Noise Immunity for Strain Gage Measurements

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Overview

Strain gages are often deployed in the presence of electrostatic and electromagnetic noise. In designing a strain measurement system, care must be taken to minimize noise susceptibility and maximize signal-to-noise ratio. The conductors in the measurement circuit can pick up noise from ambient electric fields via capacitive coupling and from electromagnetic fields via inductive coupling. It can be difficult to identify and remove all potential sources of noise, and while proper cable design can reduce interference, it is generally impossible to eliminate noise pickup altogether. However, the common mode rejection of the differential amplifier in a strain gage measurement circuit can greatly suppress input noise, provided a balanced circuit topology is employed.

The Differential Amplifier

Measuring the small changes in resistance produced when a strain gage is deformed requires a differential circuit. The most common setup is the traditional Wheatstone bridge (Figure 1). In this arrangement, strain gages are located in one, two, or four arms of the bridge, with completion resistors placed in the ungaged arms. An applied voltage excitation (V_{EXC}) is used to convert the incremental changes in gage resistance to a differential output signal that represents the relative voltage between the bridge corners ($V_A - V_B$).

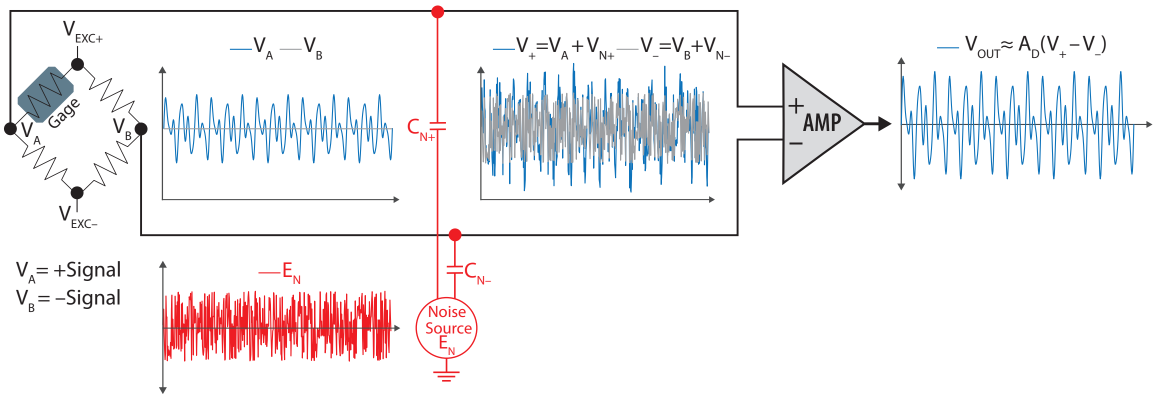

Figure 1. Diagram depicting the basic bridge-based differential circuit used to measure strain

Consider the example shown in Figure 1 with one active arm and three completion resistors. The differential signal consists of the gage signal plus the bias voltage, V_A, and the bias voltage V_B. These form the (+) and (–) signal outputs from the bridge. (Note that for bipolar excitation supplies, as is standard on Precision Filters' products, the bias voltage is nominally zero.) Both signal lines are exposed to a noise source that adds voltages V_{N+} and V_{N-} to each input via the stray coupling capacitances C_{N+} and C_{N-}. Hence the inputs to the differential amplifier are

$$V_+ = V_A + V_{N+},\ V_- = V_B + V_{N-} \tag{1a,b}$$

The output of the amplifier can be expressed as

$$V_{OUT} = A_D\left(V_+ - V_-\right) + A_C\left(\frac{V_+ + V_-}{2}\right) \tag{2}$$

The output consists of a difference-mode component with gain A_D and a common-mode component with gain A_C. Notice that voltages common to both signal lines (V_+ and V_-) – whether noise or a DC bias – are eliminated from the difference-mode component and retained only in the common-mode component. The power of the differential amplifier therefore lies in its common-mode rejection ratio (CMRR), defined as:

$$CMRR = \frac{A_D}{A_C} \tag{3}$$

If the CMRR is high, the amplifier will effectively suppress noise that is common to both of the signal inputs (i.e. $V_{N+} = V_{N-}$), producing a clean differential output signal that accurately measures the voltage difference between the bridge corners (Figure 1). The CMRR of a differential amplifier is commonly specified in dB; in modern signal conditioners, values usually range from 60-80 dB below 1 kHz. Beyond a kHz, the CMRR typically drops by ~6 dB per octave.

Between (1) and (2), it should be obvious that the amplifier will only suppress noise that is common to both inputs. To ensure this is the case, a balanced circuit topology must be employed. Yet some of the most common circuits used for strain measurements are fundamentally unbalanced and therefore cannot take advantage of the noise-suppressing capability of the amplifier's CMRR.

