UNIVERSITI TEKNOLOGI PETRONAS

FINAL EXAMINATION
JANUARY 2025 SEMESTER

COURSE : **EEB2053/EFB2063 - INSTRUMENTATION AND MEASUREMENT**

DATE : **14 APRIL 2025 (MONDAY)**

TIME : **2.30 PM - 5.30 PM (3 HOURS)**

INSTRUCTIONS TO CANDIDATES

1. Answer **ALL** questions in the Answer Booklet.
2. Begin **EACH** answer on a new page in the Answer Booklet.
3. Indicate clearly answers that are cancelled, if any.
4. Where applicable, show clearly steps taken in arriving at the solutions and indicate **ALL** assumptions, if any.
5. **DO NOT** open this Question Booklet until instructed.

Note :

i. There are **TEN (10)** pages in this Question Booklet including the cover page and appendices.

ii. **DOUBLE-SIDED** Question Booklet.

iii. **Graph paper will be provided.**

1. Prior to installation, a resistive pressure sensor is calibrated under room temperature at 20 °C. The pressure sensor is then installed in a chemical reactor for 12 months and the average ambient temperature in that period is recorded at 30 °C. The sensor is again tested in the chemical reactor installation. Both calibration and test results are shown in **TABLE Q1**.

TABLE Q1

Gauge Pressure, P (bar)	Calibration Results (20 °C)	Test Results (30 °C)
	Resistance, R (Ω)	Resistance, R (Ω)
100	600.0	595.0
125	609.2	603.2
150	618.4	615.0
175	627.6	626.6
200	636.8	630.0
225	646.0	635.2
250	655.2	643.5
275	664.4	650.8

a. Plot the calibration results at 20 °C on the graph paper and obtain the linear relationship between pressure and resistance for the pressure gauge.

[4 marks]

b. On the same graph in **part (a)**, plot and clearly label the test results. Determine the best fit line for the test results using least-squares regression method provided in **APPENDIX A**.

[8 marks]

c. Evaluate the results for significant drifts and coefficients in the sensor:

i. zero reading, and

ii. sensitivity

after being installed at the chemical reactor unit for 12 months.

[8 marks]

2. **FIGURE Q2** shows a Schering bridge used in an experiment to measure the changing permittivity of a multiphase flow in a pipeline placed between the plates of C_3. A multiphase flow is when vapor, liquid and solid forms are present at any given time. In two different operating modes, the bridge component values at balanced condition are:

Initial flow: $R_1 = R_4 = 2$ kΩ, $C_1 = 120$ pF and $C_2 = 200$ pF

Medium flow: $R_1 = 3.6$ kΩ, $R_4 = 5$ kΩ, $C_1 = 200$ pF and $C_2 = 1$ nF

The voltage supply frequency, f in both conditions is set at 10 kHz.

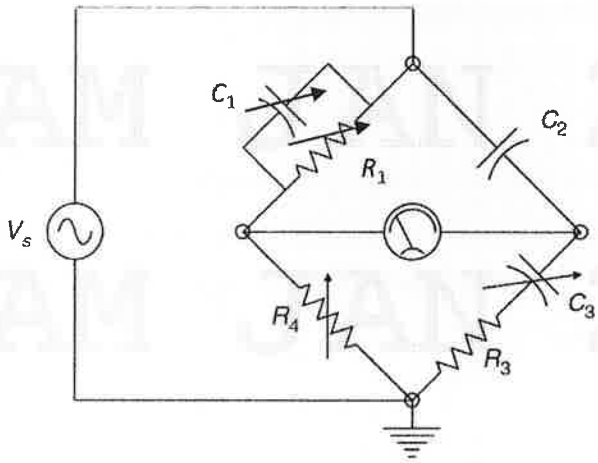


FIGURE Q2

a. Describe **TWO (2)** conditions for a balanced AC bridge.

[4 marks]

b. Derive the equations for measured impedance components, R_3 and C_3, in **FIGURE Q2** when the bridge is balanced. Show the steps clearly.

[8 marks]

c. Calculate capacitance C_3 at each initial flow and medium flow. Then determine the relative permittivity, ε_r of the medium flow given that

$$\varepsilon_r = \frac{C_{3\ at\ medium\ flow}}{C_{3\ at\ initial\ flow}}.$$

[8 marks]

3. An instrumentation solutions provider, SD Electronics is developing and testing digital voltmeters (DVMs) with reference voltage set at 5.00 V. The technical specifications require the DVM resolution to be below 20.0 mV and maximum conversion time of 0.50 ms when measuring 5.00 V. The relative error in voltage reading must not exceed ± 0.2%.

   a. The DVM uses a successive approximation A/D converter. Sketch the proposed DVM circuit and choose suitable specifications of A/D converter bit level and clock frequency. Prove that these specifications allow the DVM to achieve desired performance when measuring maximum voltage of 5.00 V.

