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Sensors for *In Situ* Monitoring of Elastic Properties

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Abstract

Preliminary experiments have been carried out to examine an invention for *in situ* monitoring of elasticity. The elasticity monitor consists of a piezoelectric material placed in contact with an elastomer to form an oscillating system. Monitoring the resonant frequency, amplitude, or "Q" value of this system provides a measure of elasticity of the elastomer. The experiments are described and their results and implications discussed.

Introduction

Elasticity is an important property of many materials. Its loss or degradation can have serious consequences, such as when a gasket deteriorates and permits leakage of an expensive or hazardous material, when an airplane tire blows out, or when a damping system begins to go awry. Changes in elasticity can also be correlated with changes in other properties such as degradation of electrical insulation,[1] loss of plasticizer in a plastic,[2] or changes in permeability of a thin film.[3] In fact, the mechanical properties of most organic compounds change when the compound degrades. Changes in elastic properties (elastic modulus, elastic recovery, and damping) are prompt and sensitive indicators of the degradation of elastomers. Thus, an elasticity sensor can be used to monitor mechanical properties and associated characteristics as well. Currently, there are no convenient or practical sensors for *in situ* monitoring of elasticity in gaskets, seals, or the like, when they are used in equipment or vehicles. This means that such materials must either be removed for inspection and testing or replaced routinely at conservative intervals based on theoretical or empirical estimates of failure times.

The late Tomas Hirschfeld invented a method for *in situ* monitoring of elasticity that provides a direct test of reliability and offers the prospect of minimal routine maintenance.[4] He likened his method to the technique of knocking on a wall to find the hollow portions; he suggested a refined approach, however, employing a miniature microphone and a loudspeaker.

Our elasticity monitor consists of a piezoelectric material (similar to that used in miniature microphones) placed in contact with an elastomer to form an oscillating system (the "sandwich" in Fig. 1). This combination constitutes a forced harmonic oscillator with damping provided by the elastomer—the greater the elasticity, the greater the damping. The elasticity of the elastomer and the characteristics of the piezoelectric material (size, shape, and composition) determine the resonant frequency of the oscillating system (i.e., the frequency of maximum displacement for given driving conditions).

For a piezoelectric oscillator of fixed properties, small shifts in driving frequency cause large changes in amplitude.[5,6] Conversely, for a fixed driving frequency, small changes in oscillator properties (e.g., damping) can also cause large changes in amplitude.[5,6] This property of piezoelectric oscillators is summarized in the statement that they are characterized by high "Q" values; that is, they respond well only in a narrow range of frequencies centered on the resonant frequency. (If one plots amplitude of response *versus* driving frequency for a damped oscillator, the resulting curve will exhibit a peak at the resonant frequency of the oscillating system. The

