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Modification of the Wheatstone-Bridge for Measurement of a Process Variable by a Resistive Transducer Using Lab VIEW

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Abstract: The small resistance of a resistive transducer generally linearly changes with a process variable, but their measurement by the usual resistive bridge circuit like the Classical Wheatstone-bridge suffers from errors due to the nonlinearity ,contact resistances, effect of the shunt resistance between bridge nodal points and the lumped resistances of leads connected to sensor as well as detector.

In this paper, virtual instrument system for the measurement of small displacement using modified operational-amplifier-based dc Wheatstone bridge circuit with strain gauge as sensor has been proposed in which the effect of nonlinearity error and lead resistance is minimized. In this instrument, sensitivity and linearity have been improved in the absence of instrumentation amplifier. The output signal has been found to be linearly related with the displacement. This output voltage has been filtered and interfaced to PC-Lab VIEW through NI-cDAQ. The proposed system is easy to implement and convenient for various applications. In the first phase of the experiment, the bridge performance has been simulated using Lab VIEW and studied with a known variable resistor, and in the second phase, the same experimentation was done by replacing the strain gauge for the measurement of displacement. The linear characteristics over a wide range of displacement with good repeatability, linearity, improved and variable sensitivity have been described. *Copyright © 2012 IFSA.*

Keywords: Wheatstone-Bridge, Strain gauge, LabVIEW, Displacement Measurement, Linearization, Sensitivity, Sensors.

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1. Introduction

In 1843 the English physicist, Sir Charles Wheatstone (1802-1875), found a bridge circuit for measuring electrical resistances. In this bridge circuit, known today as the Wheatstone bridge circuit, unknown resistances are compared with well-defined resistances [1].

Wheatstone bridges are a well-established and simple technology for improving the quality of measurement from various low-energy sensors. One very common application is in strain gages. Strain gages are widely used for measuring force, pressure and weight and are the sensing element in load cells. Strain gauges typically have base resistances of 120 Ω or 350 Ω. The variation in this resistance when a force is applied is typically a small fraction of an ohm. Measuring small differences in resistance or voltage can be difficult. Hence, there is a need of suitable signal conditioning circuit with a sensor that has a range of 120.0 Ω to 120.5 Ω or in other words, all the useful information is contained in 1/240 of the total range of the resistance. A balanced Wheatstone bridge removes all the non-changing part of the range (the 120 Ω portion) and the only output is a small voltage varying from zero to maximum. The Wheatstone bridge is a very useful design for isolating that varying part of the resistance range and converting it to an output voltage.

In practical applications, strain measurements are carried out over long periods of time and so the gauges are subjected to variation in ambient temperature. Temperature variations cause the major errors in the measurement of strains by strain gauges. Temperature changes cause the change in resistance in two ways. The resistance of the wire grid of strain gauge changes with the change in temperature. Another aspect of temperature effect is found in the possible differential expansion of the gauge and the underlying material. This can cause a change in strain and resistance in the gauge even though the material is not subjected to an external load. These temperature effects have been compensated in various ways and demonstrated in [2-5].

Spin-valve-based devices in a Wheatstone full bridge configuration have been demonstrated to be effective for the electrical current measurement in the range of 10 μA to 100 mA, with excellent linearity and sensitivities above 1 mV/V. mA [6]. Modified AC Wheatstone bridge network for the accurate measurement of pressure using strain gauge type sensor has been proposed in [7] for reducing errors due to the effect of stray capacitance between bridge nodal points and ground and stray inductance on the strain gauge grid respectively.

This paper proposes a design of virtual instrument system for the measurement of small displacement using modified operational-amplifier-based dc Wheatstone bridge circuit with strain gauge as sensor. The proposed instrument minimizes the effect of nonlinearity error and lead resistance in measuring circuitry. In this instrument, sensitivity and linearity have been improved in the absence of instrumentation amplifier. The output signal has been found to be linearly related with the displacement. This output voltage has been filtered and interfaced to PC-LABVIEW through NI-cDAQ. The proposed system is easy to implement and convenient for various applications.

2. Method of Approach

2.1. Modified Wheatstone -Bridge

A Classical DC Wheatstone- Bridge circuit is modified as shown in Fig. 1, where two very high gain Operational amplifiers A1 and A2 are connected with the bridge network [8, 9] with the non-inverting terminal connected to the circuit ground. This enables the bridge output nodal points B and D to be almost at the same potentials with respect to the ground and hence the effect of shunt resistance that will exist between them and also between them and ground, may be assumed to be minimized.

