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The Elastic Properties of Objects by Determining Young's Modulus for the Characterization of Metal Raw Materials Using a Speed Sensor Encoder and a Load Cell Sensor

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Abstract. The unique characteristic of a metal material can be determined from the value of Young's modulus which represents the ability of the material to deform in response to an external force given to the material. This study aims to determine the value of Young's modulus for three metal wires (copper, nickel, and steel) and the percentage of measurement errors using a self-designed Young's modulus kit equipped with a load cell sensor and speed sensor encoder. The measurement of Young's modulus was carried out in five experiments without any variation in diameter (the diameter was fixed and the same for all metals), and the results were compared with the reference values. The results showed that the values of Young's modulus for copper, nickel, and steel wires were 11.74 x 10^{10} N/m^2, 21.63 x 10^{10} N/m^2, and 20.84 x 10^{10} N/m^2, respectively. The difference between the measured values and the reference values for Young's modulus for copper, nickel, and steel wires were 6.7%, 3.0%, and 4.18%, respectively. The small differences between the measured values and the reference values indicate that the measurement approach approximates the reference values and can be used to support other measurements involving Young's modulus values of a metal material.

Keywords: young’s modulus, stress, strain, sensor

1 Introduction

The domestic downstream industry continues to grow in line with the improvement of the quality of domestic metal raw materials. The development of locally-based metal industry holds promising prospects to support the domestic downstream metal industry. The basic metal industry, which serves as the mother of all industries, provides the fundamental raw materials for other industries, such as automotive, maritime, electronics, and factory equipment [1]. The quality of metal raw materials is highly dependent on the characterization of the available metal materials. Macroscopic structural quality assessment of metal materials is used to predict material behavior at the macroscopic level. The purpose of this assessment is to estimate the desired macroscopic properties of the material [2].

The atomic structure that constitutes materials is closely related to the macroscopic scale mechanical properties. Physical phenomena can also be developed at the nanoscale by comparing it with the macroscopic scale dimensions [3]. Metal materials are widely used in daily life and as constituents of steel. The metals that are commonly used as constituents of steel include aluminum, nickel, and copper [4]. Each metal material has several specific characteristic properties such as hardness, strength, stiffness, and elasticity. The property of elasticity is the tendency of the material to return to its original shape before experiencing permanent deformation when a force is applied to the material [5]. The property of elasticity of a material indicates the material's ability to undergo elastic deformation due to an external force or stress, which is referred to as the Young's modulus. The Young's modulus shows the material's characteristic response to external force-induced deformation. The value of the Young's modulus on a stress-strain curve can be determined by the slope of the curve in the elastic deformation region [6].

The value of Young's modulus of a material is an important characteristic to determine the strength of the metal material when external force is applied to it. A material with a relatively high Young's modulus value is difficult to deform since it requires a very large amount of stress [7]. A material undergoes plastic deformation by exhibiting behavior that will not return to its original state or will remain in its final state when the force is removed. This condition occurs if the load given to the material exceeds the elastic limit of the material. Solid materials may even experience permanent damage if the deformation force given is large enough. Young's modulus is determined macroscopically by the ratio of stress (σ) to strain (ε), which is called Hooke's Law [8]. The Young's modulus is also related to Hooke's Law which states a linear relationship between stress and strain for all materials. The Young's modulus (E in Pa) values for some metals are shown in Table 1 [6].