Unbalanced Measurement Circuits

A common measurement circuit consisting of a 3-wire Wheatstone quarter bridge is shown in Figure 2. A single active strain gage (R1) is affixed to a remote test article. Exposed lead wires extend from the gage to a shielded multi-conductor cable that connects on its opposite end to a signal conditioner. The signal conditioner provides the bridge completion (R2-R4), voltage excitation, differential amplification, and filtering.

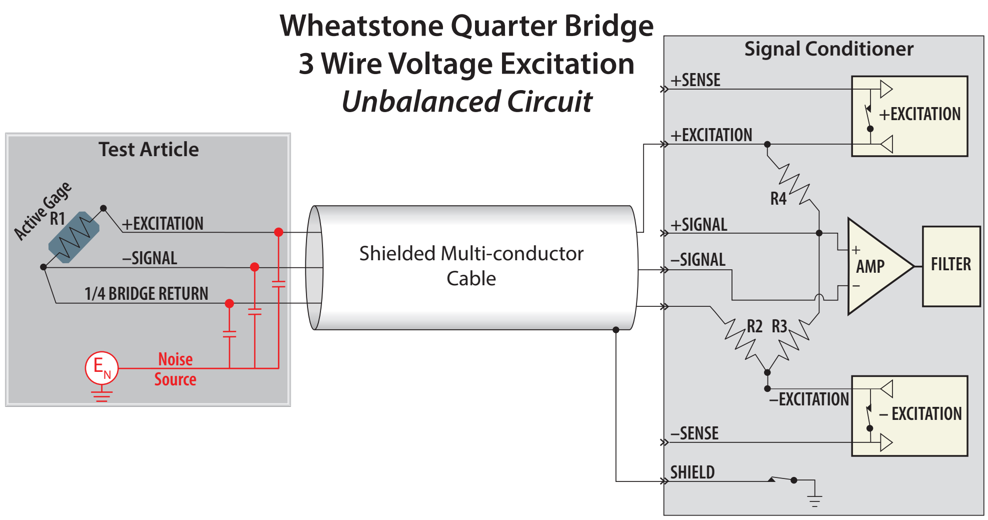

Figure 2. 3-wire Wheatstone quarter bridge circuit

The cable shield provides protection from electrostatic noise pickup over most of the cable length (typically 10s of feet), but the exposed lead wires at the test article are susceptible to noise pickup. In the 3-wire quarter bridge, this includes only one of the signal lines (−Signal): the +Signal line is entirely within the signal conditioner and is therefore shielded from the ambient noise source. Consequently, any noise will be retained in the difference-mode component and amplified by the difference-mode gain A_D. Removal of this noise will then require aggressive low-pass filtering, limiting the measurement to static strain only.

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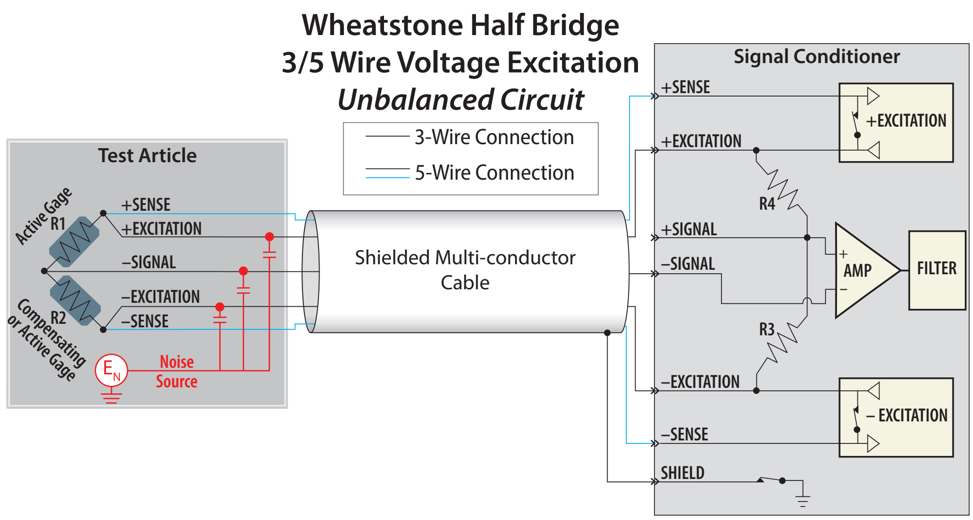

Figure 3. 3/5-wire Wheatstone half bridge circuit

Another common measurement circuit is the 3/5-wire Wheatstone half bridge (Figure 3). In this setup, an active gage (R1) is paired with either a second active gage or a compensating ("dummy") gage (R2) on the test article. (This setup can provide temperature compensation in environments where significant thermal output is expected from the gages.) The addition of remote sense connections allows for exact measurements of the voltage excitation to the bridge (negating voltage drops due to lead wire resistance), but notice that the circuit is still unbalanced with respect to noise because the +Signal line remains inside the signal conditioner. So this topology is also limited to measurement of static strain only.

