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MEASURING THE THICKNESS AND ELASTIC PROPERTIES OF ELECTROACTIVE THIN-FILM POLYMERS USING PLATE WAVE DISPERSION DATA

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INTRODUCTION

Electroactive thin-film polymers are candidate sensors and actuators materials [1,2]. They are also finding a significant potential for applications in muscle mechanisms and micro-electro-mechanical systems (MEMS). In these applications, polymer thin films of thickness varying between 20 and 300 micrometer are utilized. Actuation of these polymers is attributed to piezoelectric, electrostrictive or electrostatic effects. Recent investigations suggest that polymers may produce striction which can be stronger than that delivered by electroactive ceramics. Such response may be produced by polymers with isotacticity or syndiotacticity molecular structure, where tacticity is the position of a pendant polymer group with a strong dipole moment that is mounted on a backbone polymeric chain.

Polymer thin films undergo thickness changes under the action of electric field. These changes are linear if the material's response is piezoelectric and are quadratic under electrostrictive or electrostatic actuation. In addition to thickness changes, the film vibrates as a plate structure [3] and in some electrostrictive polymers the elastic properties are dependent upon the electric field itself. Measuring the film thickness and its changes during activation while distinguishing between the thickness value and the amplitude of film vibration is a difficult task. Techniques such as interferometry, eddy-current and capacitance yield information about the location of the top surface of the film assuming that the rear surface stays stationary. Ultrasonic pulse-echo offers an ideal tool for simultaneous determination of the location of the top surface, i.e., vibration amplitude, and the film thickness. However, to obtain an acceptable resolution for 50 to 100-micrometer thin films it is necessary to use frequencies in the range of 50-MHz or above, which is beyond the capability of conventional ultrasonic systems.

Plate wave measurements offer the capability to determine the thickness of thin films using much lower frequencies and to obtain significantly higher resolution than that can be obtained by pulse-echo technique at similar frequencies. Furthermore, using dispersion curve measurements one can also determine the elastic constants of the film, thus allowing investigation of the electrostriction behavior of polymer and determination the actuation force that the polymer induce.

The authors are currently studying the potential use of plate wave dispersion curve measurements as an effective gauging tool for electroactive thin film polymers. In this communication, we briefly describe application of this technique to measure the modulii and thickness of electroactive polymer thin films and discuss some of the preliminary results. A series of polymer thin films are used in the present study; a 1 mm s-PMMA film, and $80\mu m$ and $230\mu m$ thin polyethylene terephthalate films. The dispersion curves are measured for these materials and an inversion algorithm is applied to determine the thickness and elastic constants.

EXPERIMENTAL

The experimental technique is based on leaky Lamb wave (LLW) theory. The overall experimental setup is described in prior publications [4], and is briefly summarized here. The technique employs a pair of transmitting and receiving transducers in a pitch-catch arrangement, where the transducers are flat, immersion 20MHz, 0.125-inch diameter. A computer controlled setup which allows to articulate the angle of incidence from 12 to 80 degrees is utilized. The receiving transducer is placed at the null zone of the leaky lamb wave field. At incidence angles from 13 to 45 degrees at increments of 0.25 degree, the frequency is varied in the range of 3 to 30 MHz and the minima of the reflection spectra are acquired.

The location of the minima in the reflection spectral response are identified by a software algorithm that distinguishes between noise and modes. Certain selection criteria are enforced to eliminate falsely measured modes. A plot of the frequency of the various plate wave modes as a function of the phase velocity is defined as the film dispersion curve. Since the objective of the current study is to examine the feasibility of using LLW measurements of the thickness and elastic constants of polymer thin films, water was used as a convenient coupling medium. In future investigations where electric field will be applied to study the electroactivation behavior, water will be replaced by a silicon oil couplant to avoid potential electrolysis.

LEAKY LAMB WAVE DATA

The phase velocity, v, is determined in terms of the angle of incidence using Snell's law, $v = \alpha/\sin(\theta)$, where α is the acoustic wave speed in the coupling medium, and θ is the incidence angle. The frequencies at which reflection minima occur are associated with the platewave modes. At these frequencies, the reflection coefficient R is zero; R itself may be expressed in the form

$$R = R(\omega, v; c_1, c_2, h)$$

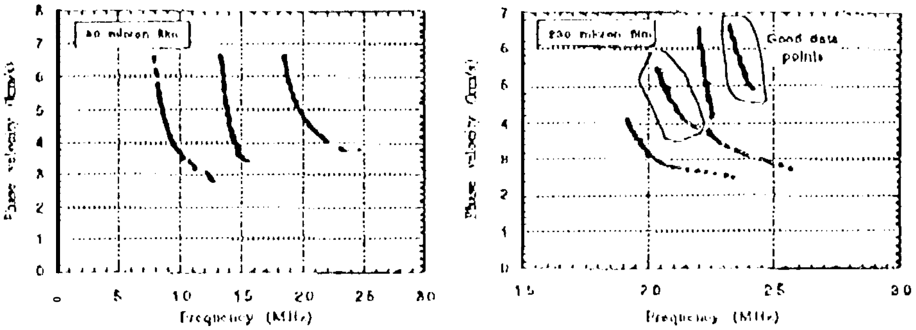

Figure 1: Dispersion data for 80 and 230 μm thin polyethylene terephthalate films.