Table 1. Young's Modulus Values of Several Pure Metals

Material	Young's Modulus E (Pa)
Aluminium	7.0×10^{10}
Brass	9.0×10^{10}
Copper	11.0×10^{10}
Lead	1.6×10^{10}
Nickel	21.0×10^{10}
Steel	20.0×10^{10}
Gold	7.9×10^{10}
Silver	8.25×10^{10}

(Source: Sulaeman, 2018)

The load applied to the metal material determines the level of stiffness of a material and is indicated by the value of the Young's modulus. The higher the value of the Young's modulus, the greater the stiffness of the material. The load applied to the metal material will indicate the level of stiffness of the material, which is indicated by the Young's modulus value. Continuously applying load to the metal material will cause the stress-strain relationship graph to become non-linear in the plastic region [9]. The plastic region of a metal material cannot return to its original shape when the applied load is removed. A material will pass its yield point, which is the point where the material undergoes deformation without an increase in load. Stress will continue to increase after passing the yield point until it reaches the maximum stress at the material's tolerance limit called ultimate tensile strength. Subsequently, the material will enter the fracture region as a result of the material's decreasing ability to withstand the load [10]. The yield point, as the yield strength and ultimate tensile strength, can be measured to provide additional information about the mechanical properties of metals. The higher the value of the modulus of elasticity, the lower these properties will be as there is a higher probability of plastic or permanent deformation occurring [11].

The determination of the Young's modulus using conventional caliper measurements is carried out by hanging a wire with a load and measuring the increase in its length [12]. The measurement of the increase in length allows for the possibility of subjective measurement errors by the observer. Therefore, more accurate measurement technology using sensor technology is needed [13].

Dita et al. have determined the Young's modulus on the Young's Modulus Determination Kit using a rotary encoder sensor to measure the length changes and a load cell sensor to measure the force [14]. The study was conducted by varying the diameters of nickelin and copper wires. The measurement results with several diameter variations produced Young's modulus values from the researcher-designed Young's modulus kit and PASCO's kit. This study only used two metal samples, nickelin and copper, and has not yet compared the Young's modulus values with other references.

In this study, the researchers developed a laboratory kit to determine the Young's modulus value using an Arduino ATmega328p with a speed encoder sensor and a potentiometer to adjust the speed of the encoder sensor, as well as a load cell sensor to measure the wire tension force. The wire samples used in this study were copper, nickelin, and steel. The measured Young's modulus values will be compared to the reference Young's modulus values [6], [15].

2 Research Method

The Young's modulus determination kit utilizes Arduino ATmega328p with speed encoder sensor and load cell sensor to determine the Young's modulus value. The wire's stress and strain values are obtained from the following equations [16].

$$E = \frac{\sigma}{\varepsilon} \tag{1}$$

$$\sigma = \frac{F}{A} \tag{2}$$

$$\varepsilon = \frac{l - l_0}{l_0} = \frac{\Delta l}{l_0} \tag{3}$$

Explanation:

F	tensile force on the metal (N)
A	surface area of the metal (m^2)
l_0	length of the metal before applying the load (m)
l	length of the metal after applying the load (m)
Δl	nge in length of the metal before and after being subjected to a load (m)

The arrangement of the modulus of elasticity kit for measuring the stress and strain of copper, nickel, and steel wires with a diameter of 3.33 mm is shown in Figure 1.

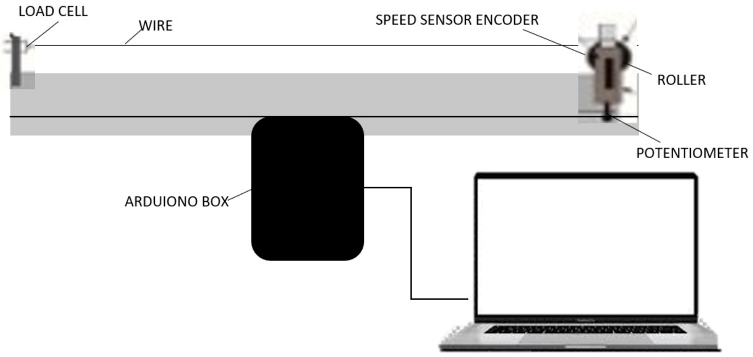

Figure 1. Young's modulus kit arrangement design

The operating principle of the Young's modulus kit is that the spool will wind the wire until it undergoes elongation. The force generated by the spool rotation on the wire end will be detected by the load cell sensor. The other end connected by the speed sensor encoder, the winding speed is adjusted by a potentiometer with a certain voltage. The force obtained from the load cell sensor reading is divided by the wire's cross-sectional area to obtain the wire's stress value. The strain value is obtained by dividing the wire's elongation by the wire's initial length before deformation is applied. The final Young's modulus value is obtained by dividing the wire's stress by its strain. Furthermore, the error percentage and its correction are calculated to support the accuracy in measuring the Young's modulus using the Young's modulus kit. The categories for the error percentage can be seen in Table 2 [17].

