TI Designs – Precision: Verified Design

Single-Supply Strain Gauge in a Bridge Configuration Reference Design

TI Designs – Precision

TI Designs – Precision are analog solutions created by TI’s analog experts. Verified Designs offer the theory, component selection, simulation, complete PCB schematic & layout, bill of materials, and measured performance of useful circuits. Circuit modifications that help to meet alternate design goals are also discussed.

Circuit Description

This strain gauge reference design accurately measures the resistance of a strain gauge placed in a bridge configuration. Changes in the strain gauge resistance create a differential voltage that is amplified by an instrumentation amplifier. The bridge excitation voltage and instrumentation amplifier reference voltage are supplied using the REF5025.

Design Resources

- TIPD170
- TINA-TI™
- INA333
- REF5025

All Design files
SPICE Simulator
Product Folder
Product Folder

Ask The Analog Experts
WEBENCH® Design Center
TI Designs – Precision Library

An IMPORTANT NOTICE at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.

TINA-TI is a trademark of Texas Instruments
WEBENCH is a registered trademark of Texas Instruments
1 Design Summary

The design requirements are as follows:

- Supply Voltage: 5 V
- Bridge Excitation Voltage: 2.5 V
- Strain Gauge Nominal Resistance: 120 Ω
- Strain Gauge Resistance Variation: 115 Ω - 125 Ω
- Reference Voltage: 2.5 V
- Output Voltage: 225 mV to 4.72 V

The design goals and performance are summarized in Table 1. Figure 1 depicts the measured transfer function of the design.

Table 1. Comparison of Design Goals, Simulation, and Measured Performance

<table>
<thead>
<tr>
<th>Specification</th>
<th>Goal</th>
<th>Calculated (max)</th>
<th>Calculated (typ)</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Uncalibrated Error (%FSR)</td>
<td>&lt;1.5%</td>
<td>1.833%</td>
<td>0.688%</td>
<td>-0.953%</td>
</tr>
<tr>
<td>Total Calibrated Error (%FSR)</td>
<td>&lt;0.01%</td>
<td>0.0072%</td>
<td>0.0042%</td>
<td>-0.0154%</td>
</tr>
</tbody>
</table>

Figure 1: Measured Output Voltage vs. Strain Gauge Resistance
2 Theory of Operation

2.1 Strain Gauge Measurement Topology

A strain gauge is a sensor whose resistance varies with applied force. The change in resistance is directly proportional to how much strain the sensor is experiencing due to the force applied. To measure the variation in resistance, the strain gauge is placed in a bridge configuration as shown in Figure 2.

Equation (1) shows the transfer function for the circuit shown in Figure 2.

\[ V_{\text{out}} = V_{\text{diff}} \times G + V_{\text{ref}} \]  

Where:

- \( V_{\text{ref}} \) = the reference voltage of the instrumentation amplifier.
- \( G \) = the gain of the instrumentation amplifier.

As the strain gauge resistance varies from its nominal value, a differential voltage, \( V_{\text{diff}} \), is produced across the bridge. Equation (2) calculates the differential voltage across the bridge.

\[ V_{\text{diff}} = \frac{R_3 R_1 - R_{\text{sg}} R_2}{-R_1 R_2 - R_3 R_1 - R_5 R_2 - R_5 R_3 - R_{\text{sg}} R_2 - R_{\text{sg}} R_3 - R_{\text{sg}} R_5} \times V_{\text{excite}} \]  

Typically, resistors, \( R_1 \), \( R_2 \), and \( R_3 \), are set equal to the strain gauge nominal resistance so that a 0 V differential voltage is produced across the bridge when the strain gauge is not experiencing strain. With \( R_1 = R_2 = R_3 \), the differential voltage across the bridge can be simplified to Equation (3).

\[ V_{\text{diff\_simple}} = \frac{R_1^2 - R_{\text{sg}} R_1}{-2R_1^2 - 3R_2 R_1 - 3R_4 R_1 - 2R_{\text{sg}} R_1 - R_{\text{sg}} R_4 - R_{\text{sg}} R_5} \times V_{\text{excite}} \]
2.2 Measuring the Differential Bridge Voltage

An instrumentation amplifier is typically used to amplify the differential bridge voltage. Instrumentation amplifiers have very high input impedance and therefore introduce negligible error with respect to the bridge resistance. The output voltage ($V_{out}$) of the instrumentation amplifier can be calculated using Equation (1).

