Development of Piezo-Beam Type Sensor Device Using Longitudinal Vibration for In-Situ Measurement of Polymer Gel Characteristics

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Abstract: This paper is concerned with the development of a piezoelectric transducer for high accuracy measurement and evaluation of the thickness variation and swelling ratio of temperature-sensitive polymer gels in aqueous solution. In order to improve the measurement accuracy in practical use, the cantilever beam with the polymer membrane is actuated in longitude vibration. The influence on the measurement due to the polymer length change is investigated in detail and it is found that there exists an adaptive polymer length for better estimate the polymer characteristics. Furthermore, the method for estimation of the thickness and the swelling ratio is observed on the piezoelectric impedance measuring technique. Finally, a novel piezoelectric beam type sensor device is proposed, which is designed more conveniently for practical use.

Key Words: *piezoelectric transducer, structural analysis, longitudinal mode, polymer gel, estimation, thickness, swelling ratio, impedance-based measuring technique.*

1. Introduction

Stimulus-sensitive polymer system has been attracted much attention for its technologic and scientific importance. There are many reports on polymer characteristics change due to the surrounding conditions such as pH, photo, concentration, temperature[1-4], etc. Among them temperature-sensitive polymer system was focused by the researches. Poly N-isopropylacrylamide (PNIPAAm) is a typical temperature-sensitive polymer. PNIPAAm exhibits remarkable hydration-dehydration reversible changes in aqueous solution in response to relatively small changes of temperature around a Lower Critical Solution Temperature (LCST). PNIPAAm chains hydrate to form an expanded structure below LCST and dehydrate to form a shrinkage structure above LCST. Since hydration-dehydration of PNIPAAm is readily controlled by just changing the temperature, it is used as a chemical valve[5], cell culture substrate[6], separate film[7], etc. The hydration-dehydration characteristic of the polymer gel plays a primary role in many application fields.

Usually the hydration-dehydration characteristic of the polymer gel can be represented by equilibrium swelling ratio of the polymer. The swelling ratio of the polymer is radical property in development of new material of temperature-responsive copolymer. There are several methods for measuring the swelling ratio of temperature-responsive polymer: electronic balance[8], caliper[9], buoyancy technique[10]. In the electronic balance method, the sample has to be taken out from water after it reaches the equilibrium and then measure its weight. The swelling ratio H is then calculated by $(W_s - W_d)/W_d$, where W_s and W_d are the weight of the swollen and dried samples, respectively. It is not available to measure the swelling ratio in-situ. By the caliper

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and buoyancy method, the swelling ratio H is defined as $(V_t - V_0)/V_0$, where V_t is the volume of the polymer in liquid at certain temperatures and V_0 is the volume of the dried polymer sample. In this way, the sample should be a certain large size and is also taken out of the water to measure it.

Jiang et al.[11] reported a piezo-cantilever transducer to measure the swelling ratio of temperature-responsive polymer gel in-situ with a small sample based on piezo-impedance measuring technique. A small mass change in the polymer can be detected by piezoelectric impedance response at the high frequency of the transducer. However, there are some factors affected the accuracy and sensitivity of this piezo-cantilever transducer when measuring the polymer characteristic in-situ. First, the piezoelectric cell actuates the cantilever vibrating in bending mode which seems not available working in solution because the vibrating amplitude attenuates greatly in liquid and it causes noise easily. Next, when the temperature-responsive polymer swollen, not only its mass but also its length and thickness are changed. The frequency shift represents the equivalent mass change of the polymer. It includes its length change and thickness change. In practical case, the sample are difficult to be cut exactly in a same size in every experiments, a little length change of the polymer would cause the measuring errors. The third, the piezo-cantilever consisted of two parts: the probe and cantilever transducer. At the measuring process, the probe had to be assembled to the cantilever transducer by double sticky-tape. The double sticky-tape could not firmly stick the probe to the transducer longer in liquid. So it is necessary to improve the structure and make it easy to handle in application.

