantage.

Fig. 5 *Single-strain gauge setup connected to LAN-XI Module Type 3057. Note that this is not a bridge circuit*



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The sensitivity of the single current-fed strain gauge, however, is the same as that of a full bridge with a bridge factor of 4 and equal excitation voltage ($R_g I_{exc} = V_{exc}$). This is the main advantage compared to the quarter bridge. Also, operating at constant current, another possible advantage is that the output from the sensor is linear with the resistance change. With many bridge configurations, and in particular the quarter bridge, this is not the case.

The main drawback of the circuit is that it is not suited for DC measurements. Since the voltage across the strain gauge would be coupled directly to the input of the module and includes a large DC bias resulting from the excitation current, drift in the excitation level due to, for example, temperature changes, would be indicated as large strain contributions, causing poor accuracy at DC. Furthermore, the DC bias would cause overload in the 316 mV input setting of Type 3057, and the nulling circuitry would not have sufficient range to compensate bias voltages greater than 4 V in the 10 V range. Therefore, in practice this setup is used with AC coupling and is intended for measurement of dynamic signals only.

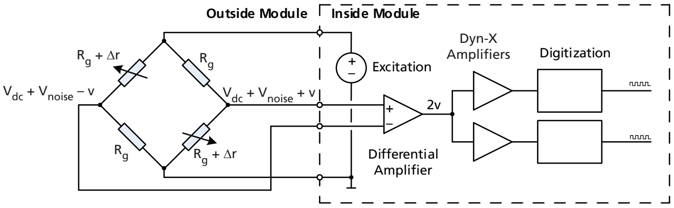
Regarding noise sensitivity, since the negative wire of the strain gauge is ground-connected, any noise pick up is purely differential and, therefore, will not be suppressed by the differential input of Type 3057. Noise sensitivity is, therefore, higher than with a full bridge or other bridge type with remote completion.

Diagonal Bridge

The diagonal bridge is a bridge topology using two active elements located in one of the bridge diagonals rather than in neighbouring arms of the bridge. Because of the sensor location, this type of bridge is sometimes referred to as a "double-quarter bridge"[1]. In terms of sensitivity, the diagonal bridge is equivalent to the half bridge and the maximum bridge factor is 2.

The diagonal bridge is employed in experimental stress analysis, for example, when it is required to cancel a bending strain component.

Fig. 6 *Diagonal-bridge circuit connected to LAN-XI Module Type 3057. Bridge completion is done externally*



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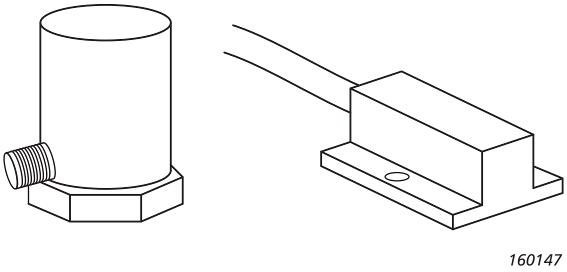
Type 3057 supports diagonal bridges if external bridge completion is used. Bridge completion may be done locally by mounting the completion resistors on the connector at the front panel of Type 3057, or remotely by mounting them on the transducer itself (strain gauge setup).

Type 3057 is designed for use with bridge transducers frequently employed in the aerospace, defence and automotive sectors. Below are examples of transducers used in these fields, with focus on the electrical interface to Type 3057.

Vibration Transducers (Accelerometers)

Bridge accelerometers come in a wide range of types and specifications but are all configured electrically as either full bridges or half bridges.

Fig. 7 *Examples of bridge accelerometers*



Supported configurations:

- Full bridge
- Half bridge with built-in completion
- Half bridge without completion

Typical input resistance:

- 300 Ω – 3 kΩ

Typical full-scale output:

- Max. 500 mV @ 10 V excitation (passive)
- Max. 2 V (preconditioned)

Supported bridge excitation:

- Voltage

Supported technologies:

- Piezoresistive (passive)
- Variable capacitance (preconditioned)

The vast majority of piezoresistive transducers are passive types, that is, they are without any conditioning electronics built in other than the sensor elements themselves. These transducers can operate from an arbitrarily small supply voltage up to a given maximum determined by the transducer's power dissipation limit. Remember, however, that the calibration applies for one specific level of bridge excitation.

Variable capacitance accelerometers have built-in preconditioning, and therefore have an additional requirement for minimum supply voltage. Variable capacitance transducers relevant for use with Type 3057 produce a differential output and are compatible with full bridges.

Supply Requirements

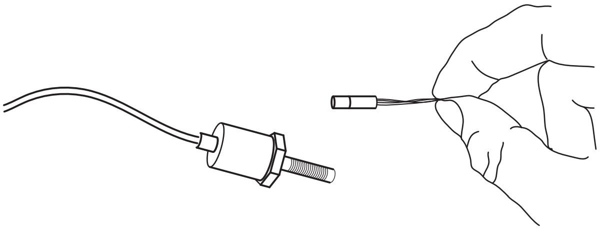
When selecting drive conditions for the accelerometer, bear in mind that for passive transducers, the sensitivity of the transducer is strongly dependent on the excitation voltage. The calibrated sensitivity therefore applies at one specific voltage level only. This is further explained under Prefabricated Bridge Transducers. If operating the transducer at a different level, the sensitivity must be corrected by recalibration.

Furthermore, you must pay attention to the specification for input resistance or current consumption given in the accelerometer's datasheet in order to ensure a predictable bridge excitation level. See the requirements under Restrictions on Bridge Excitation with LAN-XI Module Type 3057. With some transducers, particularly piezoresistive accelerometers, these parameters vary significantly with temperature, etc. For this reason, these devices must be voltage-supplied and not current-supplied. Failing to pay attention to this will cause the output to be strongly temperature-dependent and, therefore, unpredictable.

Pressure Transducers

Bridge pressure sensors are passive transducers configured as full bridges. Bridge completion should, therefore, not be used. Pressure sensors generally have high bandwidth.