A reference voltage must be supplied to the instrumentation amplifier because strain gauge can increase and decrease in resistance which produces a positive and negative differential bridge voltage. The reference voltage should be one-half of the supply voltage. A reference voltage at mid-supply biases the output voltage of the instrumentation amplifier to allow differential measurements in the positive and negative direction.

2.3 Common Mode Resistors

The common mode resistors, $R_4$ and $R_5$, have two main functions; limit the current through the bridge and set the common mode of the instrumentation amplifier. The current through the bridge determines how large of a differential signal will be produced by the bridge. However, there are limitations on the current through the bridge due to self-heating effects of the bridge resistors and strain gauge. There is also typically a maximum current specification for the strain gauge that cannot be exceeded without damaging the strain gauge. The current through the bridge can be calculated using Equation (4).

$$I_{bridge} = \frac{3R_1 + R_{sg}}{2R_1^2 + 3R_4R_1 + 2R_{sg}R_1 + R_{sg}R_5 + 3R_4R_1 + R_{sg}R_4} \times V_{excite}$$

Equation (4) can be simplified to Equation (5).

$$I_{bridge} = \frac{V_{excite}}{R_4 + R_5 + R_{bridge}}$$

Where:

$$R_{bridge} = \text{the total resistance of the bridge.}$$

To ensure the instrumentation amplifier can produce the maximum output voltage swing, the common mode of the instrumentation amplifier must be set correctly. The input common mode voltage ($V_{cm}$) can be calculated using Equation (6).

$$V_{cm} = \frac{3R_5R_1 + 2R_{sg}R_1 + R_{sg}R_5}{2R_1^2 + 3R_3R_1 + 2R_{sg}R_1 + R_{sg}R_5 + 3R_4R_1 + R_{sg}R_4} \times V_{excite}$$

Equation (6) can be simplified to Equation (7).

$$V_{cm} = \frac{R_{bridge}}{2} + R_5 \times V_{excite}$$

Where:

$$R_{bridge} = \text{the total resistance of the bridge.}$$
3 Component Selection

3.1 Bridge Resistors ($R_1$, $R_2$, and $R_3$)

The bridge resistors $R_1$, $R_2$, and $R_3$ are chosen to be 120 $\Omega$ to match the resistance of the strain gauge nominal resistance. Matching the bridge resistors with the strain gauge resistance produces a 0 V differential bridge voltage when the strain gauge resistance is at its nominal value. The tolerances of the resistors were chosen to be 0.05% to minimize the offset and gain errors due to the bridge resistors.

3.2 Instrumentation Amplifier

The instrumentation amplifier chosen for this design is the INA333 for its low input offset, low input offset voltage drift, low input bias current, and rail-to-rail output voltage swing.

3.3 Common Mode Resistors ($R_4$ and $R_5$)

$R_4$ was chosen to be 0 $\Omega$ to allow for the maximum current through the bridge and ultimately the maximum differential bridge voltage. $R_5$ is chosen to be 1.27 k$\Omega$ to place the input common mode voltage of the INA333 at approximately 2.4 V. Having a common mode of 2.4 V allows for the maximum output swing of the instrumentation amplifier. Figure 3 shows the output voltage vs. common mode voltage plot of the INA333; notice a common mode voltage of 1.5 V to 3.5 V produces the largest possible output voltage swing. The tool used to create Figure 3 can be downloaded here.

Figure 3: Vcm vs. Vout of INA333

3.4 Instrumentation Amplifier Gain

The gain of the instrumentation amplifier is set to 1000V/V by choosing the gain-setting resistor, $R_g$, to be 100 $\Omega$. A tolerance of 0.01% was chosen to minimize the gain error due to resistor tolerance. Equation (8) calculates the gain of the instrumentation amplifier.

$$
G = \frac{V_{out_{max}} - V_{out_{min}}}{V_{diff_{max}} - V_{diff_{min}}} = \frac{4.72V - 225mV}{2.22mV - (-2.27mV)} = 1001V/V
$$

(8)
3.5 Bridge Excitation Voltage/Amplifier Reference Voltage

The REF5025 was chosen to supply the bridge excitation voltage and INA333 reference voltage because of its high initial accuracy, low noise, and low drift performance. Using a 2.5 V reference voltage for the INA333 biases the output voltage to mid-supply when a 0 V differential voltage is measured.
4 Simulation and Error Calculations

4.1 Simulation

Figure 4 shows the TINA-TI circuit used for simulation.

