Development of Wheatstone bridge and Kelvin bridge Simulation Experiment System Based on LabVIEW

YANG Tie-Zhu*, LAI Xiao-Lei, LONG Qian-Xin

1Department of Basic Course, Zhengzhou College of Science and Technology, Zhengzhou 450064, China
2School of materials science and engineering, Guilin University of Electronic Science and Technology, Guilin 541004, China
*Corresponding author’s e-mail: 2004011@mail.zit.edu.cn

Abstract : The method of circuit bridge for measuring resistance is one of the very important contents in experiment physics teaching. Taking DC bridge for example, by using LabVIEW through programming, CTL interface beautification, local variables and Property Node setting, the experiment of measuring resistance by DC bridge is simulated. In the process of development, the galvanometer current formula in the Wheatstone bridge and Kelvin bridge is unified, the calculation is carried out with matlab. The system realizes the whole process of experiment operation, processing and simulation of experimental data and expression of complete experimental results in the same simulation software.

1. Introduction
The method of circuit bridge combines theory with experiment, can measure resistance accurately[1-3]. The method of circuit bridge can measure Simple DC resistance, also can measure high precision instrument and equipment, it has a wide range of applications. The method of circuit bridge is a comparison method, that is, the resistance of the same nature with known resistance value is used as the comparison standard, then the resistance to be measured is determined to be equal to the multiple of the known standard resistance, and then the resistance value of the measured resistance is calculated. Because it is not difficult to make standard resistance with small error, the accuracy of resistance measurement by bridge method is very high.

In order to adapt to the requirements of the era of the transformation of the relationship between teaching and learning under the condition of informatization, the construction and application of virtual simulation experiment came into being. It uses computer language or program to build a virtual experimental environment, so as to help teachers "teach" and students "learn". LabVIEW (Laboratory Visual Instrument Engineering Workbench) is a typical graphic programming language, also known as "G language", which represents the program in the form of block diagram[4-13]. The simulation experiment system of DC bridge designed in this paper is developed based on LabVIEW program. It can be controlled and operated by mouse on personal computer. It can also use VI to generate application program (exe), which can be shared on the network to enrich the teaching resources of college physics experiment course.

2. DC bridge and its experimental principle
DC bridges are mainly divided into Wheatstone bridge and Kelvin bridge, which are also called single
arm bridge and double arm bridge respectively. Wheatstone bridge is used to measure medium resistance (1 ~ 10^6 Ω), and Wheatstone bridge is used to measure low resistance (below 1 Ω).

2.1 Wheatstone bridge

2.1.1 Equilibrium condition

Figure 1 is the basic circuit diagram of Wheatstone bridge. The four arm resistances of the bridge are \( R_1, R_2, R_3, R_x \). B and d is connected with galvanometer G (internal resistance is \( R_g \)) When the potentials of b and d are equal, there is no current flowing through bd branch. At this time, the bridge reaches balance, and when the bridge is balanced, it can be obtained \( I_1 = I_3 \), \( I_2 = I_x \), then we can get

\[
\begin{align*}
I_1R_1 &= I_2R_2 \\
I_1R_3 &= I_2R_x
\end{align*}
\]

The above two formulas are divided by two sides respectively

\[
R_x = \frac{R_2}{R_1}R_3
\]

Let the ratio be \( M \), \( M = \frac{R_2}{R_1} \),

Then, \( R_x = MR_3 \) (1)

When the bridge is balanced, if \( M \) and \( R_3 \) are known, we can get the resistance of \( R_x \).

2.1.2 Sensitivity

It is generally considered that when the deflection range of galvanometer pointer is less than 0.1 grid, it is difficult for human eyes to distinguish. Although there is still a small current flowing through the galvanometer, the experimenter will think that the bridge has reached balance, but there will be systematic error in the experiment. In order to measure the accuracy of measurement, it is necessary to calculate the sensitivity of the bridge, the sensitivity calculation formula is shown in formula (2).

\[
S = \frac{\Delta n}{\Delta R_3/R_3}
\]

where \( \Delta n \) means that when the bridge is balanced, a slight change in the value of \( R_3 \) was found to be \( \Delta R_3 \), the grid of galvanometer pointer deflection (If a digital galvanometer is used in the experiment, then \( \Delta n \) means units of the last significant number of galvanometer has changed. In this experiment, digital galvanometer is used).

