Measuring Young's modulus of polymer sheets by ultrasonic Lamb waves

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Abstract. Young's modulus of PET sheets is usually measured in destructive tests, which involve specific sample preparation and time-consuming testing procedures. In this study, a Young's modulus measurement approach based on guided Lamb waves is proposed, which allows for non-destructive and efficient measurement of Young's modulus of PET sheets. In this approach, the group velocity of zero-order symmetric Lamb waves propagating in PET sheets is measured experimentally. The semi-analytical finite element method [1] (SAFEM) is used for the calculation of the theoretical group velocity based on the geometry and material properties of the sheets. Experimental and theoretical group velocities are then used to infer Young's modulus using particle swarm optimisation where their difference is minimised as the properties are varied.

Introduction

The extensive use of PET plastic bottles in everyday life has caused serious environmental pollution and resource consumption. The use of bio-based materials as an alternative has become an inevitable trend. In this research area, biaxial stretching tests on PET sheets are often used as a more controllable way to study the influence of different material compositions and process conditions on product properties. Accurate and rapid measurement of the mechanical properties of stretched PET sheets is therefore very beneficial for the evaluation of these factors. However, there are currently very limited methods available for measuring the mechanical properties of PET. The most widely used among these methods is still the conventional tensile test [2] although another method that has been emerging in recent years is based on full-field strain measurements using the DIC technique [3]. However, both of these measurement methods involve an extra sample preparation step, which significantly limits the efficiency of the measurement. Therefore, the main objective of this work is to develop an efficient method for measuring Young's modulus for PET sheets based on guided Lamb waves.

Experimental procedure

The adopted experimental setup is shown in Fig. 1. In this setup, the USB-UT350T (US Ultratek, Inc.) ultrasonic tone burst pulser/receiver is used to generate and collect voltage signals. Three PZT discs (STEINER & MARTINS, Inc.) are used in each test. Among them, one is used for ultrasonic signal excitation and the other two are used to receive signals at different positions in the wave propagation path. The switch between the two receiving PZT discs is implemented by a multiplexer (hasseb Inc.). A LabVIEW program is designed for device control and signal processing purposes.

Tests with this experimental setup were carried out on PET sheets stretched under different process conditions, as shown in Fig. 1. In the tests, PZT discs were first attached to the sheet's surface and then the distance between two receiving PZT discs was measured for later velocity calculation. After that, S0 mode Lamb waves with frequencies of 300 kHz or 450 kHz (the resonant frequencies of the PZT discs) were generated on the sheets. Fig. 2 shows two typical signals received from two different positions along the wave propagation path on a PET sheet. Time of flight (TOF) between the two receiving PZT discs was then extracted from the received signals using a cross-correlation method [4]. With the known distance and TOF, the group velocity of the propagating waves can then be calculated. Three tests were carried out at different positions on each sample, as demonstrated in Fig. 1, and the average of the group velocities from three repeats was calculated as the final group velocity value for Young's modulus estimation.