![TINA-TI simulation circuit](image)

**Figure 4: TINA-TI simulation circuit**

Figure 5 displays the simulated output voltage for a strain gauge resistance from 115 Ω to 125 Ω. Notice when the strain gauge has a resistance of 120 Ω, equal to the bridge resistors, the output voltage is equal to the reference voltage of 2.5 V. When the strain gauge resistance is above 120 Ω, the output voltage is above 2.5 V and when the strain gauge resistance is below 120 Ω, the output voltage is below 2.5 V.

![Simulation Results](image)

**Figure 5: Simulation Results**
4.2 Error Calculations

4.2.1 Errors Due to Bridge and Common Mode Resistors

The tolerance of the bridge resistors, R₁, R₂, and R₃, and common mode resistor, Rₛ, create both an offset and gain error. The majority of the offset error is due to the bridge resistors tolerance and the majority of the gain error is due to the common mode resistor tolerance. Equation (9) calculates the bridge differential voltage (V.diff.bridge). Setting R₁ and R₃ with a negative tolerance and R₂ with a positive tolerance gives the worst-case offset error due to the bridge resistors. Setting Rₛ to have a negative tolerance gives the worst-case gain error due to the common mode resistors. The offset error (V.offset.error) is calculated using Equation (10). The gain error in the positive (V.gain.error.pos) and negative (V.gain.error.neg) direction is calculated using Equation (11) and Equation (12), respectively. The worst case offset and gain error referred to the input (RTI) due to the bridge and common mode resistors is calculated to be 81.02 µV and -2.95 µV, respectively.

\[
V_{\text{diff}_{\text{bridge}}} = \frac{R_3 R_1 - R_{sg} R_2}{-R_1 R_2 - R_3 R_1 - R_{sg} R_1 - R_5 R_2 - R_5 R_3 - R_{sg} R_2 - R_{sg} R_3 - R_{sg} R_5} \times V_{\text{excite}} \tag{9}
\]

\[
V_{\text{offset}_{\text{error}}} = V_{\text{diff}_{\text{tolerance}@120\Omega}} - V_{\text{diff}_{\text{ideal}@120\Omega}} \tag{10}
\]

\[
V_{\text{gain}_{\text{error}_{\text{pos}}}} = (V_{\text{diff}_{\text{tolerance}@125\Omega}} - V_{\text{diff}_{\text{ideal}@125\Omega}}) - (V_{\text{diff}_{\text{tolerance}@120\Omega}} - V_{\text{diff}_{\text{ideal}@120\Omega}}) \tag{11}
\]

\[
V_{\text{gain}_{\text{error}_{\text{neg}}}} = (V_{\text{diff}_{\text{tolerance}@115\Omega}} - V_{\text{diff}_{\text{ideal}@115\Omega}}) - (V_{\text{diff}_{\text{tolerance}@120\Omega}} - V_{\text{diff}_{\text{ideal}@120\Omega}}) \tag{12}
\]

Where:

- \(V_{\text{diff}_{\text{tolerance}@120\Omega}}\) = the bridge differential voltage with the bridge resistors maximum tolerance at a strain gauge resistance of 120 Ω.
- \(V_{\text{diff}_{\text{ideal}@120\Omega}}\) = the ideal bridge differential voltage with a strain gauge resistance of 120 Ω.
- \(V_{\text{diff}_{\text{tolerance}@125\Omega}}\) = the bridge differential voltage with the bridge resistors maximum tolerance at a strain gauge resistance of 125 Ω.
- \(V_{\text{diff}_{\text{ideal}@125\Omega}}\) = the ideal bridge differential voltage with a strain gauge resistance of 125 Ω.
- \(V_{\text{diff}_{\text{tolerance}@115\Omega}}\) = the bridge differential voltage with the bridge resistors maximum tolerance at a strain gauge resistance of 115 Ω.
- \(V_{\text{diff}_{\text{ideal}@115\Omega}}\) = the ideal bridge differential voltage with a strain gauge resistance of 115 Ω.

4.2.2 Errors Due to INA333

The errors associated with the INA333 are due to input offset voltage, common mode rejection ratio (CMRR), gain error, and gain non-linearity. These errors are listed in Table 2.