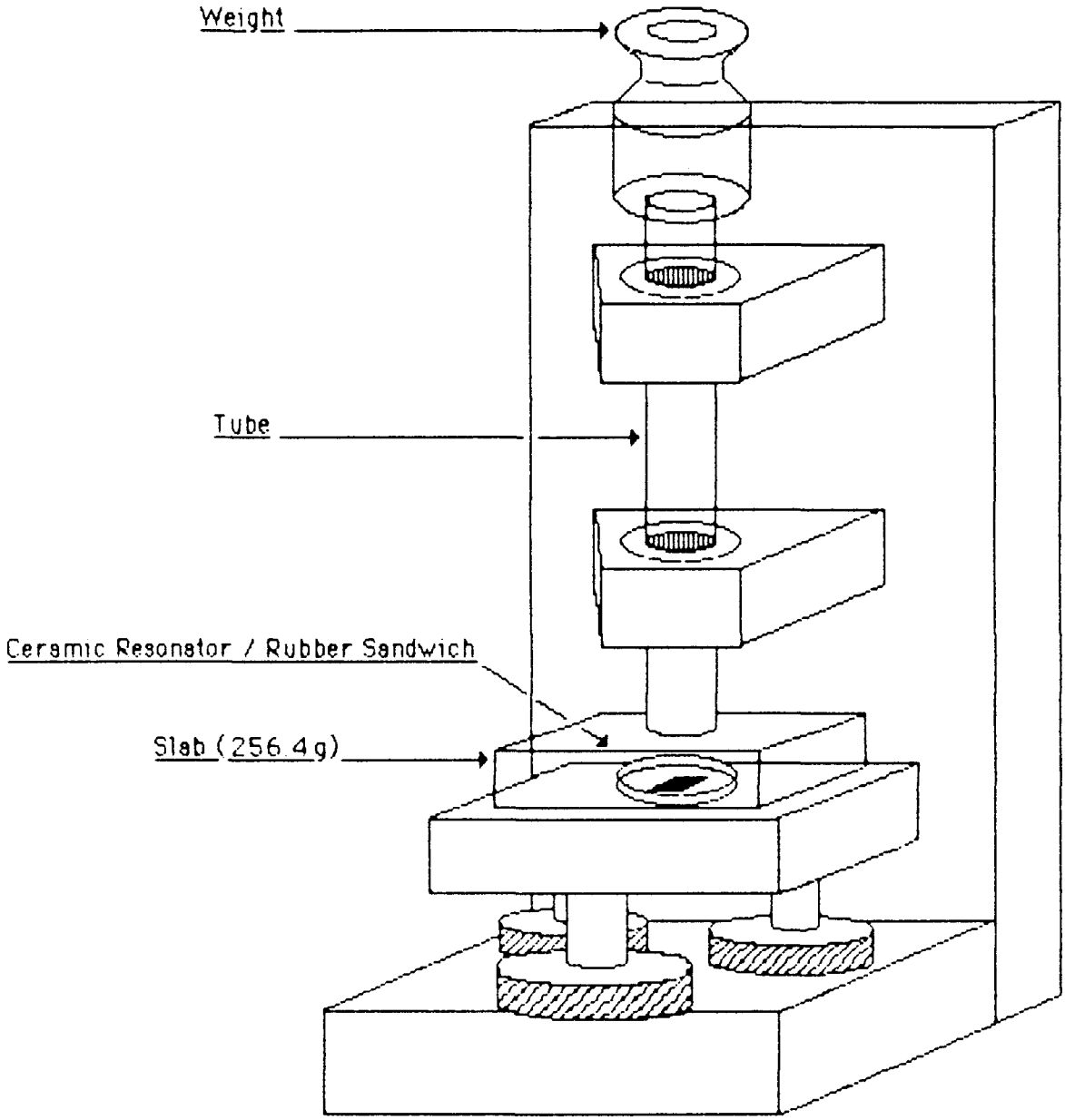

Figure 1. Weight bench used to hold the rubber-resonator sandwich for all tests.

shape of this peak is related to the Q value of the oscillator, high peaks of narrow width being associated with large values of Q.) Both the amplitude of response and the resonant frequency are sensitive to various oscillator properties, including damping. Since the vibrational characteristics of the materials can be predetermined, observations of the resonant frequency, amplitude, or Q of the oscillating system can provide a measure of elasticity of the elastomer.

Experimental

For these experiments, the elasticity sensor was a commercially-available 6-Mhz barium titanate piezoelectric-ceramic resonator 0.65 cm on a side and a few tenths of a millimeter thick. We

removed the casing from the resonator and soldered fine wire leads to two corners of the ceramic square.* The resonator was placed in intimate contact with the elastomer; it was sandwiched between two pieces of neoprene, gum, or silicone rubber, each measuring $1.9 \times 1.9 \times 0.15$ cm. We used both new rubber samples and rubber samples that had been exposed to ozone-contaminated atmospheres (8 ppm for 7 hours) to simulate aging. The rubber-resonator sandwich was placed on a weight bench with various loads on the piston to provide pressures ranging from 78 to 203 g/cm^2 (see Fig. 1).