Table 2. Categories of measurement error percentage

Measurement Error Percentage	Category
>1%	Very good
1% - 2%	Good
2% - 5%	Adequate
5% - 10%	Poor
>10%	Very poor

Here is the flowchart of the modulus of elasticity kit with Arduino ATmega328p.

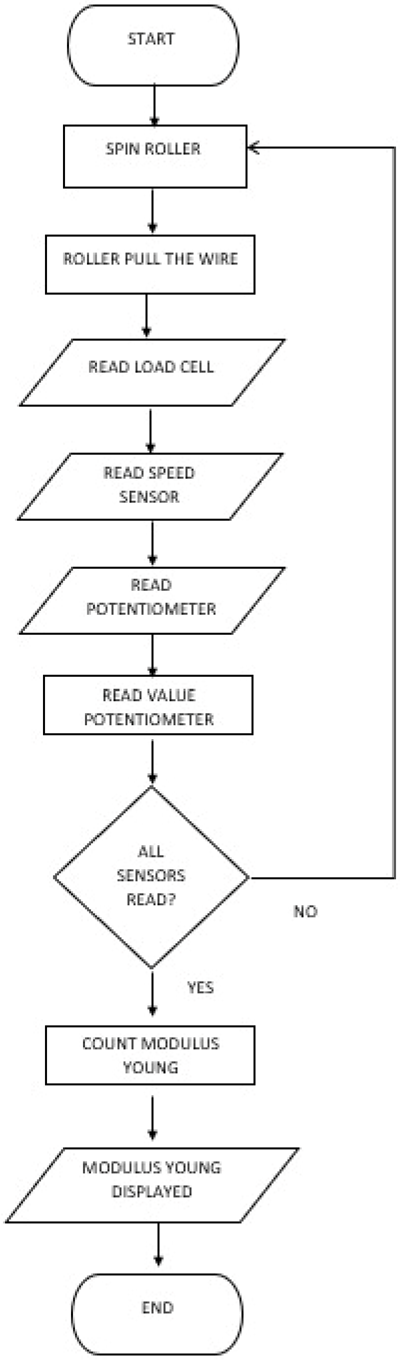

Figure 2. Flow chart for measuring Young's modulus values

3 Results and Discussion

The Young's modulus kit uses an Arduino ATmega328p equipped with a speed sensor encoder and a load cell sensor to determine the strain and stress values of copper, nickel, and steel metal materials. The metal wire is stretched horizontally with each end tied and connected to the load cell and speed sensor encoder. The load cell sensor is equipped with an HX-711 module as a wire voltage meter when the metal wire moves to be rolled up. One end is connected to the speed sensor encoder to measure the wire voltage value and is equipped with a potentiometer to determine the wire end position to know the increase in wire length due to the rolling process and also to adjust the rolling speed. The Young's modulus kit schematic is shown in Figure 3.

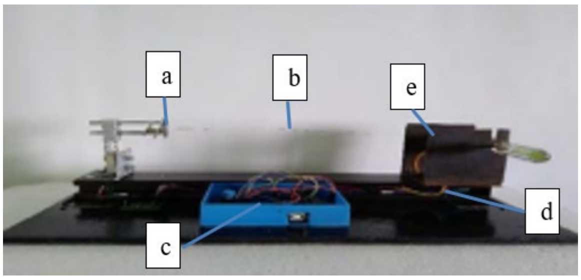

Figure 3. Young's modulus kit arrangement

Explanation:

a. *Load cell* Sensor
b. Metal Wire Sample
c. Arduino ATmega328p box
d. Potentiometer
e. *Speed sensor encoder*