In this research, we studied a new type piezo-beam sensor device to improve the accuracy in measuring the sensitive-stimulus polymer by reducing the influence of the sample's length effect. The piezo-beam sensor is driven by longitudinal vibration which is actuated by two piezoelectric cells. The longitudinal vibration, in general, receives smaller damping effect in liquid than the bending vibration. Furthermore, the impedance responses to variation of physical properties of the polymer gel, such as the length, thickness and density, are investigated. Selecting an adaptive polymer length can improve the accuracy of the cantilever transducer. The thickness change of the polymer can be calculated with more accuracy by using average value of different resonant frequencies. The swelling ratio of the polymer gel is obtained theoretically. Finally, a novel piezo-beam type sensor device driven by longitude vibration is proposed, which is also designed more conveniently for practical use.

2. Simulation Method and Results

It is possible to measure the swelling ratio of polymer gel by a piezo-cantilever transducer [11]. The cantilever resonant frequency is varied with the change of polymer gel mass and volume due to the hydrophilic and hydrophobic characteristics. In the simulation, the mathematical model of the piezo-cantilever transducer is considered as a bending mode. The frequency shift Δf is function of the equivalent mass change $\Psi'(\Delta m)$. However in substantial, the resonant frequency change of the piezo-transducer is related comprehensively to the polymer physical properties, such as the length, thickness, mass, etc. It should be defined as a function of $\Delta f = \Psi(\Delta l, \Delta h, \Delta m)$, here Δl means the length change, Δh is the thickness change, Δm indicates the mass change. Further, the length of the polymer sample piece is difficult to be made exactly as desired size, and the thickness is still unknown. How to measure the thickness and how to reduce the effect of length on the measurement accuracy are the problems to be solved for practical use of this kind of transducer.

In order to measure both the thickness and the swelling ratio by the simple piezo-cantilever transducer with a high accuracy, a piezo-cantilever is designed in this section, and the actuating method for driving it vibrated in both bending modes and longitudinal modes are described in detail.

2.1 Actuated in bending modes and longitudinal modes

Imaging to vibrate a beam in liquid, it is easily understand that

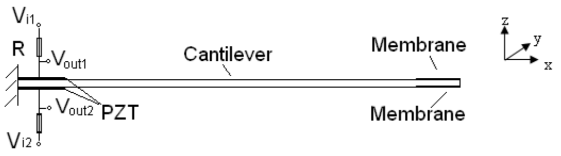

Figure 1 Analytic model for piezo-cantilever transducer.

Table 1 Material characteristics.

Aluminum		
Young's modulus (Pa)	E	7.00e+10
Poisson's ratio	ν	0.345
Density (kg/m^3)	ρ	2689
Polymer		
Young's modulus (Pa)	E	1.23e+6
Poisson's ratio	ν	0
Density (kg/m3)	ρ	1300
Piezoelectric cell		
Density (kg/m3)	ρ	8000
Elastic constant (m2/N)	S^E_{11}	1.48e-11
	S^E_{33}	1.81e-11
Specific Inductive Capacity	$\varepsilon^T_{11}/\varepsilon_0$	5000
	$\varepsilon^T_{33}/\varepsilon_0$	5440
Piezoelectric Constant(m/V)	d_{31}	-2.87e-10
	d_{33}	6.5e-10
	d_{15}	9.30e-10

the beam vibrated in longitudinal modes has smaller damping than it vibrated in bending modes. A piezo-cantilever transducer is designed to be actuated in both bending modes and longitudinal modes simply by controlled the phase of the input voltage.

Figure 1 shows the analytic model of the designed piezo-cantilever transducer. Two piezoelectric cells are patched on the parallelism position of the cantilever surfaces. Two piezoelectric cells have the same polarity in Z-direction. The contact surfaces to the cantilever are used as common ground. When voltages applied to both PZTs with the same amplitude and in same phrase, $V_{i1} = V_{i2} = A\cos(\omega t + \phi)$, both PZTs compressed or extended simultaneous in x-direction (longitudinal direction) and generated a longitudinal vibration along the cantilever. When the applied voltages to the two PZTs are at same amplitude but in different phase, especially with antiphase, $V_{i1} = -V_{i2}$ a bending motion will happen in the beam.