<table>
<thead>
<tr>
<th>Table 2: INA333 Performance Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>INA333 Specification</td>
</tr>
<tr>
<td>Input Offset Voltage (µV)</td>
</tr>
<tr>
<td>Common Mode Rejection Ratio (dB)</td>
</tr>
<tr>
<td>Gain Error (%FSR)</td>
</tr>
<tr>
<td>Gain Non-Linearity (ppm)</td>
</tr>
</tbody>
</table>

The input offset voltage RTI (V_{os,µV}) of the INA333 is calculated using Equation (13) and has the units of microvolts.
The total calibrated error is calculated by taking the root sum square (RSS) of all errors associated with the bridge and INA333. Equation (19) calculates the total error of the system in units of volts. Equation (20) converts the total error to a percentage of the full scale range. The total RTI error of the system is calculated to be 1.833 %FSR. The total RTI error calculated in Equation (20) assumes a worst case scenario for the bridge resistors tolerance. However, this is unlikely to occur. Using typical tolerance values the total RTI error is calculated to be 0.688 %FSR. The majority of the total error is due to the offset error of the bridge.

\[
V_{Total\_Error(V)} = \sqrt{V_{offset\_error}^2 + V_{gain\_error\_pos}^2 + V_{os\_\mu V}^2 + V_{os\_CMRR(V)}^2 + V_{GE(V)}^2 + V_{os\_linearity(V)}^2} \tag{19}
\]

\[
V_{Total\_Error(\%FSR)} = \frac{V_{Total\_Error(V)} \times FSR_{input}}{FSR_{input}} = \frac{82.4603 \mu V \times 100}{0.0045 V} = 1.833\%FSR \tag{20}
\]

4.2.4 Total Calibrated Error

The total calibrated error is calculated by taking the RSS of errors associated with the CMRR and gain non-linearity of the INA333. Equation (21) calculates the total calibrated error in units of volts. Equation (22) converts the total calibrated error to a percentage of the full scale range. The total RTI calibrated error of the system is calculated to be 0.004 %FSR.

\[
V_{Total\_Cal\_Error(V)} = \sqrt{V_{os\_CMRR(V)}^2 + V_{os\_linearity(V)}^2} = \sqrt{178.498 nV^2 + 55 nV^2} = 186.779 nV \tag{21}
\]
\[ V_{\text{Total}_\text{Cal}_\text{Error}(\% \text{FSR})} = \frac{V_{\text{Total}_\text{Cal}_\text{Error}(V)} \times 100}{FSR_{\text{input}}} = \frac{186.779nV \times 100}{0.0045V} = 0.0042\% \text{FSR} \]
5 PCB Design

The PCB schematic and bill of materials can be found in Appendix A.

5.1 PCB Layout

Figure 6 shows the PCB layout for the design. The traces for the bridge and common mode resistors were kept as short and balanced as possible to minimize the possibility of a differential voltage in the signal chain due to trace impedance mismatch. The terminal block, J1, was placed on the bottom of the PCB to allow for a close connection of \( R_4 \) and \( R_5 \). Finally, the gain setting resistor, \( R_g \), was placed as close to the pins of U1 as possible to minimize stray capacitance and trace impedance. General layout guidelines, such as, placing decoupling capacitors close to the devices as possible and pouring a solid ground plane, were also used.

![Figure 6: PCB Layout](image-url)
6 Verification & Measured Performance

6.1 Output Voltage vs. Strain Gauge Resistance

Figure 7 shows the measured output voltage of the INA333 vs. strain gauge resistance. The data was collected by placing different values of resistors in the terminal block, J1, to represent the strain gauge resistance. Each resistor used was accurately measured before being placed in the terminal block. High accurate low drift resistors were used to prevent a change in resistance due to heating while handling the resistors when placing them into the terminal block or from self-heating due to the bridge current.

![Output Voltage vs. Strain Gauge Resistance](image)

**Figure 7: Output Voltage vs. Strain Gauge Resistance**

6.2 Uncalibrated Error

The total full scale uncalibrated error is calculated using Equation (23).

\[
Error_{\%\,FSR} = \frac{V_{out\,measured} - V_{out\,ideal}}{FSR_{output}} \times 100
\]  

(23)

Where:
- \(V_{out\,ideal}\) = the ideal output voltage
- \(V_{out\,measured}\) = the measured output voltage
- \(FSR_{output}\) = the ideal full scale output voltage range

To calculate the ideal output voltage, the resistor used to simulate the strain gauge resistance was measured, recorded, and then used to calculate the ideal differential bridge voltage. The ideal values for the bridge resistors and common mode resistors were used. The ideal differential bridge voltage is calculated using Equation (3). Equation (1) is used to calculate the ideal output voltage.
Figure 8 shows the total full scale uncalibrated error. Notice the majority of the error is an offset error caused from the resistors in the bridge.