Balanced Measurement Circuits

In the previous examples, completion of the Wheatstone bridge inside the signal conditioner resulted in an unbalanced circuit. To ensure balance for CMRR noise suppression, all gages and completion resistors must be remotely located with the test article. Figure 4 shows the same paired gage setup as Figure 3, but with the completion resistors R3 and R4 collocated with the gages. This results in a 4-wire (or 6-wire if remote sense is included to eliminate lead-wire resistance effects) connection between the remote full bridge and the signal conditioner. In this setup, both signal lines are exposed on the gage side of the circuit, and should therefore couple to the same noise source.

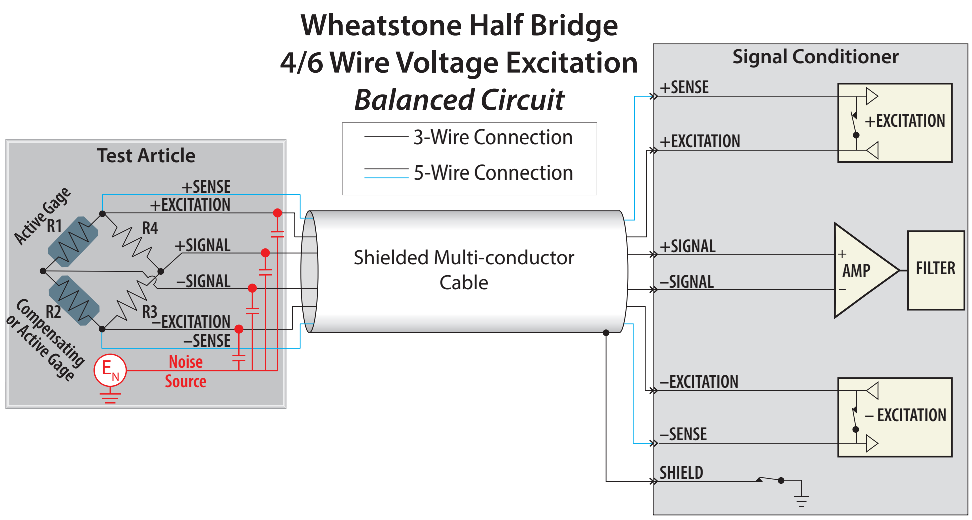

Figure 4. 4/6-wire Wheatstone half bridge with gages and completion resistors collocated

The requirement for collocated gages and completion resistors, and a minimum of 4 connecting wires, can pose problems for some strain measurement applications. An alternative setup that uses a constant current to excite the gages provides an inherently balanced circuit with respect to noise suppression.

Figure 5 shows an example of a 2/4-wire Balanced Constant Current™ (BCC™) circuit with a single active strain gage. In this configuration, current is "pushed" through the gage from the + Excitation source and returns ("pulled") to the – Excitation source. Changes in gage resistance are measured as a voltage difference across the gage by the +Signal and –Signal lines. A 2-wire connection can be used to effectively measure both static and dynamic strain if the cable lead-wire resistance is negligible. A 4-wire Kelvin connection separates signal and excitation leads to eliminate lead-wire effects. In either case, the circuit is balanced with respect to noise pickup.

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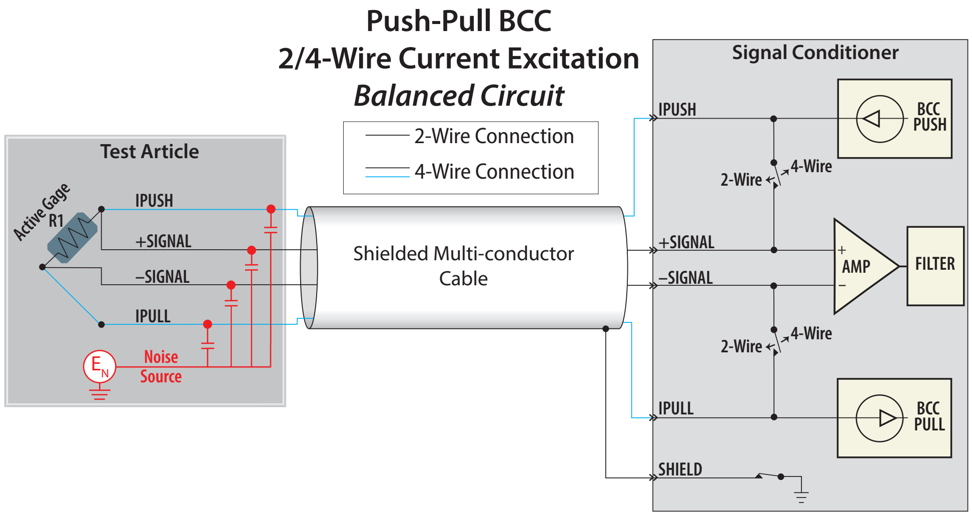