For some experiments, the entire weight bench was placed in an incubator and maintained at a temperature setting of either 40 or 55 °C. The sensor was monitored remotely with a simple oscillator circuit and an HP3585A spectrum analyzer with tracking generator. Spectrum analyzers are not normally well suited to field monitoring; nevertheless, because this initial work was designed to provide proof-of-principle, we used a spectrum analyzer to observe all of the variables at one time. A mixer circuit, with a reference oscillator and a frequency counter to examine beat frequencies, could be used if frequency turns out to be the best variable to monitor. If amplitude is to be measured, a simple peak-height monitor with LED readout could be used.

Observations

The experimental observations included resonant frequency, amplitude, and Q value. Three types of experiments were conducted.

In the first type, observations were made at room temperature with a rubber-resonator sandwich subjected to a pressure of 78 g/cm^2 (the pressure resulting from the unloaded weight bench). With the observations completed, pressure was removed from the sandwich for a period of five minutes to let the rubber relax. Next, 30 grams were added to the weight bench, yielding a total pressure on the sandwich of 108 g/cm^2, and the observations were repeated, followed by another five-minute period of pressure-free relaxation. This procedure was repeated twice more, with added weights of 45 grams and 60 grams, respectively. The entire set of experiments was repeated at 40 and 55 °C, and at room temperature using only the "aged" samples. As can be seen in Figs. 2 and 3 for silicone rubber, there is a shift in resonant frequency and a reduction in amplitude with increased pressure (increased damping). Although the data for gum and neoprene rubber are not reproduced here, we observed similar changes for these rubber types. It should be pointed out that elastomer samples pretreated with ozone (referred to as "Aged" in Figs. 2–6.) showed changes in resonant frequency, amplitude, and Q value relative to the untreated samples, even though there were no visible changes in the samples.

In the second type of experiment, initial observations were made with a rubber-resonator sandwich subjected to the pressure of the weight bench only. Next, 100 grams were added for a period of five minutes and removed; measurements were made immediately thereafter with only the pressure of the weight bench. This loading/unloading procedure was carried out with added weight in 50-gram increments up to a total added weight of 250 grams. These experiments were also performed at 40 and 55 °C, and at room temperature only using "aged" samples. Figures 4, 5, and 6 show the effects of fatigue (increased signal amplitude) for the three different types of rubber when the sandwiches were subjected to a pressure of 78 g/cm^2. Note that, at all three

* Originally, Hirschfeld had envisioned using an annular resonator of the type used in audio buzzers. These resonators have low "Q" values, however, making it difficult to detect small changes in vibrational properties.