In this study, the piezo-cantilever (Fig.1) is made of

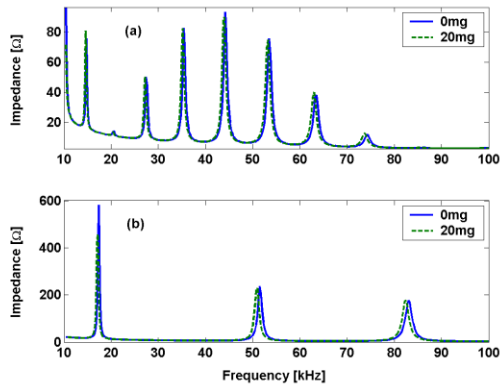

Figure 2 Impedance response variations due to the extra mass change. (a) actuated in bending modes.(b) actuated in longitudinal modes.

aluminum with 75×5×1.2 mm thick, fixed at one end. Two piezoelectric cells with 10×5×0.3 mm are patched in parallel to the surfaces of the cantilever at the fixed end. The polymer gel is coated at the free end of the cantilever. The size of the polymer is about 10×5×0.1 mm in the analysis. Their material properties are list in Table 1.

Simulation is done by using the finite element method. The input voltage $V_{in} = Ae^{(\omega t + j\phi)}$, applied on the resistor R gives the output voltage V_{out} on the surface of the PZTs, the electric impedance can be calculated by following formula:

$$Z(\omega) = \frac{RV_{out}(\omega)}{V_{in}(\omega) - V_{out}(\omega)} \quad (1)$$

In the harmonic simulation, the amplitude of input voltage is given by 1V and the resistor is 1kΩ. The frequency is swept from 10kHz to 100kHz. Assuming mass change by absorbing water in the polymer gel is 0mg and 20mg respectively. Fig.2 depicts the results of the real part impedance responses with the mass change. Fig.2(a) shows the responses corresponding to the bending modes with inputs $V_{i1} = -V_{i2}$ Fig.2(b) is the ones related to the longitudinal modes with inputs $V_{i1} = V_{i2}$. Comparing with these results, the resonant frequency, at about 53.5kHz (the 11th bending mode), is shifted left about 250Hz. In contrast, the frequency at the 2nd longitudinal mode (at about 51.9kHz) is shifted about 500Hz, which is bigger than the one in bending modes.

These results show that either the bending modes or the longitudinal modes can be used to evaluate the change in the polymer gel. Furthermore, both the two type modes can be actuated very easily by adjusting the phase delay of the input voltages.

2.2 Influence of the polymer length

As mentioned above, the longitudinal modes will be a good choice for measuring the physical change in polymer gels especially when it is used in the liquid measurement. For practical use, it should be investigated in detail to know what kinds of factor affect the accuracy and how to improve the measuring accuracy by the longitudinal modes.

The length variation of polymer gel will be one of the factors to affect the accuracy of the impedance measurement. In fact, it is difficult to cut or make the target sample piece in exactly the same size always. Also the target polymer will be swelling or shrinking as it is measured in the aqueous liquid. To check the effect of the polymer length, the polymer density and thickness are given as a constant, and its length is treated as a variable in the simulation. The polymer density is given by 1300kg/m^3 (Table 1). Let the polymer length variation related to the length of the cantilever transducer. The polymer length variation are set as 0.1L, 0.15L, 0.2L, 0.25L, 0.3L, 0.35L, 0.4L respectively in the following simulations, where the length of the cantilever is fixed by L=75mm. For the polymer thickness, it will be changed coinstantaneous as the polymer swelling or shrinking. In simulation on polymer length change, the thickness is set in several levels. The dry polymer usually has thickness of about 0.1mm. Considering the possibility on polymer expansion with absorbed aqueous solution, the thickness of the polymer are set as 0.1mm, 0.15mm, 0.2mm, 0.25mm, 0.3mm. According to the results in Fig.2, two scaning frequency regions are investigated in detail. One is at [49kHz, 55kHz] for comparison of the 11th bending mode (f_{res} =53.7kHz) to the 2nd longitudinal mode (f_{res} = 51.9kHz). Another one is set at [81kHz, 87kHz] for comparison of the 14th bending mode (f_{res} =85.9kHz) to the