Fig. 8 *Examples of bridge pressure transducers*



Supported configurations:
- Full bridge

Typical input resistance:
- 700 Ω – 3 kΩ

Typical full-scale output:
- Max. 500 mV @ 10 V excitation

Supported bridge excitation:
- Voltage

Supported technologies:
- Piezoresistive (passive)

Supply Requirements

The same considerations regarding supply requirements apply to bridge pressure sensors as for Vibration Transducers (Accelerometers). In summary, the transducer must be voltage-fed, and you must be careful not to exceed the specifications of the bridge excitation supply as described under Restrictions on Bridge Excitation with LAN-XI Module Type 3057.

Strain, Stress, Force Transducers (Strain Gauges)

Strain gauges may be used in situations where it is desired to either measure strain, or where a given mechanical input or property can be related to a measurable strain. Examples include mechanical stress, force, mass, etc.

Fig. 9 *Example of an HBM strain gauge that can be used with Type 3057*

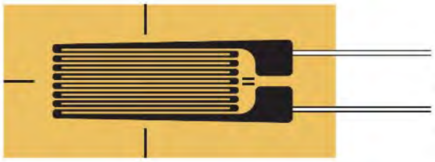


Illustration courtesy of HBM Test and Measurement

In contrast to the transducers listed earlier, strain-gauge measurements typically require you to build the transducer or measurement system from scratch. It is your task as the user to mount the sensor elements on the test object and select a suitable way to do so in order to determine the final sensitivity of the system. Depending on the measurement task, you may select any of the bridge or single-sensor configurations discussed under Supported Bridge Configurations. The various considerations related to the sensitivity of a strain gauge setup are described under Strain Gauge Measurements.

Strain gauges are used extensively in experimental stress analysis. These applications usually involve measurement at DC or very low frequency and often require high precision. Another application area is vibration testing, which is used, for example, for testing resonances in turbine blades in aircraft engines. Type 3057 was developed with dynamic measurements in mind and is not optimized for applications requiring extreme DC precision. DC accuracy sufficient for many bridge applications is, however, obtainable with Type 3057, providing the module is operated in thermal steady-state in a temperature controlled environment. Please consult the Type 3057 product data for DC drift specifications.

Supported configurations:
- Full bridge
- Half bridge
- Quarter bridge
- Single current-fed strain gauge
- Diagonal bridge

Common strain gauge resistance values:
- 120 Ω
- 350 Ω
- 1 kΩ

Supported bridge excitation:
- Voltage
- Current

The various considerations related to the sensitivity of a strain gauge setup are described under Strain Gauge Measurements.

Strain gauge measurements in particular involve many degrees-of-freedom and in general require trained technicians to produce sensible and accurate measurements.

Force, Mass, Torque Transducers (Load Cells)

Load cells are transducers intended for measurement of force, mass, etc., and are usually based on strain gauges arranged in a full-bridge circuit. Load cells are typically involved with DC measurements, and therefore are not core transducers for Type 3057, which has not been optimized for high DC precision.

Supported configurations:
- Full bridge

Supported bridge excitation:
- Voltage

For reliable operation, you must be sure to obey the requirements given under Restrictions on Bridge Excitation with LAN-XI Module Type 3057 for the loading of the excitation supply.

Transducer Sensitivity

This section describes the parameters that affect the sensitivity of bridge transducers.

Prefabricated Bridge Transducers

With prefabricated transducers, which in this document means anything other than strain gauges, the bridge excitation level is the only factor that significantly influences the transducer sensitivity. Other parameters are essentially fixed and are given by the transducer design, although temperature can have a small influence.

The sensitivity of a prefabricated transducer can be read from the calibration chart provided by the manufacturer and applies for a specific value of bridge excitation. Alternatively, the sensitivity can be determined by calibration with a known input.

Influence of Bridge Excitation Level

Since a bridge transducer's sensitivity in general is proportional to the excitation level (see exceptions below), operating the transducer at a level different from the nominal will change the sensitivity to:

$$S_{actual} = \frac{V_{exc\ actual}}{V_{exc\ nominal}} S_{nominal} \qquad \text{(Eq.1)}$$

This dependency also means that it is important to operate the excitation supply within its specifications, since exceeding these may cause the excitation level to be lower than intended, directly affecting the transducer's sensitivity. Requirements are explained under Restrictions on Bridge Excitation with LAN-XI Module Type 3057.

Exceptions

Exceptions from the above can be found in piezoresistive transducers, where the dependency on bridge excitation is only approximately proportional. Another exception is transducers with built-in preconditioning, such as certain types of bridge accelerometers. In some cases, these transducers contain voltage stabilization causing their output to be independent of the excitation level, as long as it is within the accepted supply range. Please refer to the transducer's datasheet and calibration chart.

Strain Gauge Measurements

With strain measurements, the final sensitivity of the transducer or measurement setup depends on a number of factors:
- The mechanical system
- The mounting and orientation of the strain gauges
- The number of active gauges used
- The sensitivity of the strain gauges
- The magnitude of excitation voltage or current
- Temperature to a limited extent

A strain gauge converts relative elongation (strain) into a relative change in resistance. In a measurement chain, it is therefore more a conversion link than a transducer in the usual sense, since it does not produce an output voltage in itself. To obtain a voltage signal from a strain gauge, it must be mounted on a test object or mechanical item, and inserted in a bridge or single-gauge circuit.

The following sections describe the various factors that affect the sensitivity of a general strain gauge setup and explain how to calculate the sensitivity using a simple, linear expression generic to all bridge configurations. The calculation method assumes the bridge output to be linear with respect to the physical strain, which in some cases is an approximation to real-world conditions. The Linearity Errors section estimates the maximum error resulting from this approximation. As it turns out, for the measurement applications that Type 3057 is intended to cover, the amount of non-linearity is usually small enough to be neglected, so the theory covered here can be readily applied.