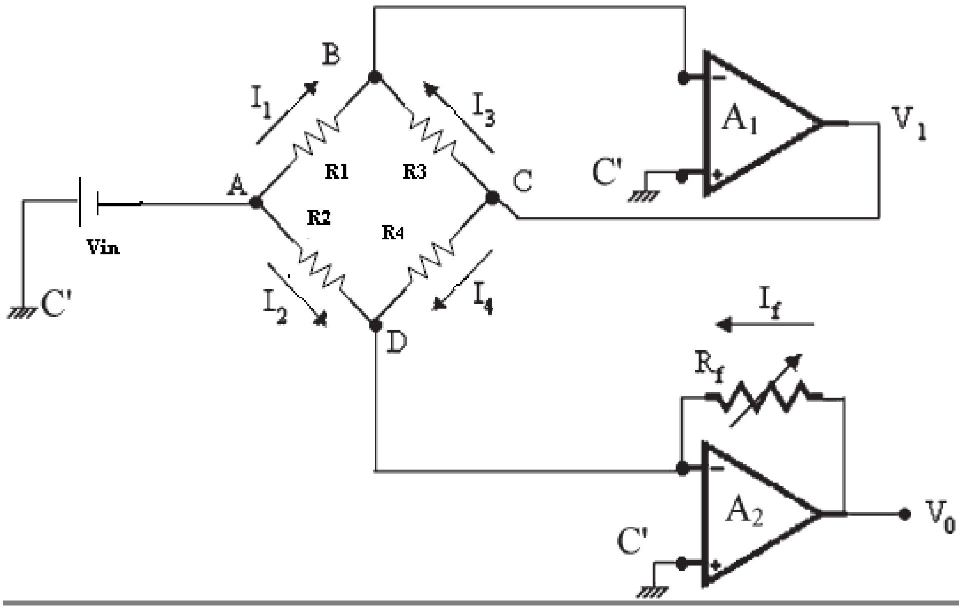

Fig. 1. Modified dc Wheatstone bridge network.

Since B and D are at virtual ground, so for the regulated dc supply voltage V_{in}, the currents through the bridge resistances R1, R2, R3 and R4 are respectively given by

$$I_1 = \frac{V_{in}}{R_1}, I_2 = \frac{V_{in}}{R_2}, I_3 = \frac{V_1}{R_3}, I_4 = \frac{V_1}{R_4}, \tag{1}$$

where V_1 is the output voltage of the operational amplifier A_1. If V_0 is the output voltage of the operational amplifier A_2 then the current through its feedback resistance is given by:

$$I_f = \frac{V_0}{R_f}$$

Applying Kirchhoff's current law

$$I_1 + I_3 = 0 \tag{2}$$

and

$$I_2 + I_4 + I_f = 0 \tag{3}$$

The equation (1) and (2) give

$$\frac{V_1}{R_1} + \frac{V_1}{R_3} = 0$$

$$V_1 = -\frac{R_3}{R_1} V_{in} \tag{4}$$

The equations (1) and (3) give

$$\frac{V_{in}}{R_2} + \frac{V_1}{R_4} + \frac{V_0}{R_f} = 0 \tag{5}$$

The equations (4) and (5) give

$$V_0 = \frac{R_f}{R_1 R_2 R_3} (R_2 R_3 - R_1 R_4) V_{in} \tag{6}$$

At balance condition of the bridge, $V_0 = 0$, which is identical with the conventional bridge network. For the modified DC Wheatstone bridge circuit, $R_3=R_0+\Delta R$.

Hence, from equation (6), the bridge output voltage is given as

$$V_0 = \frac{R_f}{R_1 R_2 R_4} \left[R_2 (R_0 + \Delta R) - R_1 R_4) \right] V_{in} \tag{7}$$

If the bridge is balanced at the minimum value of the process variable for which the resistance of a transducer is R_0, then $V_0=0$ for $R_0+\Delta R=R$, also, $\left[R_2 R_0 - R_1 R_4 \right] = 0$

ΔR is the change in resistance for a given change of the process variable above this minimum value.

The variable resistor is connected instead of ΔR.

It is commonly known that the strain gage transforms strain applied into a proportional change of resistance. The relationship between the applied strain ε (ε = L/Lo) and the relative change of the resistance of a strain gage is described by the equation

$$\frac{\Delta R}{R_0} = G_f . \varepsilon \tag{8}$$

The factor G_f, known as the gage factor, is a characteristic of the strain gage and has been checked experimentally. The exact value is specified on each strain gage package. In general, the gage factor for metal strain gages is about 2.