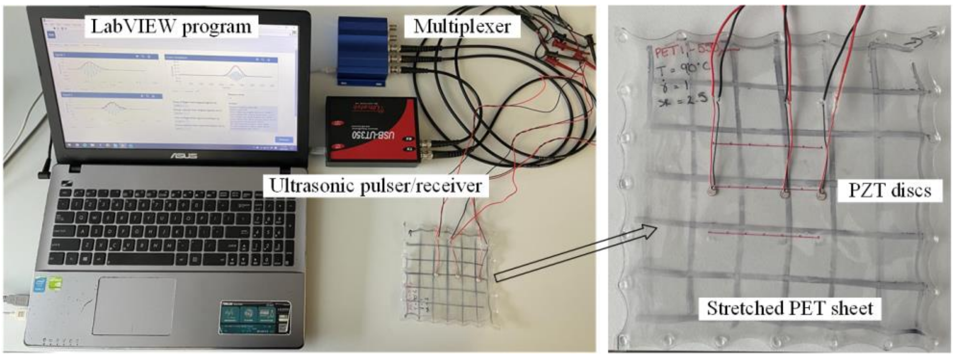

Fig. 1 Experimental setup for group velocity measurement

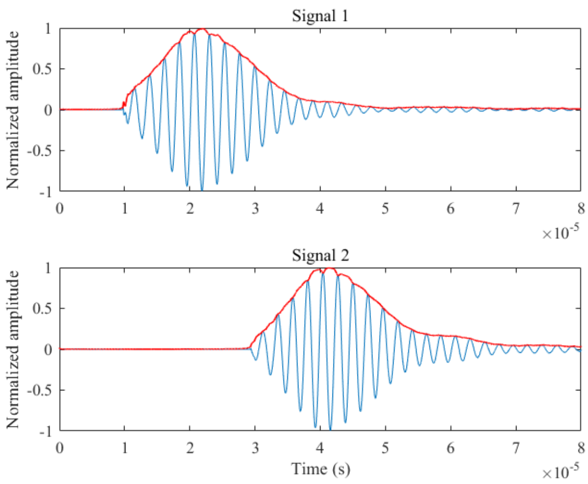

Fig. 2 The signals received at two different positions along the wave propagation path on a PET sheet

Results and Discussion

Table. 1 shows the process conditions of 8 PET sheets and Fig.3 shows the results of group velocity measurement of these PET sheets and the identified Young's modulus based on the velocity values and the corresponding tensile modulus for comparison purposes. Compared with the tensile modulus, the modulus is overestimated by the proposed method, with a minimum relative error of 7.79% for Sample 8 and a maximum relative error of 42.69% for Sample 4. However, as shown in the same changing trend of two modulus curves, the influences of the used process conditions on the resulting modulus are correctly reflected by the group velocities and identified modulus. For example, lowering the temperature, increasing the strain rate, or increasing the tensile ratio will lead to an increase in Young's modulus when all other conditions are held constant, and vice versa. Further investigation needs to be done to identify the reason for the discrepancy between the tensile modulus and identified modulus.

Table. 1 Process conditions of samples

Sample NO.	Temperature (℃)	Strain rate (s^{-1})	Stretch ratio
1	90	1	2
2	90	1	2.5
3	90	16	2
4	90	16	2.5
5	115	1	2
6	115	1	2.5
7	115	16	2
8	115	16	2.5

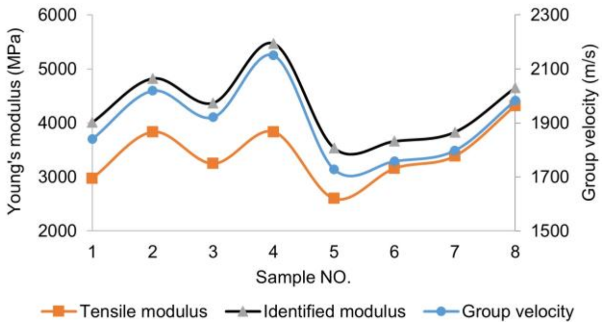

Fig. 3 Comparison between the tensile modulus and identified modulus

Conclusion

This work presents a novel method to measure Young’s modulus of stretched PET sheets based on the application of guided Lamb waves. Current results of the proposed method do not yet show a high consistency with tensile modulus. Further investigation and improved experimentation need to be performed to achieve accurate modulus measurement and realise its application on PET bottles.

References

[1] J. L. Rose, Ultrasonic Guided Waves in Solid Media, Cambridge University Press, Cambridge, 2014.

[2] L. Chevalier, C. Linhone, G. Regnier, Induced crystallinity during stretch–blow moulding process and its influence on mechanical strength of poly(ethylene terephthalate) bottles, Plastics, Rubber and Composites 28 (8) (1999) 393–400.

[3] T. T. Nguyen, Y. Luo, L. Chevalier, F. Lesueur, Stochastic simulation of top load test on poly(ethylene terephthalate) bottles: An experimental study on dispersion of elastic properties, Journal of Applied Polymer Science 138 (34) (2021) 50837.

[4] B. Hernandez Crespo, C. Courtney, B. Engineer, Calculation of Guided Wave Dispersion Characteristics Using a Three-Transducer Measurement System, Applied Sciences 8 (8) (2018) 1253.