Strain Gauge Bridges

With the above conditions given, the output from a strain gauge bridge can be expressed as:

$$V_{out} = V_{exc}\frac{k(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)}{4} \quad \text{(Eq.2)}$$

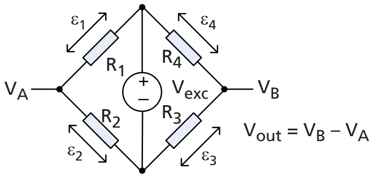
V_{exc} is the excitation voltage, k is the gauge factor, and $\varepsilon_1 \ldots \varepsilon_4$ are the individual strain components seen by each of the strain gauges $R_1 \ldots R_4$ in Fig. 10. The expression is derived and further explained in reference [1]. The strain components are defined as positive if the strain gauge is elongated and negative if it is compressed. This is indicated by the arrows in Fig. 10.

Eq. 2 implicitly applies to a full-bridge circuit but is also valid for bridge topologies using passive completion resistors if the corresponding strain values are set to zero. Thus, in the case of a half bridge, two of the strain contributions would be zero, for example, $\varepsilon_1 = 0$ and $\varepsilon_2 = 0$.

From the signs in Eq. 2, it can be seen that the bridge circuit will add strain components occurring in R_1 and R_3 to the output, while it will subtract those occurring in R_2 and R_4. The bridge can then be utilized to add or cancel strain components in a measurement setup.

It is also apparent that to maximize the output signal, all four strain gauges must contribute, which requires that both positive and negative strain (that is, tension and compression) is available in the physical setup, based on the signs.

***Fig. 10** Full-bridge circuit. The arrows define positive strain as an increase in length*



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Since the output is a mix of the individual strain components, it is not possible to distinguish them from one another in the output signal. Instead, it is common to express the bridge output as a function of the combined strain level. For this purpose, Eq. 2 is rewritten as:

$$V_{out} = V_{exc}\frac{kB}{4}\varepsilon \quad \text{(Eq.3)}$$

where ε is the measured combined strain level. B is referred to as the bridge factor[3], which is meant to account for the magnitudes and signs of $\varepsilon_1 \ldots \varepsilon_4$ in relation to one another and describes the given bridge type and measurement geometry in combination.

The expressions in Eq. 2 and Eq. 3 may be rewritten to apply for current excitation. For more information, see Bridge Excitation Level.

Sensitivity Factors

Fig. 11 (see below) illustrates a measurement example where a given physical quantity x is being measured with a bridge setup. A force is applied to a metal bar, and the resulting strain is measured with a quarter bridge. Effectively, the figure illustrates Eq. 3 graphically, with the addition of the first block k_{mech}. The physical quantity is converted first to a strain level, then to a resistance change to finally become a voltage signal V_{out} at the right side of the block diagram. From Fig. 11, the total sensitivity of the strain gauge bridge can be defined as:

$$S = \frac{V_{out}}{x} = V_{exc}\frac{kB}{4}k_{mech} \quad \text{(Eq.4)}$$

which effectively is the product of all the gain factors appearing in the individual blocks in the figure. Each of these will proportionately affect the overall sensitivity.

The individual factors: k_{mech} (mechanical sensitivity factor), B (bridge factor), and k (gauge factor) are explained in the following sections. Bear in mind that the example is simplified for ease of understanding and may need adjustment depending on the actual situation.

Mechanical Sensitivity Factor (k_{mech})

Starting from the physical input, a force is applied to a bar of a given material in its longitudinal direction. The force causes the bar to elongate, and the deformation can be described by the strain, which is the relative elongation $\varepsilon = \Delta l/l$.

The relationship between the resulting strain and the applied force depends on the mechanical properties of the bar. In general, a mechanical sensitivity factor can be defined, which is the ratio of strain to physical input:

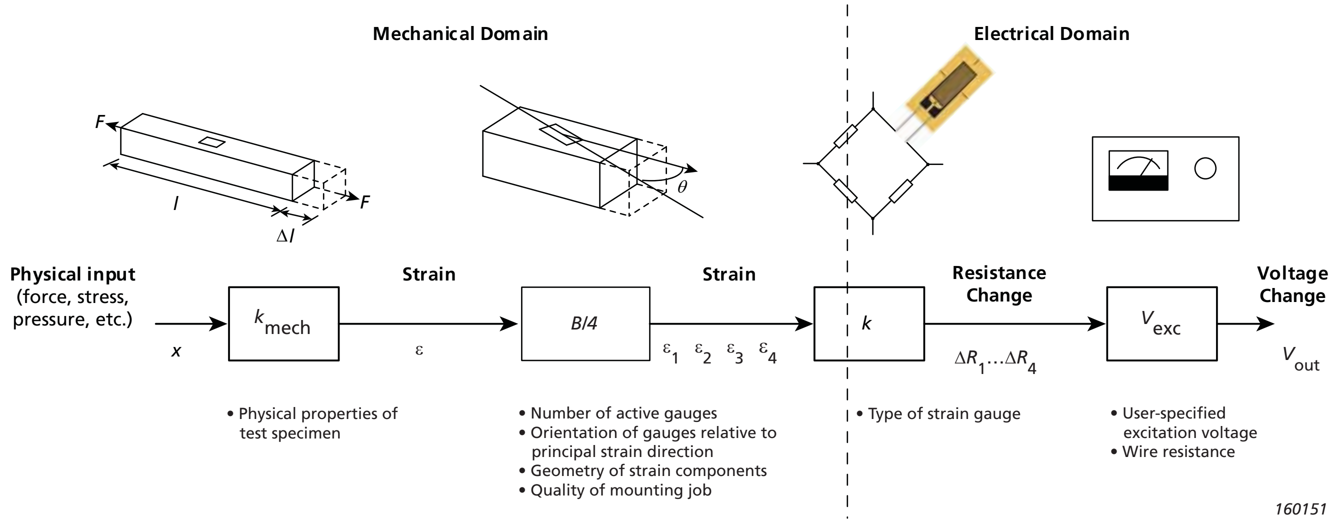
$$k_{mech} = \frac{\varepsilon}{x} \quad \text{(Eq.5)}$$

Table 1 gives examples of k_{mech} relating to the example in the figure. The expressions apply to the cross-section just below the position of the strain gauge. A is the cross-sectional area of the test object, and E is its modulus of elasticity, or Young's modulus.