The equations (7) and (8) give

$$V_0 = \frac{R_f}{R_1 R_4} \left[R_0 G_f \varepsilon) \right] V_{in} \ , \tag{9}$$

where, V_0 is bridge output voltage; V_{in} is the input excitation voltage; R_f is the feedback resistance. The equation (9) depicts the linear relationship between V_0 and ε for constant bridge excitation voltage, fixed resistors R_1, R_4 and gauge factor. The bridge sensitivity can also be improved and varied by using feedback resistor, R_f. The error may be produced due to the zero drift error and gain drift error of the op-amp, which may be minimized by selecting low-noise op-amps.

2.2. Displacement Measurement Using Modified DC Wheatstone Bridge Circuit

The strain gauges are mounted on the cantilever beam to which the measured displacement is applied as shown [10] in Fig. 2.

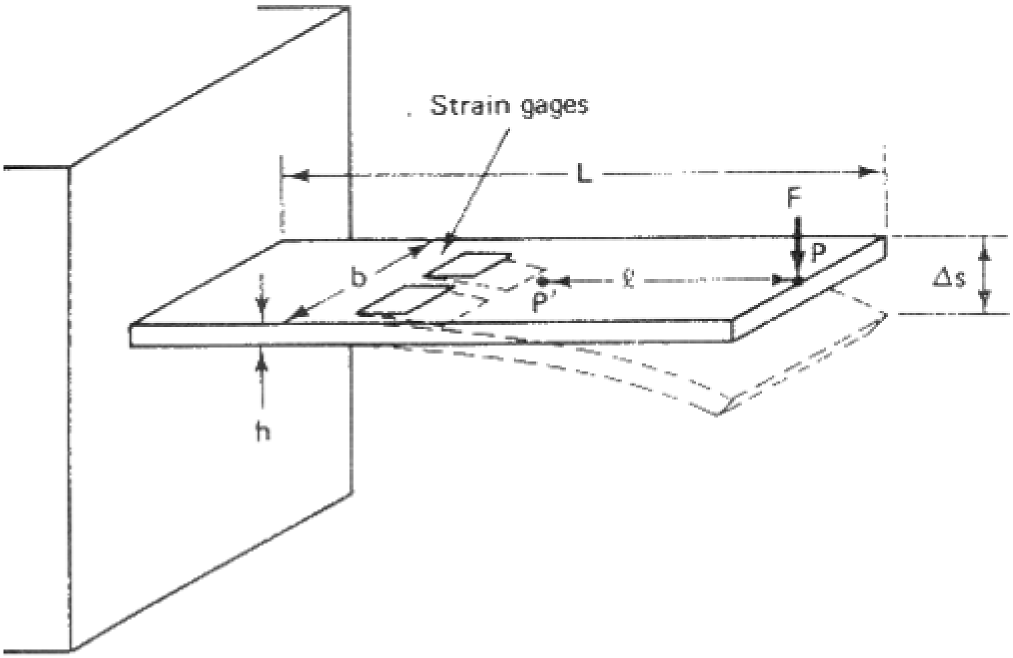

Fig. 2. Mounting strain gauges on cantilever beam to measure small displacement.

The change in displacement is described by the equation

$$\Delta S = \frac{2L^3 \varepsilon}{3lh} \tag{10}$$

where: *L (30 cm), h (0.25 cm)* are the length and thickness of cantilever beam respectively; *l* (*22 cm*) is the distance between the points of displacement applied (P) and location of strain gauges on cantilever beam; ε is the strain at P^1.

The equations (9) and (10) give

$$V_0 = \frac{R_f}{R_1 R_4}\left[R_0 G_f \frac{3.l.h.\Delta S}{2.L^3})\right]V_{in} \tag{11}$$

Hence, if the value of the bridge output voltage is V_0, then

$$V_0 = k.\Delta S \tag{12}$$

where

$$k = \frac{R_f}{R_1 R_4}\left[R_0 G_f \frac{3.l.h.}{2.L^3}\right]V_{in} = Const. \tag{13}$$

i.e., the output voltage is linearly related to the change in the process variable if the resistive transducer is linear. The equation (12) depicts the linear relationship between the bridge output voltage and displacement. The modified dc Wheatstone-bridge circuit has been used for measuring displacement, replacing the variable resistor by a strain gauges mounted on the cantilever beam. The cantilever beam is fitted with a screw gauge so that displacement can be measured.