3.1 The Percentage of Error and Measurement Error of Young's Modulus

The measurement of Young's modulus using a set of Young's modulus kit is greatly influenced by the readings obtained from the load cell sensor and the speed sensor encoder. The percentage of error in the measurement of Young's modulus using a Young's modulus kit indicates how much difference exists between the measured values obtained from the kit and the reference or theoretical value, where the reference value refers to the value of Young's modulus provided by Kane and Sterhim (1991). The percentage of error is calculated by dividing the difference between the measured value of Young's modulus and the reference value by the reference value, and then multiplying it by 100%. The measurement error in Young's modulus is simply the difference between the measured value obtained from the Young's modulus kit and the reference value [18].

Systematic error occurs when there is an error in the measuring instrument that causes the measurement results to consistently tend to be too large or too small in every measurement. This systematic error can be caused by differences between the measurement standards used in the measurement and the actual measurement standards, or by errors in the calibration or adjustment of the speed sensor encoder used to measure the rotational speed of a metal wire consisting of an encoder disc and sensor detector. The encoder disc contains a series of holes or gaps arranged regularly around the circle. When the metal wire is rotated through the encoder disc, the holes or gaps on the encoder disc allow light to pass through the sensor detector. This sensor detector measures the amount of light received when the holes or gaps in the encoder disc pass through the sensor. The signal generated by the sensor detector is then sent to a signal processing unit, which calculates the number of holes or gaps that pass through the sensor in a certain period of time. Meanwhile, the load cell sensor is used to measure the force applied to an object and works based on the principle of resistance change of the measuring wire. The change in the resistance of the measuring wire occurs due to the change in the length of the measuring wire caused by the stretching of the metal wire.

The percentage of error and error in the measurement of the Young's modulus value for three metals (copper, nickel, and steel) are shown in Table 3.

Table 3. Summary of percentage errors and measurement errors of Young's modulus

No	Type of Metal	Young's Modulus (E) (x 10^{10} N/m^2)	% Error	Error
1	Copper	11.65	5.91	0.65
2		11.83	7.55	0.83
3		11.78	7.09	0.78
4		11.74	6.73	0.74
5		11.70	6.36	0.70
	Average	11.74	6.73	0.74
6	Nickel	21.53	2.52	0.53
7		21.55	2.62	0.55
8		21.67	3.19	0.67

No	Type of Metal	Young's Modulus (E) (x 10^{10} N/m^2)	% Error	Error
9		21.62	2.95	0.62
10		21.77	3.67	0.77
	Average	21.63	2.99	0.63
11	Steel	20.69	3.45	0.69
12		20.86	4.30	0.86
13		20.83	4.15	0.83
14		20.96	4.80	0.96
15		20.84	4.20	0.84
	Average	20.84	4.18	0.84

From Table 3, it can be seen that the percentage error for copper is higher compared to nickel or steel. This is because the value of Young's modulus depends on the crystallographic properties, microstructure, and bonding between atoms in the material. Copper, steel, and nickel are materials with a single crystal or monocrystalline structure with a regular arrangement of atoms. However, despite having a single crystal structure, their physical properties are different due to differences in atomic bonding and crystal arrangement. Copper has relatively weak atomic bonding compared to steel or nickel, making it easier to stretch and deform under smaller forces. Therefore, the Young's modulus value of copper is smaller compared to steel or nickel. On the other hand, steel and nickel have stronger atomic bonding and a denser crystal arrangement than copper, making them more difficult to stretch and have a higher Young's modulus value.

3.2 Material Testing to Determine the Value of Young's Modulus

The determination of the young's modulus value for metal wires (copper, nickel, and steel with the same diameter or without diameter variation) was measured by comparing the young's modulus value from the reference according to Kane and Steirheim (1991). The obtained data are in the form of stress and strain values to calculate the young's modulus value. The reference young's modulus value used for copper is 11.00 x 1010 N/m^2, nickel is 20.00 x 1010 N/m^2, and steel is 21.00 x 1010 N/m^2.