***Table 1** Examples of conversion factors from mechanical input to strain*

Measured quantity	k_{mech}
Strain ε	1
Stress σ	$1/E$
Force F	$1/(A \cdot E)$

Fig. 11 *Illustration of the factors that affect the sensitivity of a strain gauge setup*



Bridge Factor (*B*)

The strain, and indirectly the applied force or the resulting stress, can be measured by gluing a strain gauge onto the bar and connecting it in place of, say, R_1 shown in the full-bridge circuit (see Fig. 10). This forms a quarter-bridge circuit.

The strain applied to the surface of the bar is then transferred to the strain gauge which will change resistance correspondingly. Maximum signal is produced if the strain gauge is aligned with the direction of the force causing the strain. With the definitions given in Fig. 10, this means that the strain component ε_1 will represent the measured strain ε, while the remaining strain contributions are zero because they are represented by passive resistors. Hence $\varepsilon_1 = \varepsilon$ and $\varepsilon_2 = \varepsilon_3 = \varepsilon_4 = 0$. By solving Eq. 2 and Eq. 3 for B, it then turns out that in this case, $B = 1$.

In general:

$$B = \frac{\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4}{\varepsilon} \qquad \text{(Eq.6)}$$

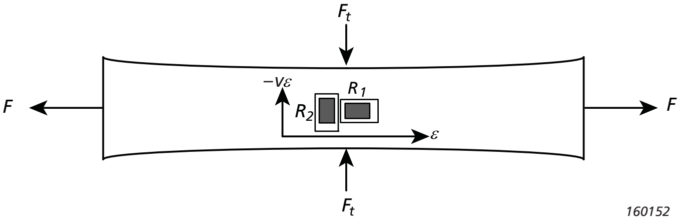
If the strain to be measured should instead occur at an angle to the strain gauge, the gauge would only measure the net strain level occurring along its own axis, which would be less than the main component. Thus, $\varepsilon_1 < \varepsilon$ and the output would therefore diminish, which implies that $B < 1$.

To summarize, the sensitivity in general depends on the mounting direction of the strain gauge and on the geometry of the forces occurring in the test object.

Poisson Strain

In many cases, the output can be increased further by using two or four active strain gauges. Note that both full-bridge and half-bridge circuits require that both positive and negative strains are available. In the example with the bar under tension above, every part of the surface sees an increase in length, which means that along the axis of the bar only positive strain is available. If the active gauges are aligned in this direction, a full bridge or a half bridge would produce no output because the strain seen by each of the gauges would cancel each other ($B = 0$). Instead, if the gauges in one diagonal, say R_2 and R_4, are turned 90° as shown in Fig. 12, these can be used to sense the Poisson strain.

Fig. 12 *Inclusion of Poisson strain* $-v\varepsilon$ *in the measurement. For most metals* $v \approx 0.3$. *In the full bridge case,* R_3 *and* R_4 *are located on the opposite side of the beam*

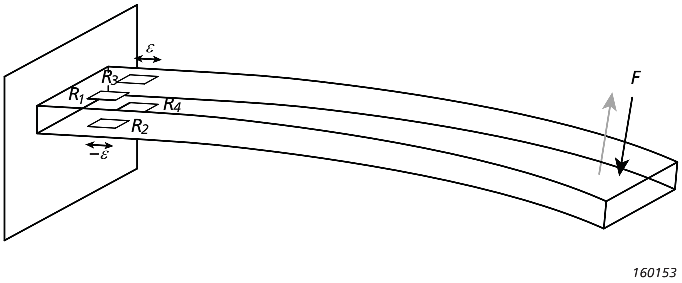


This strain component occurs in the transversal direction and describes the mechanism by which a given object becomes thinner when it is pulled longer. For most metals it is about −0.3 times the value of the main component, that is to say, it is negative. In this case, the strain components are $\varepsilon_1 = \varepsilon_3 = \varepsilon$ and $\varepsilon_2 = \varepsilon_4 = -0.3\varepsilon$. Inserting this in Eq. 6 then shows that the full bridge will have a sensitivity corresponding to $B = 2.6$. The half bridge would be half this at $B = 1.3$ since ε_3 and ε_4 would be zero.

Bending Beam

Had the case instead been a bending beam with the force applied in transversal direction as shown in Fig. 13, positive strain would have been available on one side of the beam and negative on the other. Aligning the strain gauges with the axis of the beam in that case would give $B = 4$ for the full bridge and $B = 2$ for the half bridge.

Fig. 13 *Bending beam*



From these examples, it can be seen that the bridge factor is not necessarily a fixed integer number applying to a certain type of bridge, but rather that each bridge type has a given maximum value that the bridge factor can assume (see under Supported Bridge Configurations). The actual, exact values depend on geometric relations. To obtain maximum sensitivity, the operator will try to maximize the bridge factor when this is feasible seen from an application point of view, but the available options may be limited by the actual measurement scenario.

Gauge Factor (*k*)

At the output of the $B/4$ block in Fig. 11, the signal is still represented as strain and will subsequently be converted into the electrical domain by the strain gauges. The conversion from strain to relative change in resistance is given by:

$$\frac{\Delta R_g}{R_g} = k\varepsilon \tag{Eq.7}$$

where k is the gauge factor that can be thought of as the sensitivity of the strain gauge itself. R_g is the unloaded resistance and ΔR_g is the absolute change caused by the physical input. Since the output from the bridge depends on $\Delta R_g/R_g$ as described in reference [1], the output depends equally on the gauge factor as on the strain level.

For most metal foil strain gauges, the gauge factor has a value of 2 – 3.6 with the former value being the most typical. Metal foil strain gauges are used frequently in experimental stress analysis and vibration measurements, and are the core type for Type 3057 support.

Semiconductor strain gauges have a gauge factor in the neighbourhood of 100 and thus provide about 50 times higher sensitivity than metal foil gauges in a given case. Their application is more restricted, however, since they are both more fragile and more expensive than the metal foil variety[1]. Another possible issue is that the much higher value of $\Delta R_g/R_g$ may cause the output from the bridge to become more non-linear than acceptable, making it necessary to correct the measured values unless small signals are being measured.

