Volume 9 Number 2, August 2024, pp. 190~197
P-ISSN:2477-7935
E-ISSN: 2548-6225
DOI: 10.59052/edufisika.v9i2.36578

THE EFFECT OF FREQUENCY ON THE ELASTIC PROPERTIES OF MATERIALS

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Article Info
Recieved: 7 Aug 2024
Accepted: 26 Aug 2024
Publication: 26 Aug 2024

Abstract :
The elastic properties measurement of materials is important to determine their potential application in industries. Hence, the effect of frequency on the elastic properties is crucial in estimating the material's behavior with the change of frequency. Thus, this study was conducted to determine the effect of frequency on the elastic properties of materials. Five parameters of elastic materials were found in this study: bulk modulus, shear modulus, longitudinal modulus, Young's modulus, and lame constant. The elastic properties of three samples; stainless steel, aluminium and PMMA were measured for 2.25 MHz, 5 MHz and 10 MHz frequency. The method used is non-destructive testing using pulse-echo ultrasound techniques. The findings indicated that the longitudinal modulus, Young's modulus, shear modulus, bulk modulus, and lame constant of all samples are constant as the frequency increased from 2.25 MHz to 10 MHz. In conclusion, the elastic properties of a material are independent to the change of frequency.

Keywords: Elastic Properties, Frequency, Ultrasonic Pulse-Echo Technique

INTRODUCTION

The elastic properties of a material refer to its ability to regain their original shape and size after deforming force is removed. Hence, the elastic properties measurement is important to predict the engineering behavior of materials (Boccaccio et al., 2021; Braz et al., 2021; Pabst & Gregorová, 2014). The elastic properties of materials can be determined using destructive testing (Lopez et al., 2018; Messineo et al., 2016; Nsengiyumva et al., 2021; Puchi-Cabrera et al., 2015; Wells & Liang, 2011) and non-destructive testing (Boccaccio et al., 2021). The destructive testing such as tensile tests (Bergonzi et al., 2019; Corradini et al., 2017; Dorčiak et al., 2019; Phillips et al., 2022) , compression tests (Trzepieciński et al., 2021; Wang et al., 2018; Zou et al., 2020) ,hardness tests (Mishra & Sharma, 2016; Souri, 2017; Wang et al., 2018; Zhang & Malzbender, 2015) and impact tests (EL-Wazery et al., 2017) offers the accurate results but resulting in damage to the material being tested (Hossack et al., 2022). Hence, previous researchers utilised the non-destructive testing especially ultrasonic testing (Bilici & Kaya, 2022; Erol et al., 2022; Judawisastra et al., 2019b; Souri, 2017) as an alternative to measure the elastic properties of materials.

Ultrasonic testing is the nondestructive testing that uses sound waves with frequencies beyond the human hearing limit (Carovac et al., 2011). Previous researchers measured the elastic properties of materials using two common techniques of ultrasonic testing; through transmission technique (TT) (Franco et al., 2011; Messineo et al., 2016; Sanabria et al., 2019; Tomar & Khurana, 2011; Umiatin et al., 2021; Zou et al., 2020) and pulse-echo technique (PET) (Bucciarelli et al., 2019; Dobrzanski et al., 2021; Ivanchev, 2022; Jakovljevic et al., 2018; Jordan et al., 2021; Judawisastra et al., 2019a; Wu et al., 2019; Zheng et al., 2021). In 2022, Oral and Ekrem investigated the elastic properties of epoxy resin/polyvinyl alcohol nanocomposites using the PET. However, they only calculated the Young's modulus, Poisson ratio and shear modulus from the measurement of longitudinal and shear velocities. In addition, they did not studied the effect of frequency on the elastic properties of epoxy resin/polyvinyl alcohol nanocomposites.

The need for more information on how frequency affects a material's elastic characteristics is the study's research gap. The majority of earlier research has been on computing the values of elastic characteristics of materials, which are found through longitudinal and shear velocities, such as Young's modulus, Poison ratio, and shear modulus. Investigating the relationship between the elastic characteristics of the material and the modification of the transducer frequency is, therefore, crucial. When comprehending and creating a material, the elastic characteristics of the material are crucial factors to consider (Braz et al., 2021).

The novelty of this study lies in the approach taken to explore the effect of ultrasonic transducer frequency on the elastic properties of materials, which has not been widely explored in previous studies. Although ultrasonic testing techniques, especially through the pulse-echo technique, have been used to measure the elastic properties of materials, this study broadens the understanding by analyzing the variation of five elastic properties of longitudinal modulus (L), Young's modulus (E), shear modulus (G), bulk modulus (K), and Lame's constant (λ) at three different frequencies (2.5 MHz, 5 MHz, and 10 MHz). Previously, most studies have only focused on measuring Young's modulus, Poisson's ratio, and shear modulus without considering the impact of frequency changes on these elastic properties. This study introduces a new dimension in understanding the stability of elastic properties of materials with frequency variations, which is an important contribution to the fields of materials science and non-destructive engineering (Oral & Ekrem, 2022).