Since from (12), $\Delta S = V_0 / k$, the relative measurement error (E_1) expressed in percentage may be calculated by the following equation:

$$(E_1) = \frac{(\frac{V_0}{k} - \Delta S)}{\Delta S} \times 100\% \tag{14}$$

where ΔS is the measured displacement; V_0 is the measured output voltage.

In terms of percentage of the maximum range, it changes to (E2); this may be defined as

Relative measurement error

$$(E2) = \frac{(\frac{V_0}{k} - \Delta S)}{\Delta S_{max}} \times 100\% \tag{15}$$

Again, from the measured values of V_0 at different values of ΔS, the best-fit linear characteristic may be drawn using the LABVIEW. The actual values of V_0 may be obtained from the best-fit linear characteristic at different values of ΔS, and the relative measurement error (E_3) from linearity may then be defined as:

$$(E_3) = \frac{(V_{0-actual} - V_0)}{(V_{0-actual})_{max}} \times 100\% \tag{16}$$

where $V_{0-\text{actual}}$ are the actual values obtained from the best-fit linear curve for a given displacement (ΔS).

2.3. Proposed Virtual Instrument System for Displacement Measurement

A virtual instrument consists of an industry standard computer or workstation equipped with powerful application software, cost-effective hardware such as plug-in boards, and driver software, which together perform the functions of traditional instruments.

Virtual instruments represent a fundamental shift from traditional hardware-centered instrumentation systems to software-centered systems that exploit the computing power, productivity, display, and connectivity capabilities of popular desktop computers and workstations. Although the PC and integrated circuit technology have experienced significant advances in the last two decades, it is software that truly provides the leverage to build on this powerful hardware foundation to create virtual instruments, providing better ways to innovate and significantly reduce cost. With virtual instruments, engineers and scientists build measurement and automation systems that suit their needs exactly (user-defined) instead of being limited by traditional fixed-function instruments (vendor-defined) [11].

The block diagram of proposed virtual instrument for measurement of small displacement is shown in Fig. 3.

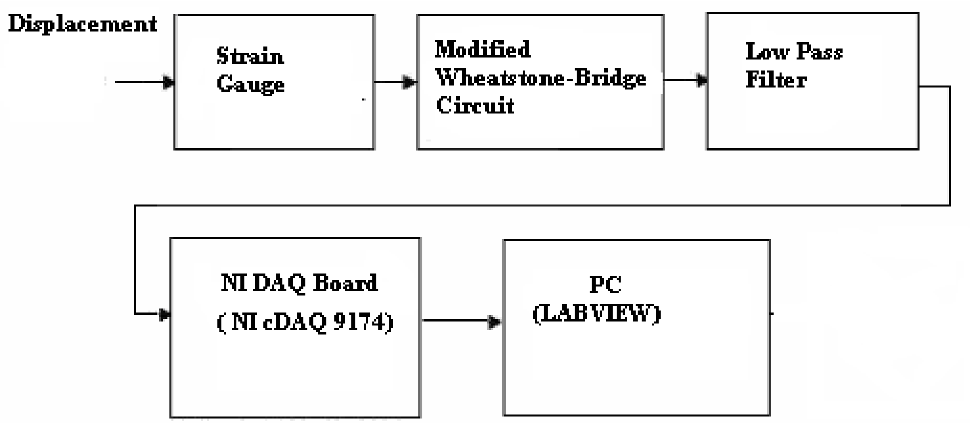

Fig. 3. Block Diagram of proposed virtual instrument system for displacement measurement.

3. Experimental Results

The experiments were performed in two phases. In the first phase of the experiment, the modified dc Wheatstone-bridge performance has been studied with a known variable resistor and stabilized dc power supply of 5 V, as shown in Fig. 1, at a selected value of R_f. The 4 (4/5) digit TX3 true digital multimeter was used as the detector. The initial bridge balance condition was obtained without ΔR for a selected value of R_f by selecting fixed resistances. The change in resistance ΔR in both increasing and decreasing modes is varied in steps, and at each step, the bridge output voltage is measured. The experiment is repeated for different values of bridge sensitivity resistance R_f. The experimental results of three sets of experiment were taken for three different orientations of the connecting wires. Experimental characteristic graphs were then drawn by plotting the bridge output voltage against the known variable resistance ΔR, which is equivalent to the resistance of the resistive transducer, for different values of the bridge sensitivity factor R_f, as shown in Fig. 4. From these experimental data the best fit straight-line curve was plotted by using LABVIEW 9 in each case, and the percentage error of the experimental data from this optimum straight line was calculated. The percentage deviation curve of the change in resistance from a straight line for different values of R_f is drawn by using (16), as shown in Fig. 5.