Bridge Excitation Level

The final link in the signal chain (V_{exc} in Fig. 11) is the conversion of the signal from a resistance change to an output voltage. The bridge output is in reality the difference between the midpoints of two parallel voltage dividers, and the sensitivity of the bridge will therefore be proportional to the excitation voltage.

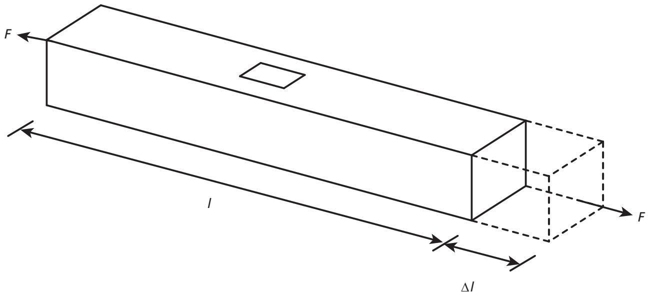
If a current is used as bridge excitation, the sensitivity will be the same as in the voltage driven case, provided that the current has a value that causes the supply voltage to the bridge to be the same. Voltage and current excitation, therefore, result in the same sensitivity when the programmed current equals $I_{set} = V_{exc}/R_{load}$

where R_{load} is the total input resistance of the bridge as defined under Restrictions on Bridge Excitation with LAN-XI Module Type 3057.

Total Sensitivity Example

The following summarizes the foregoing sections with an example that determines the overall sensitivity of a strain gauge bridge:

***Fig. 14** Bar under tension*



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It is desired to measure the stress occurring in the cross-section at the middle of the bar that is made of solid brass. A strain gauge with a gauge factor of $k = 2$ is mounted in the appropriate location on the surface of the bar in line with its axis and connected as a quarter bridge to Type 3057. The bridge excitation is 10 V. After the nulling has settled, force is applied to the bar, giving 10 mV output.

Q1: What is the sensitivity, and what is the magnitude of the stress component occurring in the longitudinal direction of the bar?

A1: Since a quarter bridge is used and the strain gauge is mounted in line with the strain component that it is being measured, the bridge factor is $B = 1$. The gauge factor is known to be $k = 2$ from the strain gauge datasheet. The bar is made of brass which has a Young's modulus of $E = 100 \cdot 10^6$ Pa. Since it is desired to measure stress, and using the conversion factors from Table 1, it follows that:

$$k_{mech} = 1/E = 1.00 \cdot 10^{-8} Pa^{-1}$$

Therefore the sensitivity is:

$$S = V_{exc}\frac{kB}{4}k_{mech} = 10V \cdot \frac{2 \cdot 1}{4} \cdot 1.00 \cdot 10^{-8} Pa^{-1} = 50nV/Pa$$

and the stress component is:

$$\sigma = \frac{V_{out}}{S} = \frac{10mV}{50nV/Pa} = 200kPa$$

Q2: To obtain temperature compensation, one additional strain gauge is mounted on the bar in the example from Q1 and is orientated at a 90° angle to the applied force, resulting in a half bridge. What is the sensitivity of the new configuration?

A2: This situation is described in Fig. 12. In this case, the bridge factor was shown earlier to be $B = 1.3$ for a half bridge, so the sensitivity would be 30% higher than in Q1, or 65 nV/Pa, with the same bridge excitation. The output from the bridge would then be 13 mV with the same physical input.

Single Constant-current-fed Strain Gauges

As described earlier, the output from the single current-fed strain gauge setup differs from that of a bridge circuit by not being differential. The voltage signal is developed directly across the strain gauge itself, and AC coupling is used to block the large DC bias caused by the excitation current. The AC component is given by:

$$V_{out\ ac} = R_g I_{exc} k \varepsilon_{ac} \qquad \text{(Eq.8)}$$

It can be seen by comparing with Eq. 3 that, providing that $R_g I_{exc} = V_{exc}$ and that the strain gauge is aligned with the strain component being measured, the sensitivity is the same as for a full bridge with a bridge factor of 4.

Calibration

The sensitivity factors described in the previous sections can be used for calculating the nominal sensitivity of a strain gauge setup. Since the exact values of the factors may not be known, however, the actual sensitivity cannot be determined purely by calculation. The sensitivity factors are affected by several parameters from both the mechanical and the electrical domains, and some of them depend on the user's exact mounting technique. Rebuilding a strain gauge setup will therefore normally require recalibration.

Direct Calibration

To determine the actual sensitivity with the best possible accuracy, it is necessary to perform a calibration of the whole measurement chain by applying a known physical input to the test setup. This is known as direct calibration.

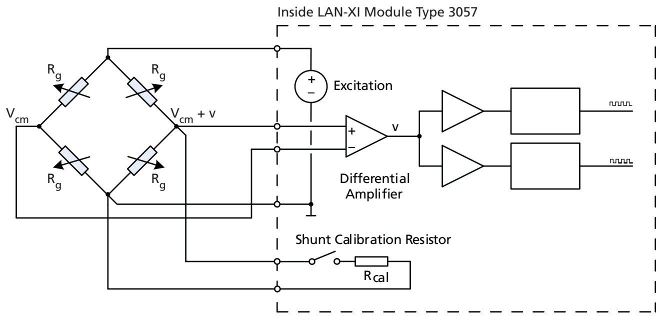
Shunt Calibration

In strain gauge setups, direct calibration may not always be practical, or possible. In such cases, an alternative is shunt calibration (also referred to as "indirect calibration"). The method involves connecting a known large-valued resistor in parallel with one of the arms in the bridge, making the total resistance drop and thereby simulating the resistance change that a corresponding physical input would cause.

To simulate a given strain level requires a specific value of parallel resistance which must be selected in relation to both the gauge resistance and to the bridge factor and gauge factor. Finally, to relate the strain back to the physical input requires one more conversion by the nominal value of k_{mech}.

In reality, shunt calibration only tests the electrical side of the measurement setup and relies on nominal values for the mechanical side. Therefore, it is not as accurate as direct calibration, which is why direct calibration is preferred when possible.