3.2.1 Copper Wire Testing

The graph of the copper wire testing using the Young's modulus kit can be seen in Figure 4.

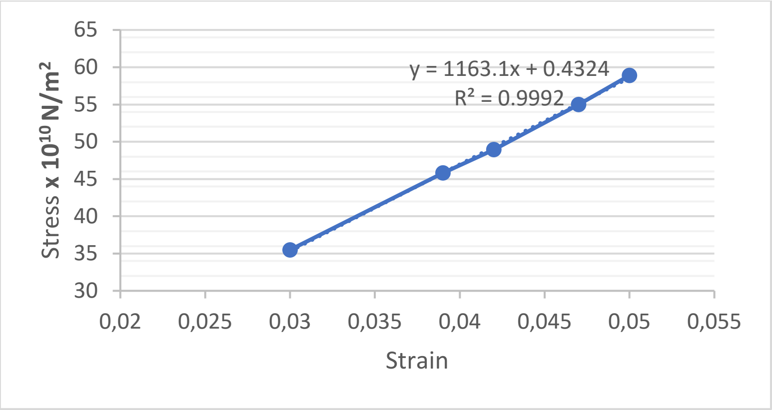

Figure 4. Young's modulus of copper wire

The average value of the Young's modulus for the copper wire obtained from the measurement results is 11.74 x 1010 N/m2, with the reference Young's modulus value of 11.00 x 1010 N/m2. The measurement using the Young's modulus kit has a percentage difference of 6.7% with the reference Young's modulus value, with the measurement error percentage of 6.73%.

3.2.2 Nickel Wire Testing

The graph of the nickel wire testing using the Young's modulus kit can be seen in Figure 5.

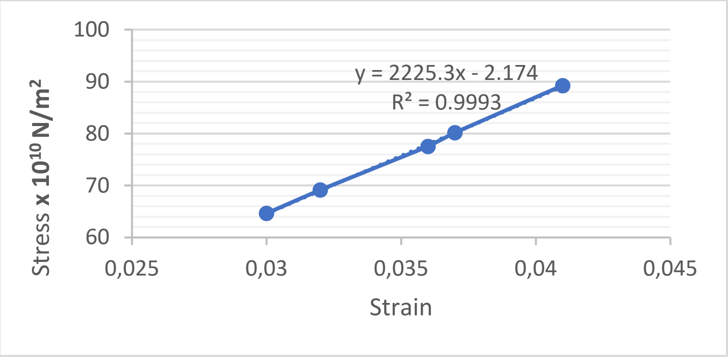

Figure 4. Young's modulus of nickel wire

The average value of the Young's modulus for the nickel wire obtained from the measurement result is 21.63 x 1010 N/m2 and the reference Young's modulus value is 21.00 x 1010 N/m2. The measurement result using the Young's modulus kit has a percentage difference of 3.0% compared to the reference Young's modulus value with a measurement error percentage of 2.99%.

3.2.3 Steel Wire Testing

The graph of the steel wire testing using the Young's modulus kit can be seen in Figure 6.