![Figure 1. Schematic diagram of single arm bridge](image1)

![Figure 2. Schematic diagram of double arm bridge](image2)

2.2 Kelvin bridge

In the measurement of low resistance resistance, wire resistance and contact resistance can not be ignored, so Wheatstone bridge can not be used to measure low resistance, but the design idea of
Wheatstone bridge can still be borrowed. Fig. 2 is the circuit schematic diagram of Kelvin bridge. When the current flowing through the galvanometer is zero, the bridge is balanced, the results are as follows:

\[ R_x = \frac{R_N}{R_1} R_3 + \frac{R_3 r}{R_3 + R_3' + r} \left( \frac{R_2}{R_1} - \frac{R_3'}{R_3} \right) \]

if the resistance selected in the experiment \( R_1 = R_2, \ R_3 = R_3' \), then

\[ \frac{R_3 r}{R_3 + R_3' + r} \left( \frac{R_2}{R_1} - \frac{R_3'}{R_3} \right) = 0 \]

so:

\[ R_x = \frac{R_3}{R_1} R_N \]

it is easy to see that the form of formula (3) is the same as that of Wheatstone bridge (1).

3. Overall design of simulation experiment system

In order to intuitively and conveniently carry out the simulation experiment of Wheatstone bridge and Kelvin bridge, the simulation experimental system of DC bridge is designed by LabVIEW programming. The system has three modules: theory explanation, simulation operation and data processing. In the process of experiment, the experiment content can be switched and the experimental error can be simulated. In the process of data processing, the uncertainty and sensitivity of the results can be calculated according to the data obtained from the simulation experiment. The function modules of the simulation experiment system are shown in Figure 3.

4 Realization of simulation experiment

4.1 Front panel of simulation experiment

According to the functional requirements of the overall design, the front panel of the simulation experimental system is shown in Fig. 4, FIG. 5, FIG. 6, FIG. 7, it mainly includes three parts:
4.2 Realization of galvanometer data

4.2.1 Data implementation

In Wheatstone bridge, the galvanometer current formula can be obtained from Figure 1 [3, 13]

\[ I_g = \frac{E(R_2R_3 - R_2R_1)}{A_1} \]  

where \( A_1 = R_g(R_1 + R_y)(R_2 + R_x) + R_1R_3(R_2 + R_x) + R_2R_x(R_1 + R_3) \).

In Kelvin bridge, the galvanometer current formula can be obtained from Figure 2:

\[ I_g = \frac{E[2R_2r + r_2N A_2A_4 + A_2A_3 - r_2^2A_2A_4]}{(A_2A_3 - r_2^2)(A_2R_1 + A_2r + r_2N A_2 + r_2N A_2 + R_2r + r_2N A_2 + r_2N A_2 + r_2N A_2 + r_2N A_2)} \]  

where the letter E is the supply voltage in Formula (5), \( A_2 = R_2 + R_3 + r \), \( A_3 = R_N + R_x + r \), \( A_4 = R_1 + R_y \). If \( R_2 = 0 \), and \( r = 0 \), \( R_3 = 0 \), here \( R_N \) amount to the one in the Wheatstone bridge of \( R_2 \), formula (5) and (4) are the same, in other words, formula (5) can be used to express galvanometer
indication \( I_g \) in Wheatstone bridge also Kelvin bridge. Therefore, formula (5) can be used as galvanometer formula in this simulation system.

4.2.2 Matlab aided calculation

For Wheatstone bridge:
Matlab programming is as follows:

```matlab
syms I_1 I_2 I_3 I_x I_G R_3 R_2 R_1 R_x U R_G
JIEGUO=solve('I_1+I_2-I_3-I_x','I_1-I_3-I_G','I_1*R_1+I_G*R_G-I_2*R_2','I_3*R_3-I_G*R_G-I_x*R_x','I_2*R_2+I_x*R_x-U','I_G','I_1','I_2','I_3','I_x')
IG=JIEGUO.I_G
pretty(IG)
```

The results are as follows:

\[
\begin{align*}
\text{JIEGUO} &= \\
&= I_1: [1x1 \text{sym}] \\
&= I_2: [1x1 \text{sym}] \\
&= I_3: [1x1 \text{sym}] \\
&= I_G: [1x1 \text{sym}] \\
&= I_x: [1x1 \text{sym}] \\
\text{IG} &= \\
&= (R_2*R_3*U - R_1*R_x*U)(R_1*R_2*R_3 + R_1*R_2*R_G + R_2*R_3*R_G + R_1*R_2*R_x + R_1*R_3*R_x + R_2*R_3*R_x + R_1*R_G*R_x + R_3*R_G*R_x)
\end{align*}
\]

The result of this calculation is the same as that of formula (4). \( U \) in the program is \( E \) in formula (4), i.e. the electromotive force \( E \) of power supply in Figure 1.