***Fig. 15** The shunt calibration resistor may be connected to any of the four bridge resistances*



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Type 3057 contains a fixed 50 kΩ shunt calibration resistor that can be switched on and off as needed. The resistor is connected to two separate pins in the input connector and can thus be connected across any of the four arms in the bridge, depending on the desired sign of the simulated strain.

The simulated strain magnitude is given by:

$$\varepsilon_{sim} = \frac{1}{kB}\frac{2R_g}{R_g + 2R_{cal}} \qquad \text{(Eq.9)}$$

where R_{cal} is the value of the calibration resistor, and R_g is the resistance of the strain gauge (or bridge completion resistor) that is being shunted. The expression applies to all types of bridges.

Another possibility is to connect a shunt calibration resistor externally using a dedicated calibration unit. In this case, the resistance needed to simulate a given strain level is:

$$R_{cal} = \left(\frac{1}{kB\varepsilon_{sim}} - \frac{1}{2}\right)R_g \qquad \text{(Eq.10)}$$

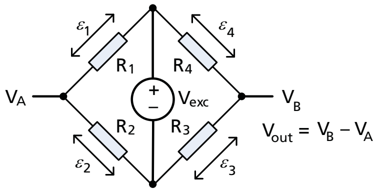
✐ **Please note:** The non-linearity effects are neglected in both of these expressions.

Linearity Errors

As noted in the previous sections, the output signal obtained with certain bridge arrangements is not linear with respect to the physical strain. Linearity deviations occur in any bridge topology where different strain levels are applied to the top and bottom resistors of the bridge, such as R_1 and R_2 in Fig. 16. This will cause the sum of the two resistors to change with the physical signal, thereby modulating the current through the strain gauge. The result is that the output is affected not only by the resistance change, but also by the modulated current, so the output becomes non-linear.

In bridge topologies where the two resistances change by an equal amount and in opposite direction, the total resistance is unchanged and the result is a linear output.

***Fig. 16** General bridge circuit. Voltage supplied*



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Whether a bridge circuit is linear or not is therefore application-specific, in that it depends on the magnitudes and signs of the individual strain components applied to each arm of the bridge.

The highest degree of current modulation occurs in the quarter bridge where one resistor changes in value while the opposite is fixed. The non-linear output from a voltage-fed quarter bridge can be written:

$$V_{out\ nonlin} = V_{exc}\frac{k\varepsilon}{2(2 + k\varepsilon)} \qquad \text{(Eq.11)}$$

assuming the strain gauge is aligned with the physical strain component.

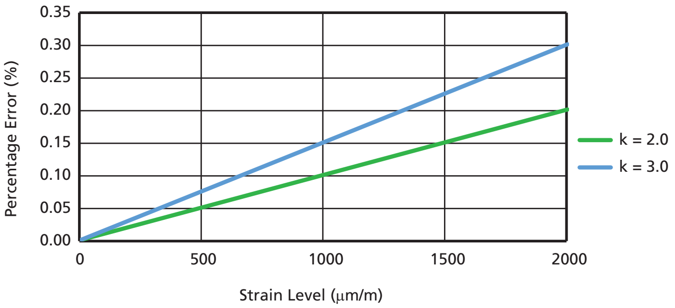
Comparing this with the linearized expression in Eq. 3 for $B = 1$, the percentage deviation can be found to be:

$$err\% = 100\% \cdot \frac{V_{out} - V_{out\ nonlin}}{V_{out\ nonlin}} = 100\% \cdot \frac{k}{2}\varepsilon \qquad \text{(Eq.12)}$$

This is the error arising from using the linearized expression instead of the actual, non-linear output. As can be seen, the error magnitude depends only on the strain level and on the gauge factor. Since the quarter bridge is the worst case in terms of non-linearity, other bridge configurations will have linearity errors either less than or equal to this.

The error magnitude has been plotted in Fig. 17 for the gauge factor values 2.0 and 3.0.

Fig. 17 *Maximum error resulting from ignoring non-linearity*



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The figure shows that with common resistive foil strain gauges operating at moderate strain levels up to 2000 µm/m, using the linear expression in Eq. 3 will cause an error of max. 0.2% regardless of the bridge configuration and measurement scenario. This is insignificant for the typical application areas for Type 3057.

On the other hand, with semiconductor strain gauges, the error magnitude is significantly higher because of the higher gauge factor. In such applications, the error may be up to about 15% in the same strain range.

It should be noted that this section applies for voltage excitation only. With current excitation, the error magnitude is calculated differently but is roughly comparable to the values given here.

In summary, linearity concerns are related to large strain values and/or large gauge factors and thus are not of concern in Type 3057's core measurement applications.

Restrictions on Bridge Excitation with LAN-XI Module Type 3057

Since the bridge excitation level directly affects the sensitivity of bridge transducers, it is important for a reliable measurement that the excitation supply is operated within its specifications. Should a current limit or an open-circuit voltage be reached, the measurement can no longer be trusted. In order to deliver predictable bridge excitation, you must be sure not to violate the following requirements for load resistance and load current. This is automatically taken care of in Brüel & Kjær's analyzer software if you enter the basic bridge setup parameters in the on-screen dialog.

Voltage excitation:

$$R_{load} \geq \frac{V_{exc}}{25mA}$$ (Eq.13)

$$I_{load} \leq 25mA$$

Current excitation:

$$R_{load} \leq \frac{10.9V}{I_{exc}} - 220\Omega$$ (Eq.14)

The load resistance is the effective input resistance of the transducer, accounting for all completion resistors. The load resistance is given by:

Prefabricated transducers:

Full bridge:	$R_{load} = R_{in}$
Half bridge with completion in the transducer:	$R_{load} = R_{in}$
Half bridge with completion in Type 3057:	$R_{load} = \frac{R_{in} \cdot 10k\Omega}{R_{in} + 10k\Omega}$

where R_{in} is the specified input resistance of the transducer. In case the input resistance is not specified, the equivalent input resistance may be calculated from:

$$R_{in} = \frac{V_{exc}}{I_{exc}}$$

where V_{exc} is the supply voltage and I_{exc} is the supply current.