![Total Full Scale Uncalibrated Error](image)

Figure 8: Total Full Scale Uncalibrated Error

6.3 Calibration

A 2-point calibration was performed to remove errors due to offset voltage, gain error, component tolerance, etc. The data points chosen for calibration were with a maximum and minimum strain gauge resistance of 115 Ω and 125 Ω, respectively. To perform a calibration, a gain correction factor, α, and an offset correction factor, β, must first be calculated using Equation (24) and Equation (25), respectively. Table 2 displays the data points used for calibration.

<table>
<thead>
<tr>
<th>Strain Gauge Resistance = 115 Ω</th>
<th>Strain Gauge Resistance = 125 Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>Ideal</td>
</tr>
<tr>
<td>Vout</td>
<td>0.1924346 V</td>
</tr>
</tbody>
</table>

\[
\alpha = \frac{V_{out\_ideal@125\Omega} - V_{out\_ideal@115\Omega}}{V_{out\_measured@125\Omega} - V_{out\_measured@115\Omega}} \tag{24}
\]

\[
\beta = (\alpha \times V_{out\_measured@115\Omega}) - V_{out\_ideal@115\Omega} \tag{25}
\]

Using Equation (24) and Equation (25), α is calculated to be 1.001277, and β is calculated to be -0.03701. Equation (26) was used to calculate the calibrated output voltage.

\[
V_{out\_calibrated} = (V_{out\_measured} - \beta) \times \alpha \tag{26}
\]
Figure 8 shows the total full-scale error after calibration. The non-linearity shown in Figure 9 is greater than the non-linearity specification of the INA333; some of this error can be attributed to noise in the system. Assuming a best-case scenario and using the input voltage noise specification in the INA333 datasheet of 50 nV/√Hz at 10 Hz, the output noise peak-to-peak is calculated to be 1.31 mVpp which is 0.029 %FSR of the output. Equation (27) calculates the output noise peak-to-peak. Equation (28) converts the peak-to-peak output noise to a percentage of the full-scale range.

\[
V_{\text{noise, pp}} = 6.6 \times G \times V_{\text{noise}} \times \sqrt{\frac{\text{BW}_n \times 1.57}{\text{FSR}}} = \frac{6.6 \times 1000}{V} \times \frac{50}{\sqrt{10\text{Hz}}} \times 1.57 = 1.31\text{mVpp} \quad (27)
\]

\[
V_{\text{noise, %FSR}} = \frac{V_{\text{noise, pp}} \times 100}{\text{FSR}_{\text{output}}} = \frac{1.31\text{mVpp} \times 100}{4.5V} = 0.029\%\text{FSR} \quad (28)
\]

Where:

\[V_{\text{noise}} = \text{the input voltage noise of the INA333.}\]

\[\text{BW}_n = \text{bandwidth of the INA333.}\]

![Total Full Scale Error After Calibration](image.png)

**Figure 9: Total Full Scale Error After Calibration**
7  Modifications

7.1  Strain Gauge

A strain gauge with a different nominal resistance can be used, typical strain gauge nominal resistances are, 120 Ω, 350 Ω, 1000 Ω, and 3000 Ω. If a different nominal resistance is used, the bridge resistors must be chosen to match the nominal resistance of the strain gauge.

7.2  Common Mode Resistors

The common mode resistors, \( R_4 \) and \( R_5 \), can be increased to reduce the current consumption of the circuit, or decreased to create a larger differential bridge voltage. If a larger differential bridge voltage is present, the gain of the instrumentation amplifier must be adjusted such that the output voltage does not exceed the output voltage swing of the device. Furthermore, \( R_4 \) and \( R_5 \), must be adjusted such that the common mode voltage of the device is not violated and the maximum strain gauge current is not exceeded.

7.3  Amplifier

Other instrumentation amplifiers can be used to measure the differential bridge voltage, such as, the INA188 for a low drift solution, the INA827 for applications that require a higher bandwidth or the INA122 for a lower power solution with higher gain.