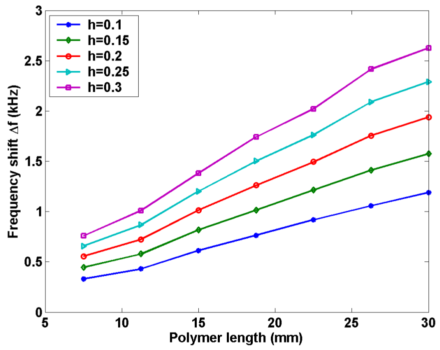

Fig. 3 Frequency shift variation at 11th bending mode as functions of the polymer length for different thickness.

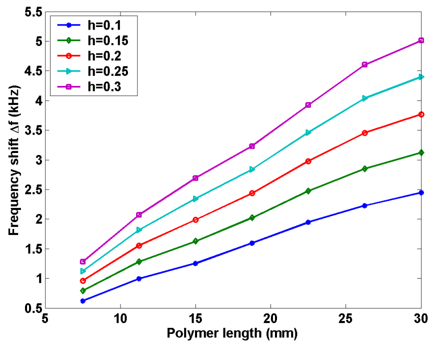

Fig. 4 Frequency shift variation at 14th bending mode as functions of the polymer length for different thickness.

3rd longitudinal mode (f_{res} =83.5kHz). Figures 3 to 6 show the resonant frequency shifts as functions of the length and thickness of the polymer. The horizontal axes in these figures represent the length of the polymer and the vertical axes are the frequency shift in kHz. Figure 3 and Fig.4 depict the results for the frequency shifts at the 11th (f_{res} =53.7kHz) and the 14th (f_{res} =85.9kHz) bending mode resonant frequencies, respectively. While Fig.5 and Fig.6 are the results for the 2nd (f_{res} = 51.9kHz) and the 3rd (f_{res} = 83.5kHz) longitudinal mode resonant frequencies.

Figures 3 and 4 show the frequency shifts are increased almost linearly with an increase of the polymer length while its thickness is a constant. It means a small change in polymer length might cause a relative big frequency shift when the transducer is actuated vibrating in bending modes. Figures 5 and 6 show the different behaviors. While the polymer thickness is a constant, the frequency shifts almost keep the

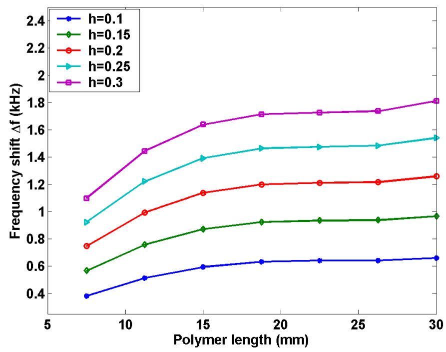

Fig. 5 Frequency shift variation at 2nd longitudinal mode as functions of the polymer length for different thickness.

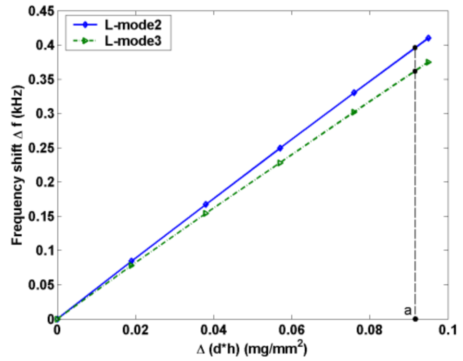

Fig. 7 Frequency shift variations to an increase of the mass parameter $\Delta(d \times h)$ at the polymer length of 16mm.

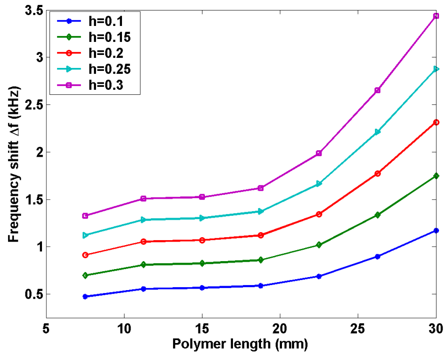

Fig. 6 Frequency shift variation at 3rd longitudinal mode as functions of the polymer length for different thickness.