Therefore, this study was performed to investigate the effect of frequency on the elastic properties of materials using the PET. The variations of five elastic properties (Workman & Kishoni, 2007); longitudinal modulus, L, Young's modulus, E, shear modulus, G, bulk modulus, K, and lame constant, λ, of stainless steel, aluminium and PMMA (polymethyl methacrylate) with frequency were determined from the single measurement of the longitudinal velocity. The elastic properties of samples were determined at three different frequencies; 2.5 MHz, 5 MHz and 10 MHz.

RESEARCH METHOD

Sample

This study involves three samples; stainless steel, aluminium and PMMA. The dimensions for each sample are $(10.00 \times 5.00 \times d)$ cm^3 where d is the thickness of the sample. Table 1 summarizes the thickness, density and Poisson ratio for each sample.

Table 1. The thickness, density and Poisson ratio for stainless steel, aluminium and PMMA.

Material	Thickness, d (cm)	Density, ρ (kg m^{-3})	Poisson ratio, υ
Stainless steel	2.5	7750	0.30*
Aluminium	2.0	2710	0.33**
PMMA	1.5	1180	0.34***

*(Fischer-Cripps, 2004)
**(Fischer-Cripps, 2004)
***(Afifi, 2003)

Experimental Setup

Figure 1 shows the experimental setup for the elastic properties measurement of materials using the PET. An electric pulse was generated by a pulser/receiver generator (Olympus Panametric NDT model 5072PR) and converted to in to the mechanical energy to create an ultrasonic pulse by a transducer (Olympus Panametric NDT) (Greenwood et al., 2015; Khatib et al., 2019; Thi & Hoa, 2017). The ultrasonic pulse was transmitted in the sample and reflected into its original path at the back interface of the sample (Chen et al., 2023; Qodir & Putra, 2016). The reflected pulse was detected and converted into the electrical signal by the transducer (Fathoni et al., 2013; Oglat et al., 2018). The pulser/receiver generator amplified and conditioned the signal and the digital oscilloscope (LeCroy Wave Surfer 42 MXs-B 400MHz 5GS/s) displayed the signal. Three transducers with different center of frequencies were employed for this study; 2.5 MHz, 5 MHz and 10 MHz.

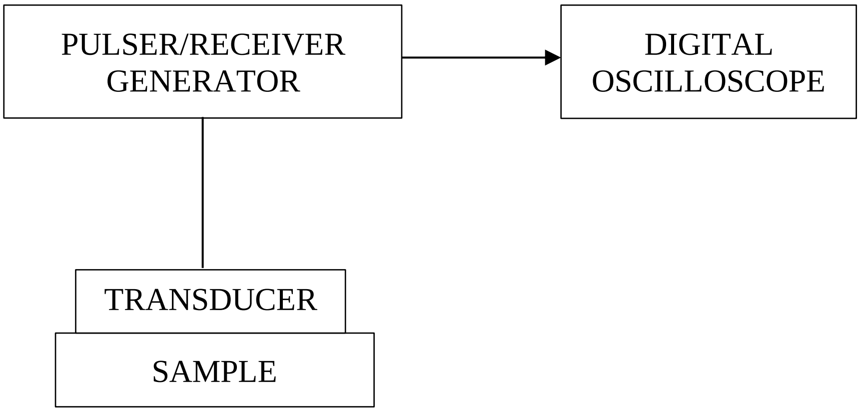

Figure 1. Experimental setup for elastic properties measurement of materials

Elastic Properties

This study involves the measurement of five elastic properties of a material (Sigrist et al., 2017); L, E, G, K, and λ. The values of L, E, G, K, and λ of a material are calculated from its density, ρ, longitudinal velocity, v_l, and Poisson ratio, υ using equation 1 (Halimah & Eevon, 2019), equation 2 (Halimah & Eevon, 2019; Judawisastra et al., 2019a), equation 3 (Halimah & Eevon, 2019; Jordan et al., 2021), equation 4 (Fu et al., 2021; Halimah & Eevon, 2019) and equation 5 (Jie et al., 2021; Rose, 2014; Tsuji et al., 2019)

$$L = \rho v_l^2 \quad (1)$$

$$E = \frac{L\,(1+\nu)(1-2\nu)}{1-\nu} \quad (2)$$

$$G = \frac{E}{2(1+\nu)} \quad (3)$$

$$K = \frac{E}{3(1-2\nu)} \quad (4)$$

$$\lambda = L - 2G \quad (5)$$

Where its longitudinal velocity, v_l, is calculated from the time of the first reflected pulse at the back interface, t_1, the time of the second reflected pulse at the back interface, t_2, and its thickness, d, using equation 6 (Phani, 2008; Rajzer et al., 2016) .

$$\boldsymbol{v_{L1}} = \frac{\boldsymbol{2d}}{\boldsymbol{t_2 - t_1}} \quad (6)$$

RESULTS AND DISCUSSION

Table 2 shows the elastic properties of stainless steel, aluminium and PMMA at 2.25 MHz, 5.00 MHz and 10 MHz. According to Table 2, the values of L, E, G, K, and λ of stainless steel were consistent within the range of 262.69 GPa to 270.87 GPa, 195.14 GPa to 201.22 GPa, 75.05 GPa to 77.39 GPa, 162.61 GPa to 167.68 GPa and 112.58 GPa to 116.08 GPa, respectively even the frequency was increased from 2.25MHz to 10 MHz. The values of L, E, G, K, and λ of aluminium and PMMA also show the similar trend with the change of frequency. It indicated that the elastic properties of materials are independent to the change of frequency.