Strain gauge setups:

Full bridge:	$R_{load} = R_g$
Half or quarter bridge with external completion:	$R_{load} = \frac{2R_gR_c}{R_g + R_c}$
Half or quarter bridge with completion in Type 3057:	$R_{load} = \frac{2R_g \cdot 10k\Omega}{2R_g + 10k\Omega}$
Diagonal bridge:	$R_{load} = R_g$

where R_g is the strain gauge resistance and R_c is the value of each of the half bridge completion resistors.

The cable used to connect the bridge transducer or strain gauge setup to Type 3057 may itself affect measurement accuracy because the wire resistance and cable capacitance will cause attenuation of the measured signal. The resistance and capacitance are proportional to the length of the cable, and the effects, therefore, become more pronounced as cable length increases. If not accounted for, they will give rise to measurement errors.

Cable Resistance

Voltage-Fed Transducers

When a bridge transducer is operated, the supply current drawn from the excitation supply inevitably creates voltage drop across the wire resistance in the cable. With voltage-fed transducers, this drop results in a reduction of the effective bridge excitation voltage, causing a loss in sensitivity. For metal foil strain gauges, the reduced sensitivity can be expressed by:

$$S_{reduced} = \frac{R_{in}}{2R_s + R_{in}} S \qquad \text{(Eq.15)}$$

where S is the ideal sensitivity at zero voltage drop, R_{in} is the input resistance of the transducer, and R_w is the resistance of each of the supply conductors in the connection cable.

The sensitivity loss can be avoided by using the remote sense options in Type 3057. This feature measures the voltage across the bridge rather than at the output of the module and thereby makes it possible to correct for the drop.

Three settings are possible:

- **Off:** No remote sensing is used. Estimate the contribution to the measurement error using Eq. 15 or use calibration to determine actual sensitivity
- **Single:** Uses one extra connection wire to obtain remote sensing. Connect the RS– pin in the input connector to the low end of the bridge (EXC–). The connection must be made in the transducer end of the cable, and the RS+ pin must be unconnected. When configuring the settings for the measurement channel, a settling time of about 1 second must pass before bridge excitation is reliable. Compensation for wire voltage drop is done before the measurement
- **Double:** Uses two extra wires to obtain remote sensing. Connect the RS+ pin to the top end of the bridge (EXC+) and RS– to the low end (EXC–), both at the transducer end of the cable. Dual-wire remote sensing is instantaneous, meaning there is no settling time, and compensation is done continually during the measurement. Use this option for best long-term accuracy

Current-Fed Transducers

With current-fed transducers, Type 3057 controls the current passing through the cable and the transducer, rather than the voltage. The voltage applied across the bridge is therefore unaffected by the wire resistance, and in consequence there is no sensitivity loss. Remote sensing is, therefore, not required if current is used as bridge excitation.

Please note: Current excitation is not suited for transducers with temperature dependent input resistance (PR) or with built in active electronics (VC).

In order to deliver the intended excitation current, it is important that the total load resistance connected to Type 3057, including the wire resistance $2R_w$ in series with the transducer, is no greater than the value given Eq. 14 (see Restrictions on Bridge Excitation with LAN-XI Module Type 3057). The GUI in the Brüel & Kjær PC software will give a warning in such cases. Eq. 14 includes a margin for up to 100 m of cable (20 Ω total resistance added).

Cable Capacitance

The capacitance in the connection cable forms an RC filter with the output resistance of the bridge, causing a frequency-dependent attenuation and phase shift of the measured signal. The amount of attenuation and phase shift increases with the length of the cable and depends on the number of wires connected to the bridge since each of these introduce capacitance to a neighbour wire or to ground.

Remote Bridge Completion

Depending on the type of bridge and bridge completion method used, several variations of the RC filter will be possible. The following gives an example of the case where all four bridge resistors are placed in the transducer. That is, it may be a full bridge or any bridge topology using remote completion resistors. Furthermore, it is assumed that all four bridge resistances are equal in value.

***Fig. 18** Wire capacitances in a bridge setup with remote completion.*
***Top:** Voltage-fed. **Bottom:** Current-fed*

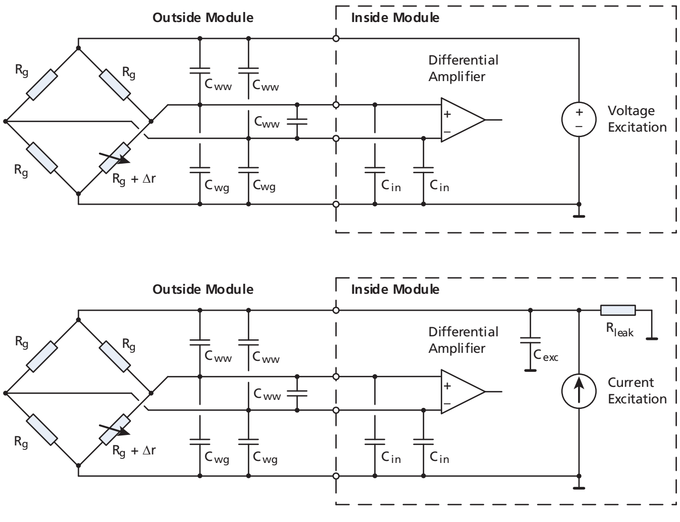

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Fig. 18 shows a schematic drawing of the situation as described above. All wire-to-wire capacitances in the transducer cable are assumed to be equal and are symbolized as C_{ww} while those occurring between a wire and ground are likewise equal and denoted C_{wg}. For the current controlled setup, C_{exc} is the output capacitance of the excitation supply in parallel with the corresponding cable capacitance. This capacitance is irrelevant with voltage control. C_{in} is the capacitance between each input of Type 3057 and ground, approximately 120 pF.

With these conditions, the sensitivity of the transducer is multiplied by the factor:

$$H(s) = \frac{1}{\frac{R_g}{2}(C_{in} + C_{wg} + 3C_{ww})s + 1} \qquad \text{(Eq.16)}$$

which effectively is a low-pass filter.