Figure 5. 2/4-wire Push-Pull BCC circuit for a single active strain gage

BCC excitation can also be applied to paired gages (i.e. the half bridge in Figure 4) using the Push-Push method (Figure 6). In this setup, matched excitation currents are "pushed" through each gage and returned to ground through a third wire. As with the Push-Pull method, the circuit is balanced with respect to noise pickup, and separating the signal and excitation lines (5-wire connection) will eliminate any lead-wire resistance effects. It's worth emphasizing that to achieve the same level of noise protection and insensitivity to lead-wire resistance, the BCC measurement circuit will always require fewer wires than a traditional Wheatstone bridge. As a case in point, if lead-wire resistance is negligible and a remote ground connection is available at the sensor, the Push-Push circuit can provide simultaneous measurements of static and dynamic strain with only a 2-wire connection.

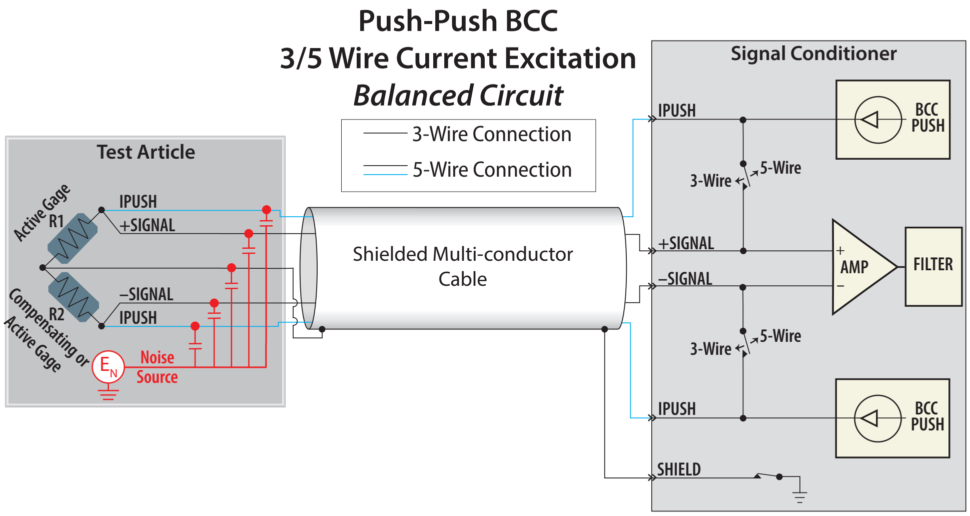

Figure 6. 3/5-wire Push-Push BCC circuit for paired strain gages

Characterizing a circuit topology as balanced assumes that noise coupling will be equivalent on the signal lines so long as they are similarly exposed. For this condition to be realized, the difference in stray coupling capacitances C_{N+} and C_{N-} should be minimized. Use of shielded twisted-pair cable will ensure that the signal lines are proximal – and hence equidistant from interfering noise sources so that $C_{N+} \approx C_{N-}$ – and, where shielded, protected from electrostatic noise coupling (Figure 7).

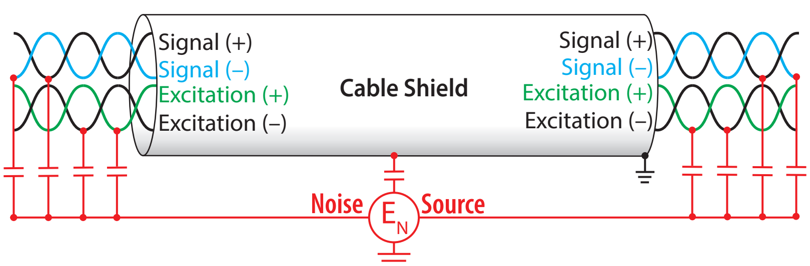

Figure 7. Preferred cable (shielded twisted-pair) for balanced strain gage measurement circuits

It should be noted that electrostatic shielding will not protect against magnetic noise: magnetically-induced voltages will only be suppressed if their amplitude and phase are equivalent on each of the signal lines. As with stray capacitances, the use of tightly twisted conductors will ensure that the signal lines are proximal and equidistant from any interfering magnetic noise source.

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