   [6 marks]

   b. Using the specifications proposed in **part (a)**, sketch the search output diagram of the voltmeter when measuring a DC sample voltage of 3.45 V. Clearly indicate how the binary output is achieved during the search.

   [6 marks]

   c. SD Electronics is aiming to reduce random errors to within 95% of the expected voltage. The DVM is tested to measure voltage from a precision power supply set at 2.500 V. The test is monitored repeatedly within 5 minutes, which produces the set of data shown in **TABLE Q3c** (next page). Evaluate whether the random error target is achieved. If any error is not random, propose the next action to be taken. Standard normal random values, z for common confidence intervals is given in **APPENDIX C**.

   [8 marks]

TABLE Q3c

Reading	Voltage (V)
V_1	2.501
V_2	2.499
V_3	2.498
V_4	2.503
V_5	2.502
V_6	2.497
V_7	2.502
V_8	2.503
V_9	2.498
V_{10}	2.495

4. A platinum resistance temperature detector (RTD) is used to monitor the stator winding temperature of an induction motor. The maximum expected temperature during the monitoring period is 120 °C and the datasheet for HEL-700 series platinum RTD is provided in **APPENDIX D**.

   a. Discuss **TWO (2)** requirements or precautions when installing an RTD around the stator winding of the induction motor. Provide a reason for each requirement.

   [4 marks]

   b. Select a suitable RTD model from the HEL-700 series to monitor the temperature around the bearings of the induction motor. Justify your selection.

   [4 marks]

   c. The selected RTD in **part (b)** becomes the active element in a DC Wheatstone bridge. The other resistor arms are set at base resistance at 0 °C. Determine the maximum allowable supply voltage for the bridge to avoid self-heating effects and calculate the bridge output voltage when the temperature around the bearings of the induction motor reaches 97.5 °C.

   [12 marks]

5. The active element, R_u in a Wheatstone bridge is a wire strain gauge installed at the bottom of an automatic weighing scale. The system is used to measure the weight of rice packages transported over a conveyor belt. The strain gauge has a nominal resistance of 500 Ω and a gauge factor of 12. The other resistor arms are fixed at the gauge nominal resistance and the bridge excitation voltage is set at 10 V DC. For a 10 kg package of rice, the applied strain on the weighing scale is found to be 150 μ.

a. Describe **gauge factor** for a strain gauge.

[3 marks]

b. Design and sketch the Wheatstone bridge required for the system, clearly labelling the active element and other component values.

[4 marks]

c. Determine the change in gauge resistance and bridge output voltage when **FIVE (5)** packages of rice are loaded onto the weighing scale. Assume that the load is uniformly distributed across the strain gauge and the voltmeter used to measure the bridge output is ideal.

[7 marks]

d. A digital voltmeter is used to measure the bridge output voltage. Decide the minimum internal impedance of the digital voltmeter so that the bridge output voltage produced in **part (c)** is measured above 95% accuracy.

[6 marks]

- END OF PAPER –

APPENDIX A

Least-Squares Regression Method for 2 Variables

$$y = mx + c$$

where $m = \frac{S_{xy}}{S_{xx}} = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sum(x_i - \bar{x})^2}$ and $c = \bar{y} - m\bar{x}$

$$= \frac{\sum(xy) - \frac{\sum x \sum y}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}}$$

APPENDIX B

Capacitance and Phasor Equations for RLC Impedance / Admittance

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

where permittivity of air, $\varepsilon_0 = \frac{1}{36\pi \times 10^9} = 8.842\ pF/m$

Phasor Equations for RLC Impedance / Admittance

Combination	In Series	In Parallel
R-L	$Z = R + j\omega L$	$Y = \frac{1}{R} - \frac{j}{\omega L}$
R-C	$Z = R - \frac{j}{\omega C}$	$Y = \frac{1}{R} + j\omega C$

APPENDIX C

Standard Normal Values, *z* for Common Confidence Intervals

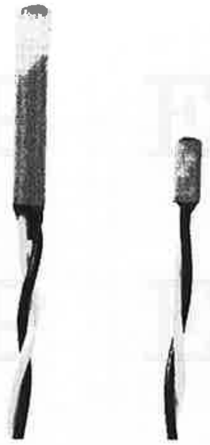
Standard Normal Value, *z*	Confidence Interval (%)
0.6745	50.0
1.0	68.3
1.645	90.0

Standard Normal Value, *z*	Confidence Interval (%)
1.96	95.0
2.0	95.4
3.0	99.7

Temperature Sensors
Platinum RTDs

EEB2053/EFB2063

HEL-700 Series



FEATURES
- Linear resistance vs temperature
- Accurate and Interchangeable
- Excellent stability
- Teflon or fiberglass lead wires
- Wide temperature range
- Ceramic case material

TYPICAL APPLICATIONS
- HVAC – room, duct and refrigerant equipment
- Instrument and probe assemblies – temperature compensation
- Process control – temperature regulation

HEL-700 Series elements are fully assembled, ready to use directly or in probe assemblies without the need for fragile splices to extension leads.