For Kelvin bridge:
Matlab programming is as follows:

```matlab
syms I_1 I_2 I_3 I_N I_g I_x R_3 R_2 R_31 R_x r R_N U R_1 R_g
Jieguo=solve('I_1*R_1+(I_1-I_g)*R_3-U','I_N*R_N+(I_N-I_2)*r+(I_g+I_N)*R_x-U','I_1*R_1+I_g*R_g-I_2*R_2-I_N*R_N-I_2*R_2+I_g+I_2)*R_31-(I_N-I_2)*r','I_g','I_1','I_2','I_N')
Ig=Jieguo.I_g
pretty(Ig)
```

The results are as follows:

\[
\begin{align*}
\text{Jieguo} &= \\
&= I_1: [1x1 \text{sym}] \\
&= I_2: [1x1 \text{sym}] \\
&= I_N: [1x1 \text{sym}] \\
&= I_g: [1x1 \text{sym}] \\
\text{Ig} &= \\
&= (R_2*R_3*R_N*U + R_3*R_31*R_N*U - R_1*R_2*R_x*U - R_1*R_31*R_x*U - R_1*R_31*U*r + R_2*R_3*U*r + R_3*R_N*U*r - R_1*R_x*U*r)/(R_1*R_2*R_3*R_N + R_1*R_2*R_31*R_N + R_2*R_3*R_31*R_N + R_2*R_3*R_N + R_1*R_2*R_3*R_x + R_1*R_2*R_31*R_x + R_2*R_3*R_31*R_x + R_1*R_2*R_N*R_g + R_1*R_31*R_N*R_g + R_2*R_3*R_N*R_g + R_3*R_31*R_N*R_g + R_1*R_2*R_N*R_x + R_1*R_31*R_N*R_x + R_2*R_3*R_N*R_x + R_3*R_31*R_N*R_x + R_1*R_2*R_g*R_x + R_1*R_31*R_g*R_x + R_2*R_3*R_g*R_x + R_3*R_31*R_g*R_x + R_1*R_2*R_3*r + R_1*R_31*R_3*r + R_2*R_3*R_31*r + R_1*R_3*r + R_1*R_31*R_N*r + R_1*R_31*R_N*r + R_3*R_31*R_N*r + R_1*R_2*R_g*r + R_2*R_3*R_g*r + R_3*R_31*R_g*r + R_1*R_2*R_x*r + R_1*R_31*R_x*r + R_2*R_3*R_x*r + R_1*R_N*R_g*r + R_3*R_N*R_g*r + R_3*R_N*R_g*r + R_3*R_N*R_g*r)
\end{align*}
\]
\[
R_1R_NR_x^r + R_3R_NR_x^r + R_1R_gR_x^r + R_3R_gR_x^r
\]
\[
\frac{R_2R_3R_NU + R_3R_31R_NU - R_1R_2R_xU - R_1R_31R_xU \cdot R_1R_31U + R_2R_3U + R_3R_NU + R_1R_xU}{R_2R_3R_31R_N + R_1R_2R_3R_x + R_1R_2R_31R_x + R_1R_3R_31R_x + R_2R_3R_31R_x + R_1R_2R_31R_x + R_1R_3R_31R_x + R_2R_3R_31R_x + R_1R_2R_NR_g + R_1R_31R_NR_g + R_2R_3R_NR_g + R_3R_31R_NR_g + R_1R_2R_NR_x + R_1R_31R_NR_x + R_2R_3R_NR_x + R_3R_31R_NR_x + R_1R_2R_gR_x + R_1R_31R_gR_x + R_2R_3R_gR_x + R_3R_31R_gR_x + R_1R_2R_xr + R_1R_3R_xr + R_2R_3R_xr + R_1R_NR_g + R_2R_NR_g + R_3R_NR_g + R_1R_NR_x + R_2R_NR_x + R_3R_NR_x}
\]
The result of this calculation is the same as that of formula (5). U in the program is E in formula (5), i.e. the electromotive force E of power supply in Figure 2. \(R_{31}\) in program is \(R'_3\) in formula (5), as \(R'_3\) in Figure 2 represents the same physical quantity.

### 4.3 Program Block Diagram

#### 4.3.1 Simulation Operation

The overall program block diagram of the experimental operation of the simulation experimental system is shown in Figure 8:

![Figure 8: Block diagram of simulation experiment system](image)

In Figure 8, the galvanometer current formula is formula (5), the letters \(R'_3, R_N\) and \(r\) are replaced by the letters \(R_4, R_5\) and \(R_6\), respectively.

#### 4.3.2 Data Processing

In the data processing, we mainly need to simulate and calculate the average value of resistance, uncertainty and experimental sensitivity. If the measured results are input into the corresponding position, the system will calculate the corresponding results and complete expression of the experimental results. It is convenient for learners to calculate the uncertainty and sensitivity. The program block diagram is shown in Figure 9.
4.4 Some explanations

(1) In the whole simulation experiment, the resistance value of galvanometer is assigned as $R_g = 0.1\Omega$, and take the resistance $R_3 = R'_3$; When simulating Wheatstone bridge, the resistance values of $R_2$ and $r$ are zero; When simulating Kelvin bridge, the resistance value of standard resistance $a$ is 100$\Omega$, the conductor resistance and the additional resistance of contact point are taken as 0.1 $\Omega$.