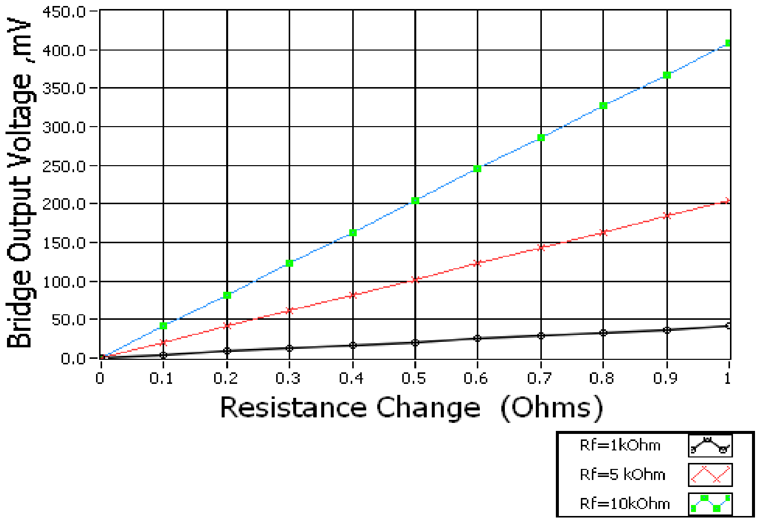

Fig. 4. Change in resistance versus bridge output voltage.

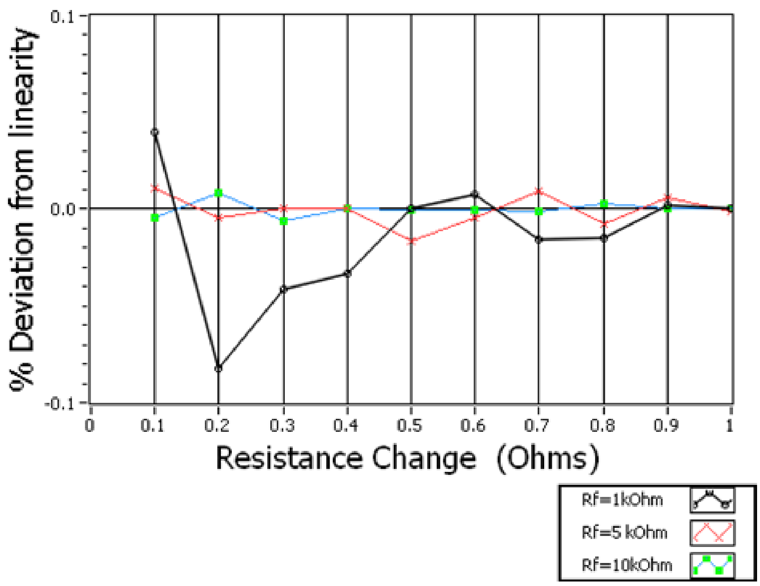

Fig. 5. Percentage deviation of the resistance from straight line characteristic.

In the second phase of experiment, the same modified dc Wheatstone-bridge circuit has been used for measuring displacement, replacing the variable resistor by a strain gauge mounted on the cantilever beam. The cantilever beam of the proposed virtual instrument system is the laboratory standard equipment with the following specification.

L:	Length of the cantilever beam, 30 cm
h:	Thickness of the cantilever beam, 0.25 cm
b:	Width of the cantilever beam, 2.8 cm
l:	Distance between the point of displacement applied and point of strain gauge bonded on cantilever beam, 22 cm
Strain gauge:	Wire-wound resistance
Bridge resistance:	350 Ω
Gauge Factor:	1.9 to 2.3
Material:	Stainless Steel

The cantilever beam is fitted with a screw gauge so that displacement can be measured. The base resistance of the strain gauge is R_0 = 350 Ω. Initially, the bridge is balanced for a particular resistance of the strain gauge, and then, the beam is strained by a screw gauge having a resolution of 0.01 mm. The bridge output voltages for different values of the screw gauge position with a selected value of R_f are measured in both increasing and decreasing modes. The variation of the unbalanced bridge output voltage with the change in displacement was found to be linear. The experimental results of the three sets of experiment were taken from different values of sensitivity factor R_f. The experimental characteristic graphs and the percentage deviation of change in displacement for different values of R_f from linearity are shown in Figs. 6 and 7, respectively.

The linear characteristics over a wide range of displacement with good repeatability, linearity, and variable sensitivity have been described. The output signal of the transducer in the virtual system has been acquired, analyzed and the results were visualized with a virtual instrument created in Lab VIEW environment as shown in Figs. 8 and 9.