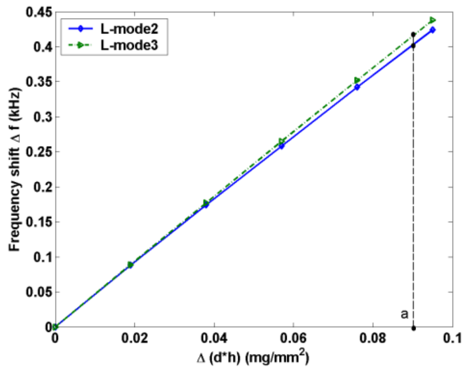

Fig.8 Frequency shift variations to an increase of the mass parameter $\Delta(d \times h)$ at the polymer length of 21mm.

same values at the polymer length between [0.2L, 0.38L] or [15mm, 28mm] for the 2nd longitudinal mode, and between [0.1L, 0.3L] or [8mm, 22mm] for the 3rd longitudinal mode. These results indicate that the frequency shifts in the longitudinal modes are nearly steady while the polymer length in certain ranges. This means that the measurement errors due to the length change can be reduced if a suitable length of the polymer is selected. For example, if the tolerant error due to the change of polymer length is set less than 20Hz, the length of polymer should be selected within [0.25L, 0.3L] or [18mm, 22mm] at the 2nd longitudinal mode, and [0.2L, 0.24L] or [15mm, 17mm] at the 3rd longitudinal mode.

2.3 Estimation of polymer thickness and swelling ratio

When the polymer is swelling in aqueous solution, its length, thickness and density will be changed simultaneously. As mentioned above, the frequency shift by the polymer length variation can be neglected if a suitable length is selected. Under this condition, it would be more efficient to estimate the polymer thickness h and swelling ration. Define a mass parameter by $(d \times h)$, combination of the density and thickness. Suppose the polymer at dry state has the density d_0 and thickness h_0. A resonant frequency at the dry state is set as the reference frequency f_0. As the polymer is swelling in the aqueous liquid, its thickness becomes h, and its density is d, the corresponding resonant frequency is f, the frequency shift $\Delta f = f_0 - f$ is related to the parameter $\Delta(d \times h)$, which is define by

$$\Delta f \propto \Delta(d \times h) \quad (2)$$

$$\Delta(d \times h) = (d \times h) - (d_0 \times h_0) \quad (3)$$

$$\Delta h = h - h_0 \quad (4)$$

Now two typical cases with the polymer length of 16mm(0.2L) and 21mm(0.28L) are simulated and their results are plotted in Figs.7 and 8. The horizontal axis in the figures represents the variation $\Delta(d \times h)$ and the vertical axis is the frequency shift Δf. The solid line is the results obtained at the 2nd longitudinal mode and the dashed line is the results at the 3rd longitudinal mode. It is clear that the frequency shift Δf and the mass parameter change $\Delta(d \times h)$ have a linear relationship and it can be described as

$$\Delta f = k\Delta(d \times h) \tag{5}$$

The coefficient k can be obtained from Figs. 7 and 8 by the least square method. If the polymer thickness variation is considered due to the absorption of water in liquid state, the parameter $(d \times h)$ can be expressed by the dry state polymer $(d_0 \times h_0)$ plus the absorbed water $(d_w \times \Delta h)$, where d_w is the water density and Δh is the variation in the thickness, i.e.,

$$(d \times h) = (d_0 \times h_0) + (d_w \times \Delta h) \tag{6}$$

Substitute Equation (6) into Equation (3), yields

$$\Delta(d \times h) = (d_w \times \Delta h) \tag{7}$$

Therefore, the frequency shift in Equation (5) gives

$$\Delta f = k\Delta(d \times h) = k(d_w \times \Delta h) \tag{8}$$

When the frequency shift is measured experimentally, the thickness can be estimated by