8  About the Author

Timothy Claycomb is an Analog Applications Engineer in the Precision Linear group at Texas Instruments. He earned his B.S. in Electrical Engineering from Michigan State University in 2013.
9 Acknowledgements & References


3. Bridge Measurement Systems Section 5 (SLYP163)

The author would like to thank Collin Wells for his technical contribution during this design.
Appendix A.

A.1 Electrical Schematic

![Electrical Schematic Diagram]

Figure A-1: Electrical Schematic
### A.2 Bill of Materials

![Bill of Materials](image-url)

**Figure A-2: Bill of Materials**

<table>
<thead>
<tr>
<th>Item #</th>
<th>Quantity</th>
<th>Designator</th>
<th>Value</th>
<th>Part Number</th>
<th>Manufacturer</th>
<th>Description</th>
<th>DigKey Part Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2</td>
<td>C1, C11, C12</td>
<td>100uF</td>
<td>TS8109528216309</td>
<td>AVX</td>
<td>CAP, TANT, 10uF, 25V, +/-20%, 1 cham, 3528-21 SMD</td>
<td>R8D8575-1ND</td>
<td></td>
</tr>
<tr>
<td>2 2</td>
<td>C3, C7, C13</td>
<td>1uF</td>
<td>SGR918BR7R105K1Z120</td>
<td>Murata</td>
<td>CAP, CERM, 1uF, 25V, +/-10%, 5.0x12.0, 0603</td>
<td>R6B-5257-1ND</td>
<td></td>
</tr>
<tr>
<td>2 2</td>
<td>C5, C9</td>
<td>0.1uF</td>
<td>0603/512A504A5</td>
<td>AVX</td>
<td>CAP, CERM, 0.1uF, 50V, +/-5%, XTR, 0603</td>
<td>R6B3720-1ND</td>
<td></td>
</tr>
<tr>
<td>4 1</td>
<td>J1</td>
<td>8005/5DG5</td>
<td>On-Shell Technology</td>
<td>Terminal Block, 6A, 3.5mm Pitch, 2-20a, TH</td>
<td>ED1514-ND</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 2</td>
<td>R1, R2, R3</td>
<td>520</td>
<td>RTD200-12-W-11</td>
<td>Sukut</td>
<td>Resistor, 12W, 1%, 1/10W, 0603</td>
<td>R010P1200CT-ND</td>
<td></td>
</tr>
<tr>
<td>6 4</td>
<td>D4, D8, D7, D8</td>
<td>100K</td>
<td>CVC0603000000101A</td>
<td>Vishay-Data</td>
<td>Resistor, 5%, 1/4W, 396, 0603</td>
<td>R41-0.050CT-ND</td>
<td></td>
</tr>
<tr>
<td>7 1</td>
<td>R5</td>
<td>1.27Ω</td>
<td>PRW-342-001271V</td>
<td>Panasonic Electronic Components</td>
<td>Resistor, 1W, 1%, 0603, SMD</td>
<td>541-1.27KHC7-ND</td>
<td></td>
</tr>
<tr>
<td>6 1</td>
<td>R6</td>
<td>68Ω</td>
<td>SKCHF1200KX106R</td>
<td>Steddy Electronics Inc.</td>
<td>RES 100-DIN 1AW 25% 1206</td>
<td>511-100MRCT-ND</td>
<td></td>
</tr>
<tr>
<td>9 1</td>
<td>DP1</td>
<td>Red</td>
<td>5005</td>
<td>Keystone</td>
<td>Test Point, TH, Compact, Red</td>
<td>6069K-ND</td>
<td></td>
</tr>
<tr>
<td>10 4</td>
<td>TP2, TP4, TP5, TP6</td>
<td>Black</td>
<td>5005</td>
<td>Keystone</td>
<td>Test Point, TH, Compact, Black</td>
<td>5069K-ND</td>
<td></td>
</tr>
<tr>
<td>11 1</td>
<td>TP7</td>
<td>Orange</td>
<td>5005</td>
<td>Keystone</td>
<td>Test Point, Compact, Orange, TH</td>
<td>5065K-ND</td>
<td></td>
</tr>
<tr>
<td>12 1</td>
<td>TR6</td>
<td>White</td>
<td>5607</td>
<td>Keystones</td>
<td>Test Point, Dipped, White, TH</td>
<td>5067K-ND</td>
<td></td>
</tr>
<tr>
<td>13 1</td>
<td>U1</td>
<td>RA1023AD9K</td>
<td>Texas Instruments</td>
<td>Micropower, Zero-Shift, 16-Bit D/A, Rail-to-Rail Instrumentation Amplifier</td>
<td>209-2305A-1.0ND</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 1</td>
<td>U2</td>
<td>REF0254AD00K</td>
<td>Texas Instruments</td>
<td>Low Noise, Very Low Drift, Precision Voltage Reference</td>
<td>REF0254A000K-8.0ND</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 4</td>
<td>U9, U10, U5, U91</td>
<td>74HC164</td>
<td>74HC164</td>
<td>Keystone</td>
<td>STANDOFF, HEX 4-48, TH, ALUM 1/4</td>
<td>2356K-ND</td>
<td></td>
</tr>
<tr>
<td>16 4</td>
<td>U12, U13, U92, U97</td>
<td>PEGIS 440 0026 PH</td>
<td>B&amp;J Fastener Supply</td>
<td>MACHINE SCREW PAN PHILLIPS 4-40</td>
<td>5752K-ND</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 1</td>
<td>D8</td>
<td>10.08</td>
<td>CVC50503000000101A</td>
<td>Vishay-Data</td>
<td>Resistor, 10ohm, 1%, 0.1W, 0603</td>
<td>R41-10RHC7-ND</td>
<td></td>
</tr>
<tr>
<td>18 0</td>
<td>C8</td>
<td>1000μF</td>
<td>CCG0013CAKX0R1802</td>
<td>Yageo America</td>
<td>CAP, CERM, 1000μF, 16V +/-20%, 1206, 0603</td>
<td>R6B3720-1ND</td>
<td></td>
</tr>
<tr>
<td>19 0</td>
<td>C10</td>
<td>0.1uF</td>
<td>5603Y5104J104A5</td>
<td>AVX</td>
<td>CAP, CERM, 0.1uF, 16V, +/-5%, XTR, 0603</td>
<td>R6B3720-1ND</td>
<td></td>
</tr>
</tbody>
</table>
IMPORTANT NOTICE FOR TI REFERENCE DESIGNS