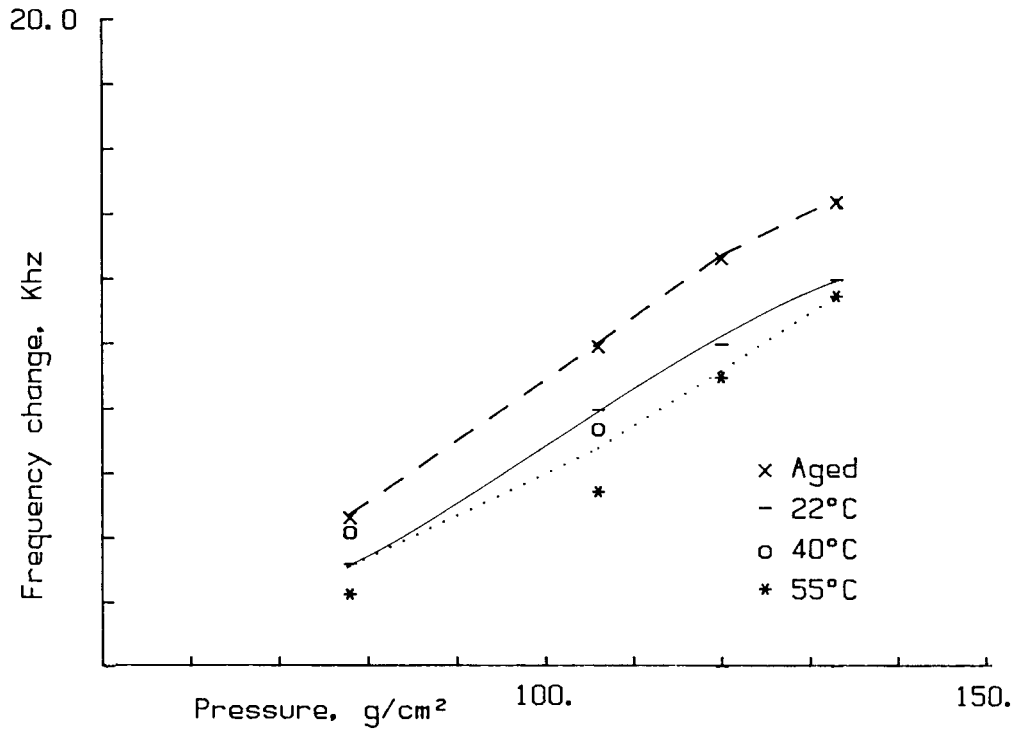

Figure 2. Changes in resonant frequency of silicone rubber samples as a function of pressure with increasing pressure.

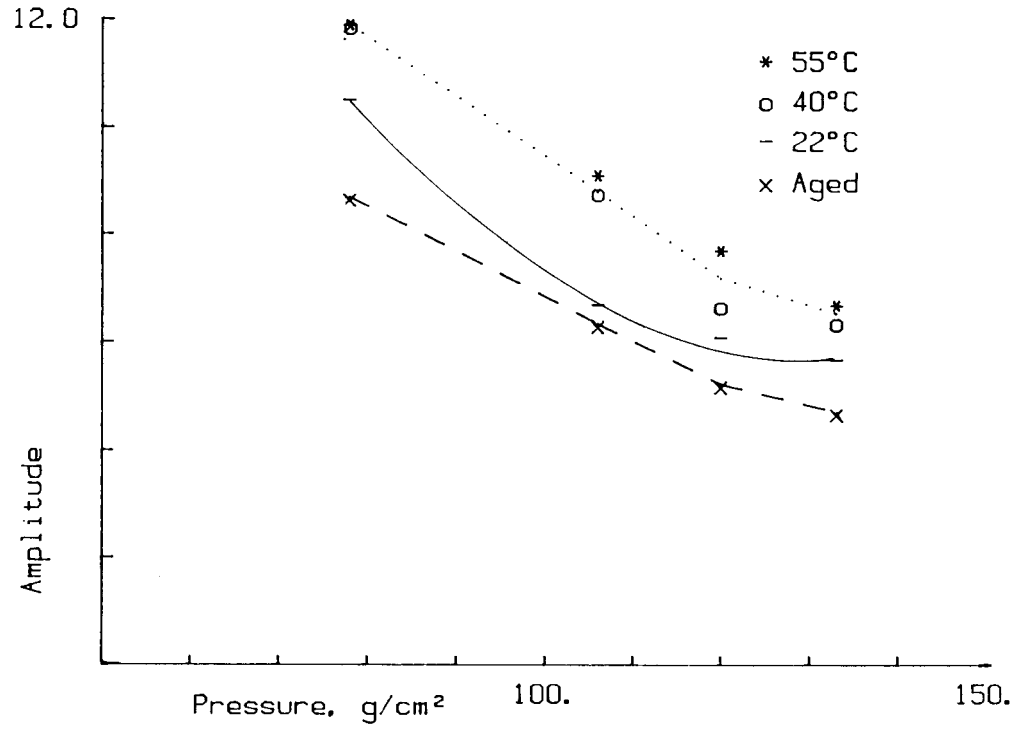

Figure 3. Amplitude changes as a function of pressure for silicone rubber samples.