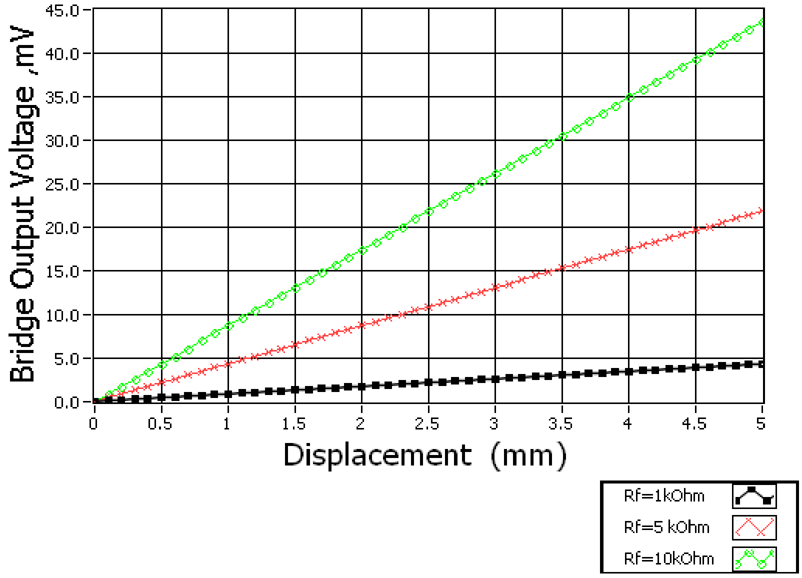

Fig. 6. Change in displacement versus bridge output voltage.

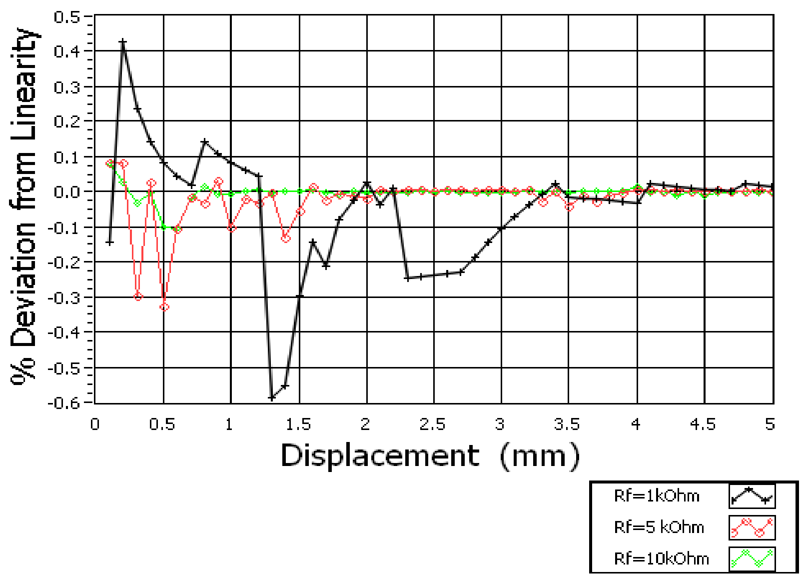

Fig. 7. Percentage deviation of the displacement from linearity.