Table 2 also shows that the stainless steel has the highest values of L, E, G, K, and λ, followed by aluminium and PMMA. It implies that the elastic properties of materials depends on its density. Molecules in denser materials are closer together than molecules in less dense materials (Duck, 1990). The shorter separation distance between molecules in the material causes a higher resistance for materials to deform. Hence, the denser material has higher elastic properties compared to the less dense material.

Table 2. The elastic properties of stainless steel, aluminium and PMMA at 2.25 MHz, 5.00 MHz and 10 MHz.

Material	Elastic Properties	Frequency, *f* (MHz)		
		2.25	5	10
Stainless steel	L (GPa)	267.67	270.87	262.69
	E (GPa)	198.84	201.22	195.14
	G (GPa)	76.47	77.39	75.05
	K (GPa)	165.70	167.68	162.61
	λ (GPa)	114.71	116.08	112.58
Aluminium	L (GPa)	115.59	107.15	104.94
	E (GPa)	78.01	72.31	70.83
	G (GPa)	29.32	27.18	26.62
	K (GPa)	76.48	70.90	69.44
	λ (GPa)	56.93	52.77	51.69
PMMA	L (GPa)	8.91	9.04	8.69
	E (GPa)	5.79	5.87	5.64
	G (GPa)	2.16	2.19	2.10
	K (GPa)	6.03	6.11	5.88
	λ (GPa)	4.59	4.65	4.47

The novelty of this study is to determine the effect of transducer frequency variations on the elastic properties of materials using non-destructive techniques with the pulse-echo ultrasound method. This study also provides empirical evidence that the elastic properties of a material will be different from other materials. This study contributes to the literature on physical materials, which can facilitate understanding the price of a material so that it will be easier to design the material. The limitations of this study are that only five elastic properties have been determined, and elastic properties such as tensile modulus and flexural modulus have yet to be determined. This study also does not use the position ratio value obtained through experiments. Future research can expand the scope of the study to include more variations in material properties against various variations in the transducer frequency used, variations in sample thickness and variations in the ultrasound technique used. In acoustic properties, the frequency transducer affects the attenuation coefficient value. The attenuation coefficient increases with increasing frequency used.

Previous research conducted by Adhikari et al. (2021) has successfully developed a comprehensive analytical framework to determine the dynamic elastic modulus of lattice materials under steady-state vibration conditions. However, the main gap that emerged between previous research and the current research is the focus on the elastic properties of the material in the context of vibration frequency. The current research focuses on the effect of ultrasonic transducer frequency on the elastic properties of materials such as stainless steel, aluminum, and PMMA using non-destructive techniques.

Unlike previous research that studied the behavior of materials under dynamic vibration conditions and involved microstructures at the lattice scale, the current research explores how changes in transducer frequency do not affect the elastic properties of materials macroscopically in a certain frequency range (2.25 MHz to 10 MHz).

This study has significant implications in the field of materials science and industrial applications involving the evaluation of elastic properties of materials. The finding that elastic properties such as Young's modulus (E), shear modulus (G), bulk modulus (K), and Lame's modulus (λ) are not affected by the variation of the transducer frequency in the range of 2.25 MHz to 10 MHz provides confidence in the stability of the elastic properties of the material across a wide range of operating conditions. This allows engineers to select and design materials without worrying about changes in elastic properties due to frequency variations, thereby increasing efficiency and reducing production costs. In addition, the validation of the use of the pulse-echo ultrasound technique as a non-destructive method for measuring elastic properties of materials strengthens the application of this technique in industrial material inspection. This study also opens up opportunities for the development of further studies that expand the testing to other material property variations and more comprehensive evaluation techniques.

CONCLUSION

The effect of frequency on the elastic properties of materials were successfully determined in this study. The findings shows that the L, E, G, K, and λ of materials are independent to the change of frequency. In contrast, the L, E, G, K, and λ of materials are increased with their density. Therefore, a further study is required to determine other factors which could affect the elastic properties of materials. Based on the findings of this study, it is recommended that further research explore other factors that may influence the elastic properties of materials other than density and frequency.

ACKNOWLEDGMENTS

The authors would like to thanks Universitas Islam Negeri Mahmud Yunus Batusangkar in Indonesia, for the financial support under scholarship SP DIPA-025-04.2.424069/2023. The authors also would like to acknowledge the facility support provided by the Applied Optic Laboratory, Department of Physics, Faculty of Science and Mathematics, Universiti Pendidikan Sultan Idris, Malaysia.

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