Texas Instruments Incorporated (“TI”) reference designs are solely intended to assist designers (“Buyers”) who are developing systems that incorporate TI semiconductor products (also referred to herein as “components”). Buyer understands and agrees that Buyer remains responsible for using its independent analysis, evaluation and judgment in designing Buyer’s systems and products.

TI reference designs have been created using standard laboratory conditions and engineering practices. TI has not conducted any testing other than that specifically described in the published documentation for a particular reference design. TI may make corrections, enhancements, improvements and other changes to its reference designs.

Buyers are authorized to use TI reference designs with the TI component(s) identified in each particular reference design and to modify the reference design in the development of their end products. HOWEVER, NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT, AND NO LICENSE TO ANY THIRD PARTY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT, IS GRANTED HEREIN, including but not limited to any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

TI REFERENCE DESIGNS ARE PROVIDED “AS IS”. TI MAKES NO WARRANTIES OR REPRESENTATIONS WITH REGARD TO THE REFERENCE DESIGNS OR USE OF THE REFERENCE DESIGNS, EXPRESS, IMPLIED OR STATUTORY, INCLUDING ACCURACY OR COMPLETENESS. TI DISCLAIMS ANY WARRANTY OF TITLE AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, QUIET ENJOYMENT, QUIET POSSESSION, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS WITH REGARD TO TI REFERENCE DESIGNS OR USE THEREOF. TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY BUYERS AGAINST ANY THIRD PARTY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON A COMBINATION OF COMPONENTS PROVIDED IN A TI REFERENCE DESIGN. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, SPECIAL, INCIDENTAL, CONSEQUENTIAL OR INDIRECT DAMAGES, HOWEVER CAUSED, ON ANY THEORY OF LIABILITY AND WHETHER OR NOT TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES, ARISING IN ANY WAY OUT OF TI REFERENCE DESIGNS OR BUYER’S USE OF TI REFERENCE DESIGNS.

TI reserves the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques for TI components are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

Reproduction of significant portions of TI information in TI data books, data sheets or reference designs is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards that anticipate dangerous failures, monitor failures and their consequences, lessen the likelihood of dangerous failures and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in Buyer’s safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed an agreement specifically governing such use.

Only those TI components that TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components that have not been so designated is solely at Buyer’s risk, and Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.