The 1000Ω, 375 alpha version, provides 10X greater sensitivity and signal-to-noise. Optional NIST calibrations improve accuracy to ±0.03°C at 0°C.

ORDER GUIDE

HEL-705	28 ga. TFE Teflon, 2-wire only
HEL-707	28 ga. Fiberglass, 2-wire only
HEL-711	28 ga. TFE Teflon (2-wire 1000Ω, 3-wire 100Ω)
HEL-712	28 ga. Fiberglass (2-wire 1000Ω, 3-wire 100Ω)
HEL-716	24 ga. TFE Teflon (2-wire 1000Ω, 3-wire 100Ω)
HEL-717	24 ga. Fiberglass (2-wire 1000Ω, 3-wire 100Ω)
-U	1000Ω, 0.00375 Ω/Ω/°C
-T	100Ω, 0.00385 Ω/Ω/°C DIN Standard
-0	±0.2% Resistance Trim (Standard)
-1	±0.1% Resistance Trim (Optional)
-12	Lead wire length, 12 inches
-00	No NIST calibration
-C1	NIST @ 0°C
-C2	NIST @ 0 & 100°C
-C3	NIST @ 0, 100 & 260°C

MOUNTING DIMENSIONS (for reference only)

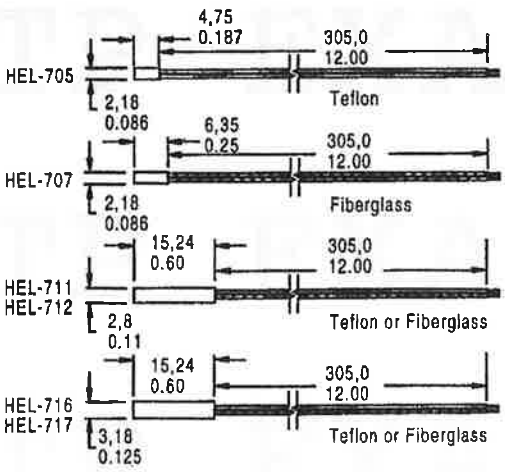


Fig. 1: Wheatstone Bridge 2-Wire Interface

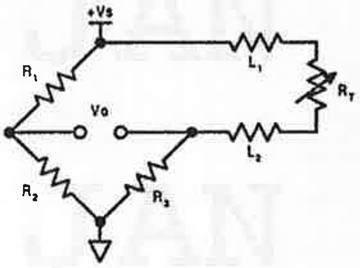


Fig. 2: Linear Output Voltage

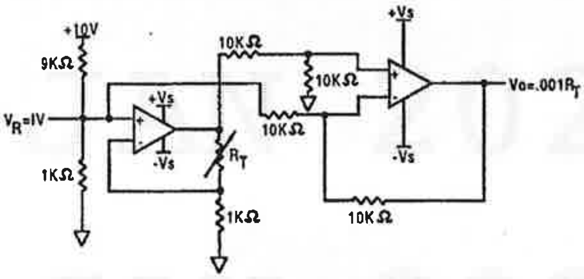
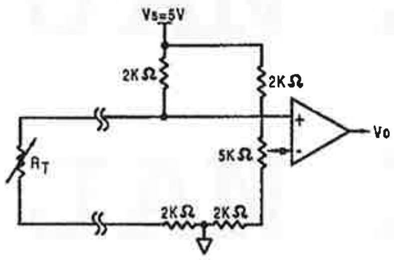


Fig. 3: Adjustable Point (Comparator) Interface



Temperature

CAUTION
PRODUCT DAMAGE
The inherent design of this component causes it to be sensitive to electrostatic discharge (ESD). To prevent ESD-induced damage and/or degradation, take normal ESD precautions when handling this product.