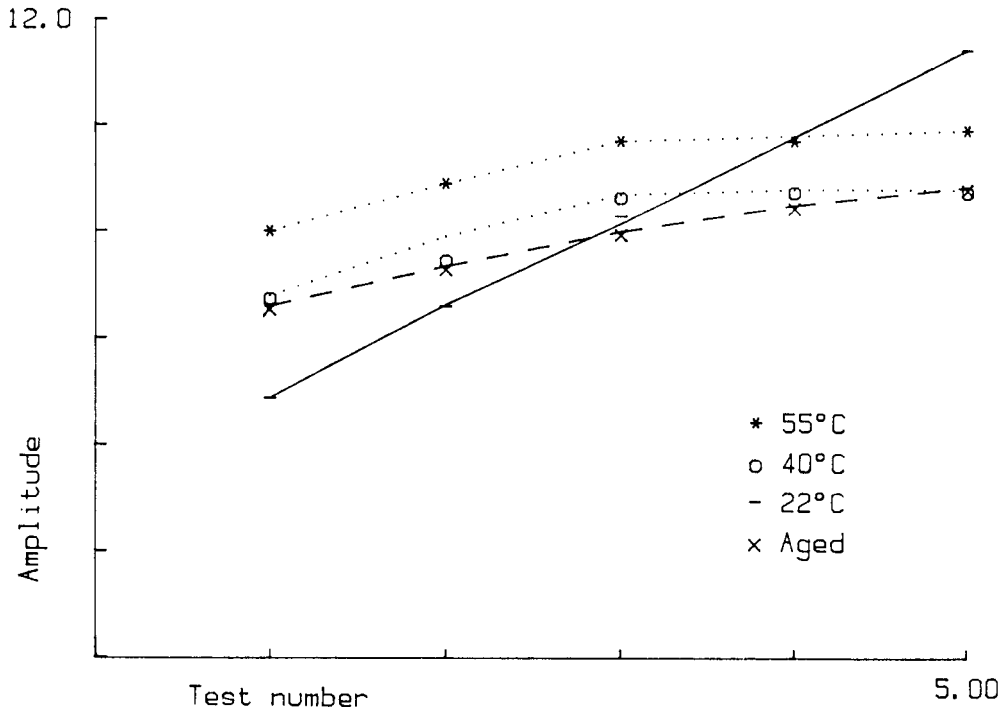

Figure 4. Amplitude changes observed in neoprene rubber samples, testing repeated at fixed pressure with the sample fatigued between measurements by increased pressure.