(2) Turn on the power switch in the lower right corner and select the power supply voltage. For single arm bridge, you can select any gear of "3V, 6V, 9V" (double arm bridge should be placed in "double bridge" position), and circuit switch $K_B$ and bridge switch $K_G$ need to be turned on, and the galvanometer switch is set to "internal (Digital galvanometer)" or "output (pointer galvanometer)"; fuse needs to be connected, otherwise the while cycle inside the program block diagram will stop running.

(3) Switching of resistance $R_X$ to be measured. Click the left mouse button in the wiring area of the front panel of the system, and the system will automatically connect the resistance to be measured or switch the resistance to be measured.

(4) Select the appropriate multiplier, that is, determine the value of $R_1$, $R_2$, and the estimated value of $R_3$.

(5) Turn on the circuit switch $K_B$ and the bridge switch $K_G$ where the galvanometer is located.

(6) Adjust the value of $R_3$ to balance the bridge, that is, the galvanometer indication is zero (if it can not display zero, select the value closest to zero).

5. Conclusions

A set of simulation experiment system of DC bridge based on LabVIEW is developed for the resistance measurement experiment of bridge method in college physics experiment. The simulation experimental system has three modules: theoretical explanation, simulation operation and data processing, which can simulate the whole process of experimental operation. In this experimental system, the wiring mode of the real instrument is simulated, which can be switched between Kelvin bridge and Wheatstone bridge, and the corresponding connection mode can be displayed. After the experimental operation, the learners can also carry out the simulation operation of data processing, which helps the learners to know the relevant knowledge of the experiment and greatly enhances the teaching effect.
Acknowledgments
The authors gratefully acknowledge the financial support by Regional fund of National Natural Science Foundation of China (No.:51861006), The training plan of key teachers in Henan Colleges and universities in 2018 (No.:2018GGJS181) and Education reform project of Zhengzhou in 2019 (No.:ZZJG-B9029).

Reference
[1] Qian Feng, Pan Renpei. (2018) College Physics Experiment [M]. Higher Education Press, Peking.
[2] YU Hong, GUO Ziqian, etc. Data Processing Method of College Physics Experiments Based on Macros [J]. Research and Exploration in Laboratory, 2020, 39(9): 142-147.
[3] Wang Yafang, etc., WIDE APPLICATION OF SIMULATION EXPERIMENT SYSTEM DURING THE TEACHING OF EXPERIMENTAL PHYSICS [J]. Physics and Engineering, 2012, 22(002): 26-28.
[4] HAN Ying-jie, LIN Hao, DUAN Qing-ming. Control Software Design of TEM Based on LabVIEW [J]. Research and Exploration in Laboratory, 2016, v.35; No.239(01): 72-75.
[5] Gu Zhenxing. Measurement system of ice melting heat based on LabVIEW software [J]. Physics Teaching, 2016, 038(005): 32-33.
[6] YUAN Jiren, HU Ping, HUANG Weijun, etc. Construction and Practice of Informatization Teaching Platform of the National-Level Physics Experiment Teaching Demonstration Center [J]. PHYSICAL EXPERIMENT OF COLLEGE, 2020, 33(3): 122-126
[7] ZHANG Conghui. Design of Mine Humidity Sensor Based on Wheatstone Bridge Principle [J]. Colliery Mechanical & Electrical Technology, 2020(4): 34-36.
[8] WANG Kaiyu, LU Cheng, JIANG Yanhong, etc. Experiment Teaching Combined by Virtual Circuit and Digital Circuit Based on Multisim and LabVIEW [J]. Research and Exploration in Laboratory, 2019, 38(02): 146-149+165.
[9] ZHAO Li-hua, ZHANG Ya-chao, JIN Yang, etc. Implementation of Virtual Laboratory Based on LabVIEW and Matlab [J]. Research and Exploration in Laboratory, 2014, 33(4): 62-64.
[10] FENG Xing-tian, ZHANG Zhi-hua, MA Wen-zhong, etc. Virtual Simulation and Training Platform of Power Quality Analysis Based on Many Kinds of Signal Process Methods [J]. Research and Exploration in Laboratory, 2015, 34(12): 78-81.
[11] Yang Jingfa, Shen Wenzeng, Yang Ziyi, etc. Design on Newton-ring Virtual Experimental Platform Based on LabView [J]. Physics Bulletin (Official journal).
[12] FAN Fengying, LI Qinlei, LI Yan, etc. Laser absorption spectroscopy monitoring system based on LabVIEW [J]. J Tsinghua Univ (Sci & Technol), 2014(11): 29-33.
[13] LIANG Wenjing, FENG Xuan. Experimental Teaching Application of Automatic Electromagnetic Data Acquisition System Based on LabVIEW [J]. Research and Exploration in Laboratory, 2019(8).