$$\Delta h = \Delta f / (k d_w) \tag{9}$$

Now take an example to estimate the polymer thickness. The coefficient at the 2nd mode in Fig.7 is calculated as k_2 = 4421(Hz/mg/mm^2), and the one of 3rd mode is k_3 =4105 (Hz/mg/mm^2). At point *a* in Fig.7 frequency shifts is measured Δf_{2nd} = 410Hz and Δf_{3rd} = 375Hz. Based on Equation (9), the thickness variation estimated by the 2nd mode is Δh_{2nd} = 0.0927 mm, and by 3rd mode is Δh_{3rd} = 0.0914mm. The results of Δh_{2nd} and Δh_{3rd} are not exactly the same. Let's evaluate the thickness by taking average

$$\Delta \bar{h} = \frac{\Delta h_{2nd} + \Delta h_{3rd}}{2} \tag{10}$$

the final estimated thickness variation from the two modes is $\Delta \bar{h}$ = 0.09205mm.

Appling the above estimation algorithm to the results shown in Fig.8, the coefficients are k_2 = 4632 (Hz/mg/mm^2) and k_3 =4684 (Hz/mg/mm^2). The frequency shift at point *a* in Fig.8 is measured Δf_{2nd} =424Hz, Δf_{3rd} =438Hz. The estimation of thickness variation are Δh_{2nd} = 0.0915 mm and Δh_{3rd} =0.0935mm. The final estimated thickness variation is $\Delta \bar{h}$ =0.0925mm. The results of Figs. 7 and 8 are obtained from two different length of the polymer. The estimated thickness changes are approximate to each other. This means the effect of the polymer length can be neglected in estimation of its thickness if a suitable length is selected. Further, the average value of thickness $\Delta \bar{h}$ has better accuracy than using only each value of Δh_{2nd} or Δh_{3rd} for estimation of thickness. This tells a fact that using two or more longitudinal modes in measurement can be compensated each other to obtain estimation accuracy.

Therefore, the swelling ratio of the polymer is then easily calculated by

$$H_e = \frac{\Delta V}{V} = \frac{S\Delta h}{Sh_0} = \frac{\Delta h}{h_0} \tag{11}$$

3. Proposal for new type Piezo-beam sensor

In practical measurement, it is a complex process for fixing the polymer on the cantilever. The process is usually conducted in liquid in different condition [11]. Figure 9 shows a proposal of a new beam type piezoelectric transducer. It consists of two parts, the piezoelectric transducer and a polymer immobilized probe. Figure 9(a) shows the piezoelectric transducer, which has two piezoelectric cells fixed on a fixture for holding the probe. Figure 9(b) is a beam probe, which has a step cross-section shape at one end to be inserted into the fixture and the other end is immobilized with the polymer. By separation from the piezo-transducer, the probe can conserve the polymer in the solution keeping its activity. Figure 9(c) is the assembled piezo-beam sensor measuring device. The probe can be assembled on the fixture simply by the screws on top and bottom, and the pushing force of the piezocells to the probe can be adjusted by the two screws on the left. When a pair of voltages are applied on the piezoelectric cells, the cells expand and contract to actuate the longitudinal mode vibrations easily on the probe through the

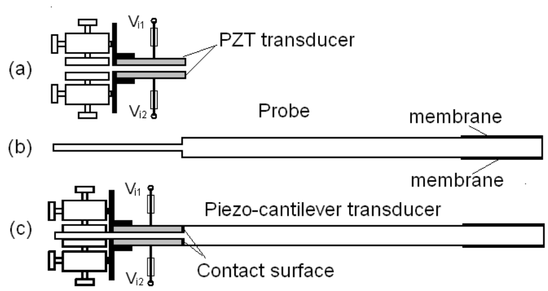

Fig.9 A novel piezo-cantilever transducer separated by two parts, (a) PZT transducer, (b) polymer immobilized probe with size 10×5×0.4mm and 65×5×1.2mm, (c) assembled system.