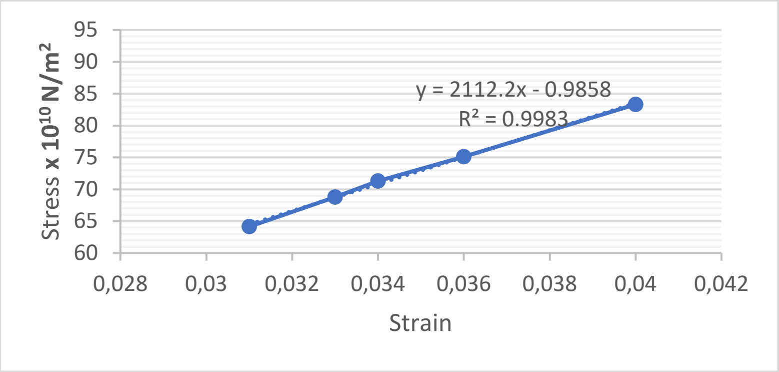

Figure 4. Young's modulus of steel wire

The average value of the modulus of elasticity for the steel wire obtained from the measurement is 20.836 x 1010 N/m^2 and the reference modulus of elasticity value is 20.00 x 1010 N/m^2. The measurement results using the modulus of elasticity kit have a percentage difference of 4.16% with the reference modulus of elasticity value and the measurement error percentage is 4.18%.

Copper, steel, and nickel are materials with a single crystal structure or monocrystalline with a regular arrangement of atoms. However, despite having a single crystal structure, their physical properties differ due to differences in atomic bonding and crystal arrangement. Copper has relatively weak atomic bonding compared to steel or nickel, making it easier to stretch and deform with smaller forces. Therefore, the Young's modulus value of copper is smaller than that of steel or nickel.

On the other hand, steel and nickel have stronger atomic bonding and a more tightly packed crystal arrangement than copper, making them harder to stretch and have a higher Young's modulus value. The relationship between stress and strain described by Hooke's law applies to linear strain in elastic materials. Linear strain occurs when a change in dimension of a body (such as length or diameter) is proportional to the applied stress on the body. In Hooke's law, stress and strain are considered proportional in the case of linear strain. This means that for an elastic material, when stress is applied, the resulting linear strain will have a constant ratio with that stress. This constant is the elasticity modulus (Young's modulus) and represents the stiffness of the material.

However, it is important to note that when the applied stress on a body exceeds its elastic limit, the body no longer follows Hooke's law and may undergo plastic deformation or even break. Therefore, the relationship between stress and strain only applies to linear strain in elastic materials within their elastic limit.

The results of stress and strain measurements to calculate the value of the metal wire modulus are shown in the graph below. The three graphs show straight line equations with high coefficient of determination values. The R^2 value in the equation is the coefficient of determination, indicating how well the data fits the straight line shown by the equation. A high R^2 value indicates that the straight line is very close to the data, so the equation can be used to predict the value of y for unknown x values with high precision.

The measurement of the modulus of elasticity was carried out at room temperature of 25°C, so the effect of temperature was not too significant. However, temperature can also have a significant impact on the measurement of the modulus of elasticity of metallic materials. This effect can cause changes in the crystal structure and chemical composition of the metallic material, which can ultimately affect the mechanical properties of the material. The higher the temperature, the lower the value of the modulus of elasticity will be as the atoms of the metallic material become more elastic and easier to move. In this study, there was no temperature treatment during the measurement of the modulus of elasticity because it required a more specialized instrument setting to maintain room and metal temperature stability. Thus, a stable room temperature was applied to maintain the stability of the measured data by the sensor [19], [20]. This study can also be developed to measure the properties of materials at the nanoscale, as the mechanical properties of metallic materials can significantly differ at the nanoscale. Nanoscale measurements require more precise and specialized techniques due to their sensitive and high precision nature. This can be done as a continuation of this study to complete the properties and characteristics of metallic materials for wider applications [21].

4 Conclusion

A study measuring the Young's modulus values of three metal wires (copper, nickel, and steel) using a Young's modulus kit resulted in the following Young's modulus values respectively: 11.74 x 1010 N/m2, 21.63 x 1010 N/m2, and 20.84 x 1010 N/m2. The Young's modulus values were measured five times by varying both stress and strain for each metal wire. The results obtained from the Young's modulus kit measurements were compared with reference values, and they showed small differences. The differences in Young's modulus values compared to reference values were 6.7% for copper wire, 3.0% for nickel wire, and 4.18% for steel wire. The measurement method using load cell and speed sensor encoder technology produced Young's modulus values that were close to the reference values. Therefore, this measurement can be used as an alternative to technology-based measurements.

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