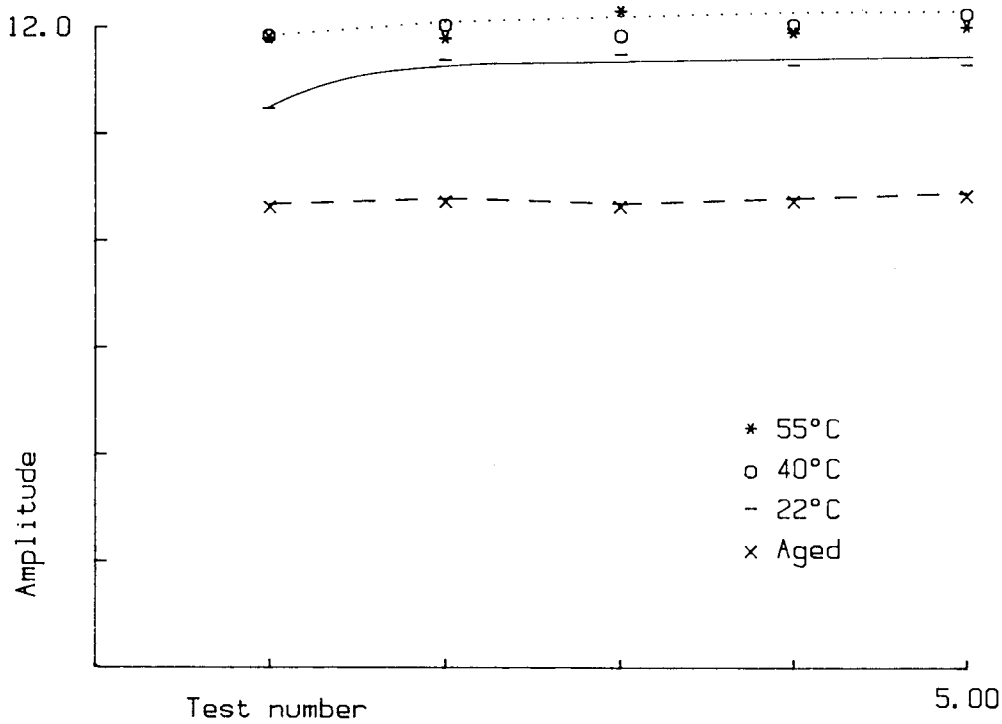

Figure 5. Amplitude changes observed in silicone rubber samples, testing repeated at fixed pressure with the sample fatigued between measurements by increased pressure.

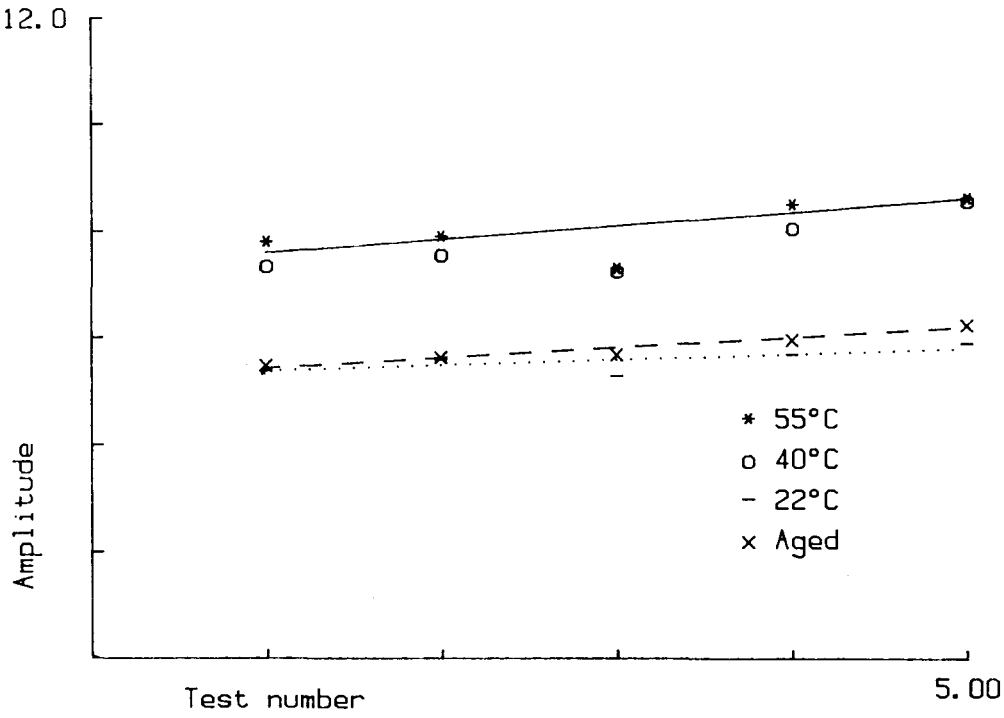

Figure 6. Amplitude changes observed in gum rubber samples, testing repeated at fixed pressure with the sample fatigued between measurements by increased pressure.

temperatures, each of the samples exhibits reduced damping (increased amplitude) with repeated measurement.

The third type of experiment involved placing a rubber-resonator sandwich on the weight bench with an added load of 100 grams and making measurements over a period of five months. Figure 7 shows the increase in Q value with time resulting from a constant pressure, indicating a decrease in damping (loss of elasticity) as the rubber fatigues.