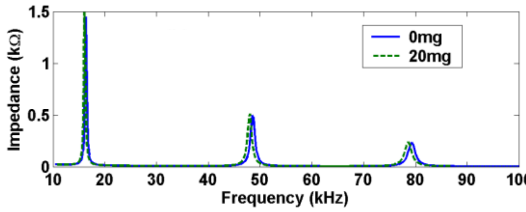

Fig.10 Impedance responses obtained in the longitudinal modes.

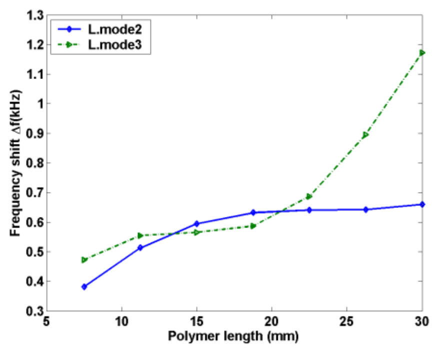

Fig.11 Frequency shift variations as functions of the polymer length simulated by the transducer in Fig. 1.

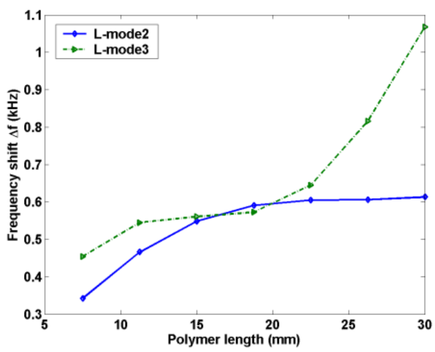

Fig.12 Frequency shift variations as functions of the polymer length simulated by the transducer in Fig. 9.

cross-section contact area.

Figure 10 shows the impedance response when two piezocells applied by the voltage with same phase $V_{i1} = V_{i2}$. Comparing Fig.10 with Fig.2(b), the three longitudinal modes are quite near to each other. It indicates that the improved structure can excite the longitudinal modes in a way same as patching the piezocells directly to the probe beam as shown in Fig. 1.

Figure 11 shows the relationship of frequency shift at the longitudinal modes simulated by the piezo-cantilever transducer shown in Fig.1. The polymer thickness is set at 0.1mm in constant. As previous discussed that the polymer length can be selected in certain range, such as [0.15L, 0.3L], to reduce the frequency shift error caused by the polymer length change. The same simulation is done to the improved structure in Fig.9(c). The probe is about 75×5×1.2 mm. The step cross-section part is 10mm long and 0.4mm thick. The piezoelectric cells have same size i.e., 10× 5×0.3 mm. The polymer thickness is set as a constant at 0.1mm and the density is 1300kg/m^3. The variation of the polymer length is given by the relative value to the probe, [0.1L, 0.15L, 0.2L. 0.25L, 0.3L, 0.35L, 0.4L]. Figure 12 shown the relationship of frequency shift obtained same at longitudinal modes for the improved structure (Fig.9(c)). It has the similar characteristic to results in Fig.11. The frequency shift has nonlinear relationship with the polymer length. In the 2nd longitudinal mode if polymer length is set at the range [0.2L, 0.4L], the frequency shift is almost the same. In contrast, as for the 3rd longitudinal mode the adopted polymer length will be along region [0.15L, 0.25L] in order to get less influence on the frequency shift changes.

4. Conclusion

The piezoelectric transducer for measuring and evaluating the characteristic of temperature-sensitive polymer gel is proposed and designed based on actuated in longitudinal mode. The obtained results are summarized as follows:

Both the bending modes and the longitudinal modes can be used to measure the change in the polymer gel. But the vibration in longitudinal mode has better characteristic than the one of bending mode, especially when the transducer is used in the liquid measurement.

There exists an adaptive polymer length which can reduce the influence due to the length change if the transducer is actuated in longitudinal mode.

A method for estimation of the thickness and the swelling ratio is proposed based on the piezoelectric impedance measuring technique.

A novel piezoelectric type transducer using the longitudinal vibration for measuring the membrane characteristics is proposed. It has better accuracy and is more practical for measurement of polymer characteristics in situ.

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