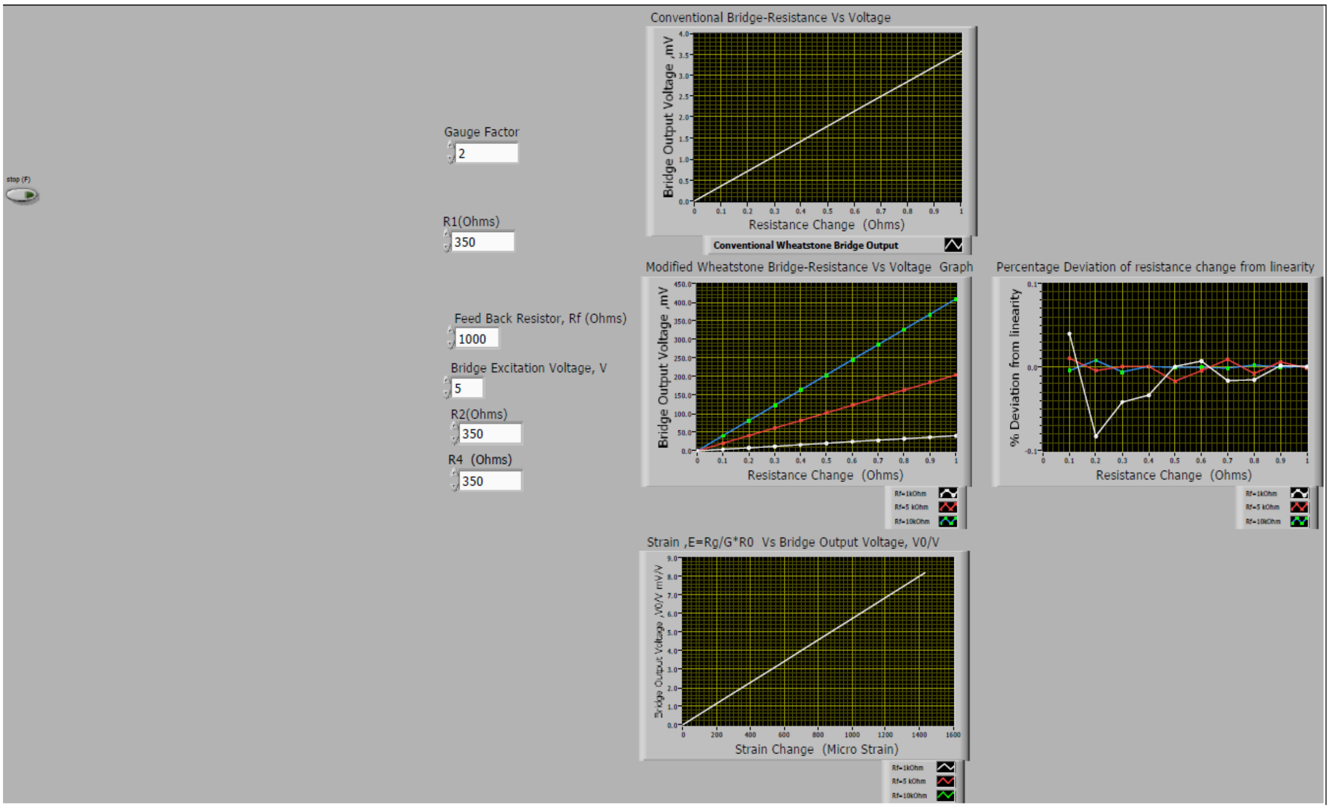

Fig. 8. Lab VIEW user (interface) front panel.