Discussion

The observed amplitude changes, on the one hand, ranged from a few percent to more than 50%. The changes in resonant frequency, on the other hand, were only a few KHz out of 6 MHz and were difficult to evaluate accurately because of the shape of the damped curve. Quartz oscillators would provide greater Q values and might simplify the measurement process. The narrower resonance shape would be necessary if one wished to use a reference oscillator, mixer, and beat frequency counter as the electronic monitor. Quartz oscillators, however, are considerably less rugged than ceramic oscillators. For this reason, we believe a ceramic oscillator and peak-height monitor would be better for an *in situ* elasticity-monitoring system.

The reduced damping that occurs with repeated measurement agrees with the expected loss of elasticity as a result of compression set. The decrease with temperature can be explained in terms of time-temperature superposition. This phenomenon, observed in polymer elasticity studies,[7] can be described as follows: For materials that exhibit time-temperature superposition, a change in temperature shifts the entire curve of an elastic mechanical property along the (log-) time axis. At

this time, we can offer no explanation for the apparent increase in elasticity of the silicone rubber sample following ozone treatment.

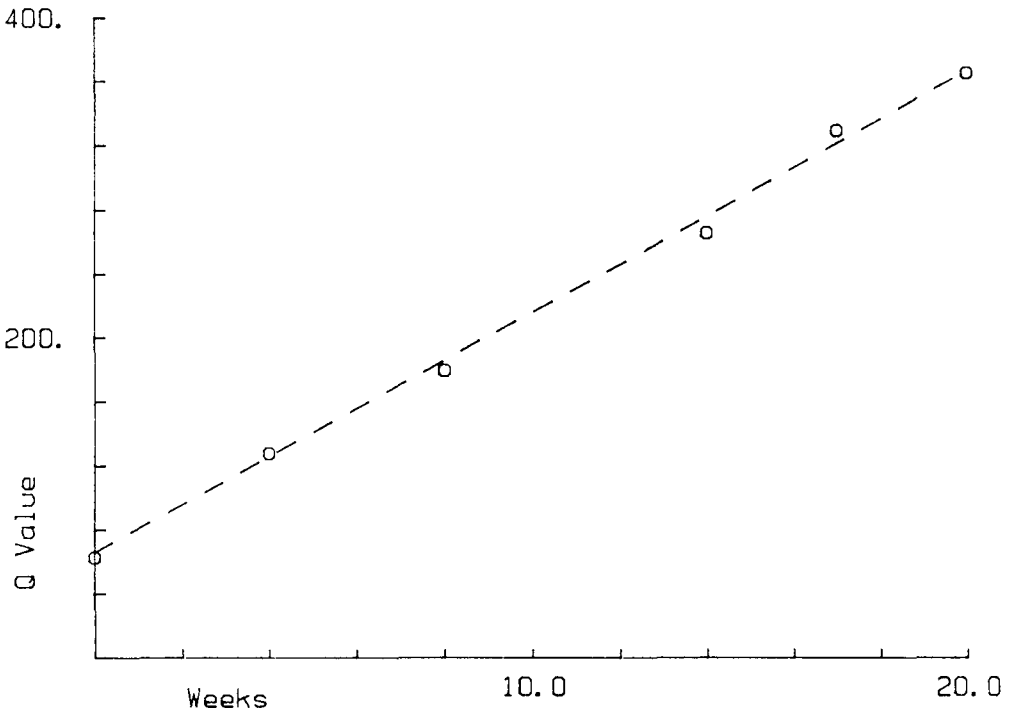

Figure 7. Observed changes in Q value over a period of weeks (periodic measurements with the sample subjected to a constant pressure).

Conclusions

These experiments clearly indicate some interesting possibilities for an electromechanical elasticity monitor of the sort employed here. The prospects look good enough to warrant further testing and the development of suitable electronic circuitry to adapt the instrument for *in situ* monitoring.

Acknowledgments

The author gratefully acknowledges the guidance and leadership of the late Tomas Hirschfeld who conceived the idea for the techniques of *in situ* monitoring of elasticity that were used in this research. The author also acknowledges the technical assistance of Keith Kishiyama, Steve Mahoney, and Robert Steinhaus.

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