where ω is the circular frequency, c_1 and c_2 are the P- and S-wave speeds of the film material, respectively, and h is the film thickness. Mathematical details are found elsewhere; see for example [5].

Examples of raw data are shown in Figs. 1 for two thin polyethylene terephthalate films whose thicknesses are $80 \mu m$ and $230 \mu m$. It is to be noted that not all of the dispersion curves are measured in a single experiment. Also, the acquired frequency minima of the reflected spectrum may still be subject to some experimental errors, which does not occur very often. In principle, careful screening of the data should lead to detection of erroneous data points, i.e., a good judgment as to which data points should be used for inversion is always required. The data shown in Fig. 1 for the $80 \mu m$ film are clean, and only some of which are used to recover the thin film parameters; thickness and elastic properties. For the $230 \mu m$ film, however, a part of the data is rejected, which either represent noise or occur in a zone where the dispersion curves representing different modes are very close to each other.

THE INVERSION ALGORITHM

Leaky Lamb wave measurements yield a set of points in the ω - v space. A analytical dispersion relationship exists, which may be written in the form

$$\mathcal{F}(\omega, v; \rho, E, \nu, h) = \mathcal{G}(\omega, v; c_1, c_2, h) = 0 \tag{2}$$

in which E, ν and ρ are Young's modulus, Poisson's ratio and the density of the film material, respectively. Let (ω_i, v_i) be the set of experimental data points. The inversion problem consists in solving the dispersion relationship

$$\mathcal{G}(\omega_i, v_i; c_1, c_2, h) = 0 \tag{3}$$

for c_1, c_2 and h. Once c_1 and c_2 are determined, E and ν can be calculated from

$$\nu = \frac{\frac{c_1^2}{c_2^2} - 2}{2\left(\frac{c_1^2}{c_2^2} - 1\right)}, \qquad E = 2(1+\nu)\rho c_2^2. \tag{4}$$

The technique used here to recover the parameters c_1, c_2 and h is based on the simplex algorithm [6]. This algorithm has been successfully used to invert leaky Lamb wave data for composite plates [7], and was found to converge much faster than algorithms based on local linearization and least square theories [8]. The algorithm is based on a search for a point (c_1^*, c_2^*, h^*) in the $c_1 - c_2 - h$ parameter space at which the sum of squares of the residuals S_{SR} is minimum, where S_{SR} is defined by

$$S_{SR} = \sum_i G^2(\omega_i, v_i; c_1, c_2, h) \tag{5}$$

Ideally speaking, at the point (c_1^*, c_2^*, h^*) the S_{SR} must be zero . An initial four vertices are selected in the $c_1 - c_2 - h$ parameter space and the response S_{SR} is calculated at each vertex. The vertices are then changes iteratively in such a way that S_{SR} is minimized. The vertex movements are governed by certain rules, which can be found elsewhere [6,7]. Eventually, these vertices become very close to the desired point. Iteration is terminated based on selected convergence criteria. To assure that inversion is accurate, only part of the data is used to recover the thin film thickness and properties. The properties and thickness are then used, in the analytical dispersion relationship, to predict all data point.

RESULTS AND DISCUSSION

Dispersion data for the two polyethylene terephthalate thin films are shown in Figs. 2 and 3, along with theoretical dispersion curves. The parameters resulting from data inversion are used to calculate these curves. For the polyethylene terephthalate films c_1, c_2, h, E and ν were respectively found to be 2.67km/s, 1.3km/s, 86μm, 5.2GPa, and 0.35 for the first (80μm) film, and 2.9km/s, 1.32km/s, 234μm, 5.3GPa and 0.37 for the second (230μm) film. E is calculate using Eq. (4) for a density $\rho = 1.15$. The values 80 and 230 were measured independently by a different method prior to the test. The difference between the values determined by inversion of leaky Lamb wave data and those measured prior to the test are small, which implies that the algorithm is reliable and can be used to invert leaky Lamb wave data with a fairly acceptable precision.