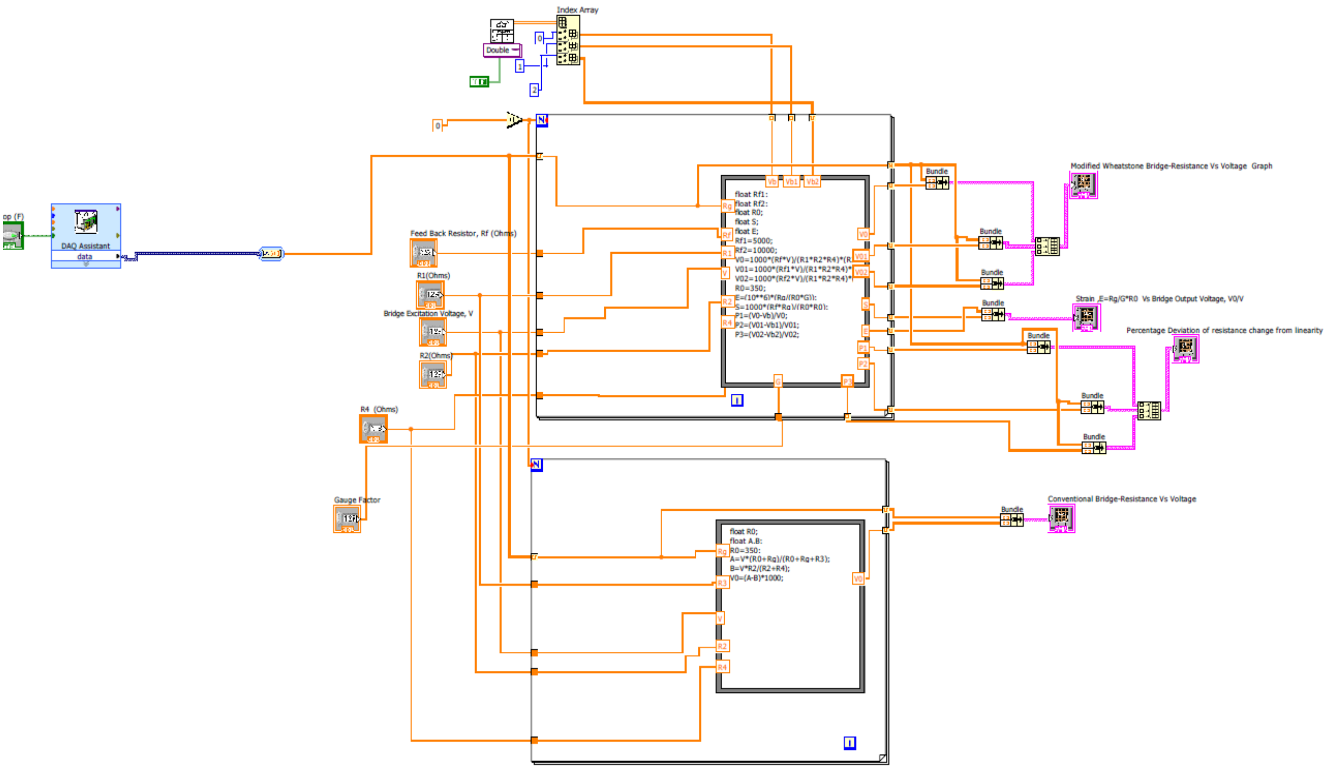

Fig. 9. Lab VIEW graphical code for the proposed virtual instrument system.

4. Conclusion

The experimental graphs shown in Figs. 4 and 6 for resistance and displacement measurement, respectively, have been found to have quite good linearity. The percentage deviation from linearity is within the tolerable limit of ±1.5 %, as shown in Figs. 5 and 7, respectively. The larger value of the percentage deviation may be due to the calibration error of the bridge components, as well as due to the aging effect of the components. The human error in taking the reading of the displacement may also contribute to a larger percentage error as the displacement has been measured by a screw gauge. However, during experimentation, it has been found that almost identical results were obtained in both increasing and decreasing modes, and the results did not vary with the change in orientation of the connecting wires with respect to the ground and observer. Hence, neglecting the bridge component error and the human error, the experimental results may be assumed to have minimum error due to lead resistance and bridge non linearity, and the proposed virtual instrument of measurement may be assumed to have very good accuracy compared to the conventional Wheatstone-bridge network- type measurement.

As a result of the investigation conducted in this paper, the possibility for the design of a displacement sensor on the basis of a modified Wheatstone-bridge circuit interfaced to PC-Lab VIEW with display and further analysis has been shown. The sensitivity of the instrument has been varied and improved without connecting additional elements such as instrumentation amplifiers in the measuring circuit.

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Guide for Contributors

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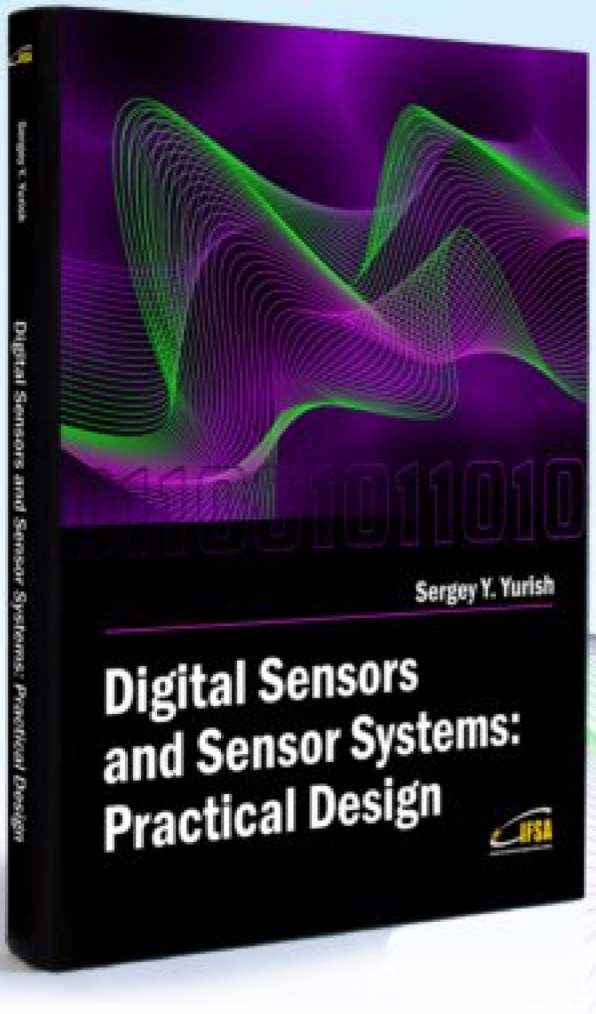

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