Temperature Sensors
Platinum RTDs

HEL-700 Series

EEB2053/EFB2063

FUNCTIONAL BEHAVIOR

$R_T = R_0(1+AT+BT^2-100CT^3+CT^4)$

RT = Resistance (Ω) at temperature T (°C)

R_0 = Resistance (Ω) at 0°C

T = Temperature in °C

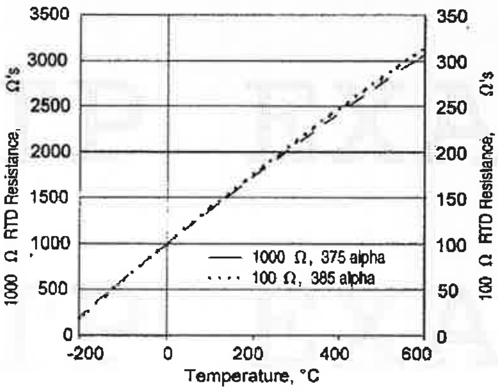
$A = \alpha + \frac{\alpha\delta}{100}$ $B = \frac{-\alpha\delta}{100^2}$ $C_{T<0} = \frac{-\alpha\beta}{100^4}$

CONSTANTS

Alpha, α (°C⁻¹) → α ($°C^{-1}$)	0.00375 ±0.000029	0.003850 ±0.000010
Delta, δ (°C)	1.605 ± 0.009	1.4999 ± 0.007
Beta, β (°C)	0.16	0.10863
A ($°C^{-1}$)	3.81×10^{-3}	3.908×10^{-3}
B ($°C^{-2}$)	-6.02×10^{-7}	-5.775×10^{-7}
C ($°C^{-4}$)	-6.0×10^{-12}	-4.183×10^{-12}

Both β = 0 and C = 0 for T>0°C

RESISTANCE VS TEMPERATURE CURVE



ACCURACY VS TEMPERATURE

Tolerance	Standard ±0.2%		Optional ±0.1%	
Temperature (°C)	±ΔR* (Ω)	±ΔT (°C)	±ΔR* (Ω)	±ΔT (°C)
−200	6.8	1.6	5.1	1.2
−100	2.9	0.8	2.4	0.6
0	2.0	0.5	1.0	0.3
100	2.9	0.8	2.2	0.6
200	5.6	1.6	4.3	1.2
300	8.2	2.4	6.2	1.8
400	11.0	3.2	8.3	2.5
500	12.5	4.0	9.6	3.0
600	15.1	4.8	10.4	3.3

*1000Ω RTD. Divide Δ by 10 for 100Ω RTD.

NIST CALIBRATION

NIST traceable calibration provides resistance readings at 1, 2 or 3 standard temperature points to yield a resistance versus temperature curve with 10x better accuracy.

Calibration	1 Point	2 Point	3 Point
T (°C)	±ΔT (°C)	±ΔT (°C)	±ΔT (°C)
-200	0.9	—	—
-100	0.5	0.27	0.15
0	0.03	0.03	0.03
100	0.4	0.11	0.07
200	0.8	0.2	0.08
300	1.2	0.33	6.2
400	1.6	0.5	8.3
500	2.0	0.8	9.6
600	2.6	1.2	10.4

SPECIFICATIONS

Sensor Type	Thin film platinum RTD; R_0 = 1000 Ω @ 0°C; alpha = 0.00375 Ω/Ω/°C R_0 = 100 Ω @ 0°C; alpha = 0.00385 Ω/Ω/°C
Temperature Range	TFE Teflon: −200° to +260°C (−320° to +500°F) Fiberglass: −75° to +540°C (−100° to +1000°F)
Temperature Accuracy	±0.5°C or 0.8% of temperature, °C (R_0 ±0.2% trim), whichever is greater ±0.3°C or 0.6% of temperature, °C (R_0 ±0.1% trim), whichever is greater (optional)
Base Resistance and Interchangeability, $R_0 \pm \Delta R_0$	1000 ± 2 Ω (±0.2%) @ 0°C 1000 ± 1 Ω (±0.1%) @ 0°C (optional)
Linearity	±0.1% of full scale for temperatures spanning −40° to +125°C ±2.0% of full scale for temperatures spanning −75° to +540°C
Time Constant	<0.5 sec. 0.85 inch O.D. in water at 3 ft/sec; <1.0 sec, 0.85 inch O.D. in still water
Operating Current	2 mA maximum for self heating errors of <1°C; 1 mA recommended
Stability	<0.25°C/year; 0.05°C per 5 years in occupied environments
Self Heating	<15 mW/°C for 0.85 O.D. typical
Insulation Resistance	>50 MΩ at 50 VDC at 25°C
Construction	Alumina case; Epoxy potting (Teflon leads); Ceramic potting (fiberglass leads)
Lead Material	Nickel coated stranded copper, Teflon or Fiberglass insulated