The expression applies both for voltage and for current control, under the assumptions made above. The magnitude and phase of this filter are given by:

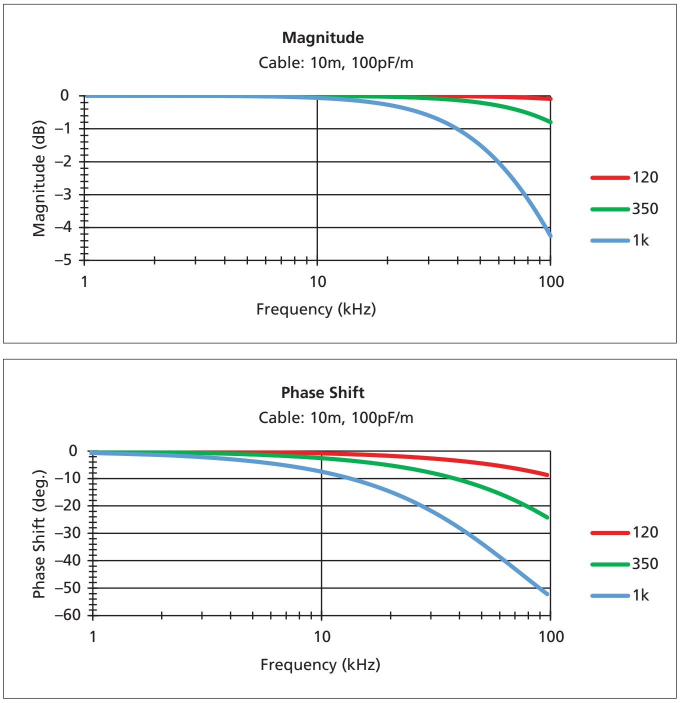
$$A(f) = \frac{1}{\sqrt{(\pi R_g[C_{in} + C_{wg} + 3C_{ww}]f)^2 + 1}} \qquad \text{(Eq.17)}$$

$$\Phi(f) = -\mathrm{Arctan}(\pi R_g[C_{in} + C_{wg} + 3C_{ww}]f) \qquad \text{(Eq.18)}$$

The expression shows that the output is insensitive to the capacitance C_{exc}, both with voltage and with current control, because no AC current flows in it. Note that this only holds if all four bridge resistors are approximately equal in value and the bridge is close to balance. The single constant-current strain gauge is sensitive to C_{exc}.

The attenuation and phase shift are plotted Fig. 19 for a cable with a length of 10 m and a wire capacitance of 100 pF per metre, which is a fairly typical value. In this case, it is assumed that both C_{ww} are C_{wg} are 1 nF.

***Fig. 19** Example of measurement errors caused by connection cable, corresponding to the wire capacitances in a bridge setup with remote completion*



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The curves are drawn for the common gauge resistance values: 120 Ω, 350 Ω and 1 kΩ. As can be seen, increasing the gauge resistance tends to pronounce the effects of cable capacitance, which may have a significant influence on the measurement results.

Attenuation and phase shift are best minimized by using a short cable, but if a given cable length is needed, a second possibility is to use a low strain gauge resistance as indicated in the figures.

If still further minimization is required, the measurements can be corrected by use of the above characteristics. Before such an approach can make sense, however, it is essential that the user has sufficient knowledge of the specific application, including accurate capacitance values for the cable.

Furthermore, if the assumptions used in the wire capacitance illustrations are not met, deviations in the characteristics may occur. This could happen, for example, if a different bridge topology is used that relies on internal bridge completion, if remote sense wires are added, or if other intended or unintended connections are made. Also, it may give rise to a difference if the bridge is significantly out of balance, or if one half of the bridge is made with a resistance value different from R_g. The values given in the graphs are therefore intended as a rough guideline only.

Monitor Output

Type 3057 is equipped with an analog monitor output that allows the differential input to be monitored for signal verification.

The monitor output is a single-ended replica of the differential input, with the modification that it is filtered through the analog input filters and gained according to the setting of the input range. Since Type 3057 uses a combination of analog and digital filters, the analog filters are not directly accessible to the user but are configured automatically depending on the user's selection of lower cut-off frequency. Fig. 20 shows the analog input filtering and monitor output, and the signal conditioning is explained in Table 2.

Fig. 20 *Type 3057 input filtering and monitor output*

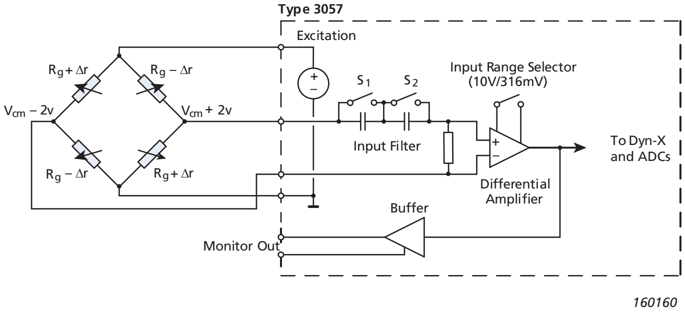

Table 2 *Signal conditioning of the monitor output*

Filter Setting (in GUI)	Monitor Output, Lower Cut-off Frequency
DC	DC
0.7 Hz (0.1 dB)	0.33 Hz (0.1 dB) = 0.1 Hz (10%)
7 Hz (0.1 dB)	
0.1 Hz (10%)	
1.0 Hz (10%)	
22.4 Hz (0.1 dB)	73 Hz (0.1 dB) = 23 Hz (10%)

Input Range (in GUI)	Monitor Output, Differential Gain
10 V	0 dB
316 mV	+30 dB

Reference List

[1] "An Introduction to Measurements using Strain Gauges", Karl Hoffmann, HBM GmbH 1989.
[2] "Instrumentation for Engineering Measurements" second edition, James Dally et al., Wiley 1993.
[3] "Applying the Wheatstone Bridge Circuit", Karl Hoffmann, HBM, doc. no. S1569-1 en, available on: www.hbm.com.

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