Although the two films are made of the same material, it is noted that slight differences in their wave speeds c_1 and c_2 values exist. At this moment the authors have not tried to explain these differences. However, it can be speculated that statistical variability may exist in film properties, particularly if one considers the complex nature of molecular chains comprising such thin films.

The results for the 1mm s-PMMA film are given in Fig. 4. For this film, c_1, c_2, h, E and ν were respectively found to be 1.94km/s, 0.92km/s, 1mm, 2.7GPa, and 0.35. E is calculate using Eq. (4) for a density $\rho = 1.15$. Young's modulus values for PMMA in the range 2.2-3.2GPa were reported [9].

SUMMARY

In this communication, a preliminary study is conducted to investigate the potential use of platewave dispersion curve measurements as a technique for indirect

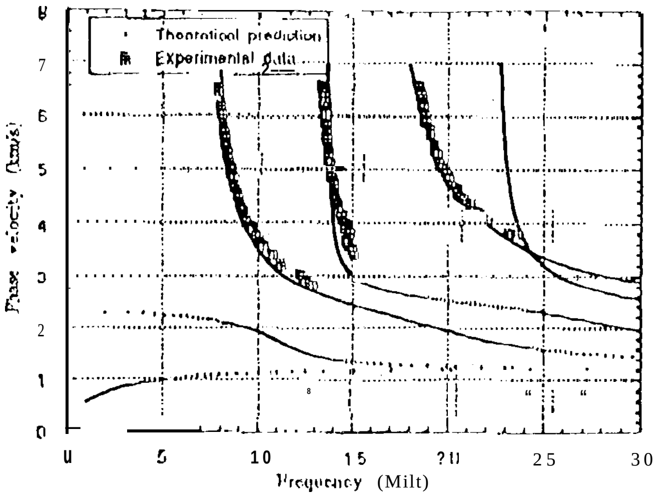

Figure 2: Comparison between experimental data and theoretical curves for an $80 \mu m$ polyethylene terephthalate film.

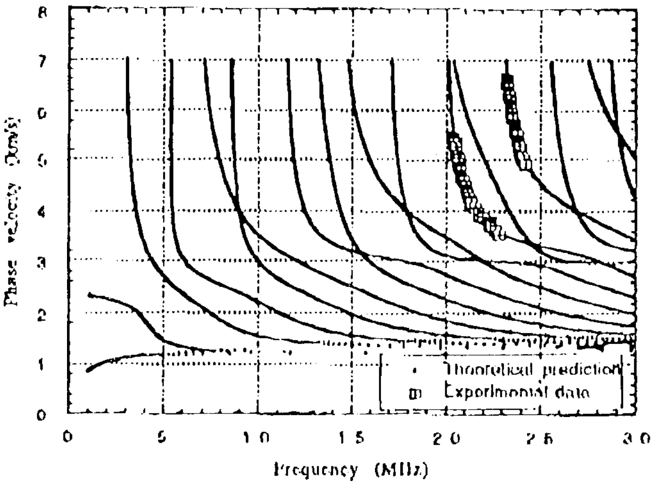

Figure 3: Comparison between experimental data and theoretical curves for a 230 μm polyethylene terephthalate thin film.

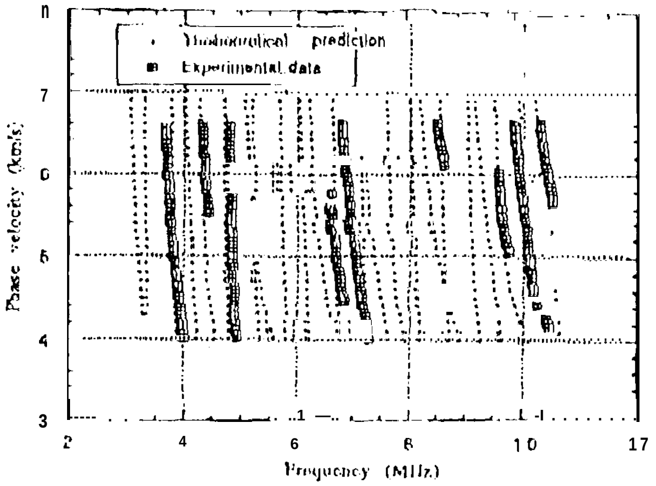

Figure 4: Comparison between experimental data and theoretical curves for a 1 mm s-PMMA film.

measurement of the elastic properties and thickness of electroactive thin film polymers. Three polymer films were tested; a 1 mm s-PMMA film, and $80\mu m$ and $230\mu m$ thin polyethylene terephthalate films. The dispersion curves are measured, and the simplex algorithm is applied to recover the thickness and elastic constants of the thin films. Preliminary results show that the technique can be a viable gauging tool for electroactive thin film polymers.

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