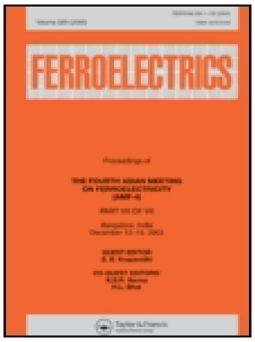

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Influences of Temperature Field on the Surface Wave Propagation Behaviors in SAW Devices

X. S. CAO,[1,2] F. JIN,[2] AND W. G. LIU[1,*]

[1]Micro Optoelectronic Systems Labs, Xi'an Technological University, No 4 North Jinhua Road, Xi'an 710032, People's Republic of China
[2]MOE Key Laboratory for Strength and Vibration, Xi'an Jiaotong University, Xi'an 710049, People's Republic of China

Analytical and numerical analyses are carried out for surface wave propagation in the layered PVDF piezoelectric structure under uniform and graded temperature field. Effects of thermo-electro-elastic properties, thermal stress and the temperature gradient on the surface wave propagation behaviors in SAW devices are discussed. Increase of temperature in the uniform temperature field or at the upper surface of the piezoelectric cover layer and exerting of a minus thermal stress can lead to the decrease of the phase velocity of the surface wave and the increase of the mode number. The results obtained indicate that the thermo-electro-elastic properties are the dominant factors affecting the thermal properties of the SAW devices, while the thermal stress and the graded temperature field are the subsidiary factors.

Keywords PVDF; surface waves; thermo-electro-elastic properties; thermal stress; temperature gradient

Introduction

As a flexible piezoelectric material, Polyvinylidene fluoride (PVDF) and its composite structure is widely used in the engineering applications including the surface acoustic wave (SAW) devices. Because PVDF is a kind of temperature sensitive material, the performance of these SAW devices may vary with temperature, it is necessary to study the temperature characters of waves in these devices for their applications.

There are two factors which affect the temperature sensitivity of the SAW devices. One is that the temperature field will influence the material properties obviously. The other is that initial stress field exists due to the difference in thermo-properties of each layer for the layered structure. Some researchers have investigated the change of material properties of PVDF caused by temperature. Singh [1] measured the AC conductivity and dielectric relaxation behavior of uniaxially stretched PVDF films varying with temperature and frequency. Zhu [2] discussed the measurement of the material complex constant and thermal properties of piezoelectric polymer PVDF, including elastic modulus, piezoelectric constant, and dielectric constant. Dos Santos [3] studied the thermal properties including density of PVDF in the temperature range from 25 to 210°C. The others studied the wave propagation behaviors under different initial biasing fields. Yang gave equations for

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*Corresponding author. E-mail: wgliu@163.com

infinitesimal incremental fields superposed on finite biasing fields in a thermo-electro-elastic body which were derived from the nonlinear equations of thermo-electro-elasticity [4] and investigated wave propagation in an electro-elastic plate under uniform initial thermo electromechanical fields [5]. Tian [6] studied the coupled piezo-thermo-elastic response under finite deformation. Liu conducted the theoretical analysis of Rayleigh wave [7] and B-G wave [8] propagation in a pre-stressed layered piezoelectric structure. Jin [9] investigated the propagation behavior of B-G wave in a piezoelectric layered structure with initial stress. For the inhomogeneous material, using WKB method, Qian [10] discussed the propagation behavior of Love waves in a functionally graded material layered non-piezoelectric half-space structure with initial stress.

In these studies [4–6], uniform temperature field was considered in the thermo-electro-elastic problem, or numerical examples were reported on the wave propagation in the plate where the thermal stress was not taken into account. Few works has been carried out on wave propagation behavior which is influenced by both thermo-electro-elastic properties and thermal stress. Furthermore, in engineering application, because PDVF has low thermal conductivity, there exists graded temperature field in the layered structure. Up to now, no report has been published concerning the wave propagation behavior in the graded temperature field.

In this paper, considering both thermo-electro-elastic properties and thermal stress, the behaviors of surface wave in the PVDF layered structure in the uniform and graded temperature field are discussed. The results reveal the effects of material thermo-electro-elastic properties, thermal stress and the temperature gradient on the wave propagation behaviors and provide theoretical guidance for either investigating the temperature compensation mechanism of these devices or utilizing the devices to measure uniform or graded temperature field.

Statement of the Problem

Consider a layered structure for the surface wave propagation, as shown in Fig. 1.

The cover layer is a transversely isotropic piezoelectric material, with a thickness of h and a free upper surface. The thickness of the substrate is much greater than that of the cover layer, so that the substrate can be regarded as a semi-infinite space. It is assumed that the xoy coordinate plane is an isotropic plane, and the polling direction is the same as the positive direction of the z-axis. The temperature in the substrate, air, and piezoelectric

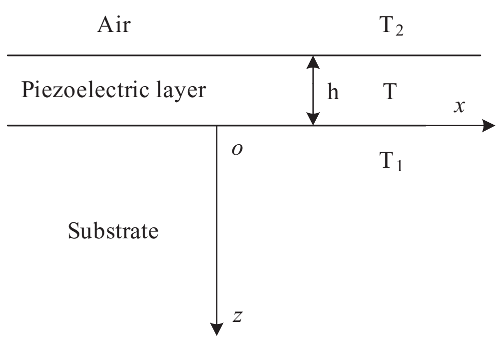


Figure 1. The layered structure and Cartesian coordinate.

layer is T_1, T_2, and T respectively. For generalized Rayleigh surface wave propagating in this structure, the displacement components and electrical potential can be expressed as $u = u(x, z, t)$, $v = 0$, $w = w(x, z, t)$ and $\varphi = \varphi(x, z, t)$. Due to the difference of the thermal expansion coefficient between the cover layer and the substrate, there exists initial stress in the thin covered layer. The field equations with initial stress can be expressed as follows [9]

$$\sigma_{ij,j} + \left(u_{i,k}\sigma_{kj}^0\right), \quad j = \rho\ddot{u}_i, \quad D_{i,i} + \left(u_{i,j}D_j^0\right), \quad i = 0 \tag{1}$$

The constitutive equations of the piezoelectric material are

$$\sigma_{ij} = c_{ijkl}S_{kl} - e_{kij}E_k, D_i = e_{ikl}S_{kl} + \varepsilon_{ik}E_k \tag{2}$$

where σ_{kj}^0 and D_j^0 are the initial stress tensor and the initial electric displacement. c_{ijkl}, e_{kij}, ε_{ik}, and ρ are elastic, piezoelectric, dielectric coefficients, and density, respectively. Because the material properties are always functions of temperature, they might vary along depth as temperature gradient exists. Furthermore, the mechanical displacement is related to strain by:

$$S_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{3}$$

The relationship between electrical field intensity and electrical potential is:

$$E_i = -\varphi_{,i} \tag{4}$$

Let u_1, w_1, and φ_1 denote in-plane displacement, out-plane displacement, and electrical potential in the piezoelectric layer, respectively, and then the governing equations for the generalized Rayleigh surface wave propagation in the layer can be expressed as follows [11] (hereafter, $\exp[ik(x - ct)]$ is omitted for brevity, where k is wave number and c is phase velocity.)

$$\begin{aligned}
&c_{44}u_1'' + c_{44}'u_1' + \left(\rho c^2 - c_{11} - \sigma_{11}^0\right)k^2u_1 \\
&\qquad + \left[(c_{13} + c_{44})ikw_1' + (e_{31} + e_{15})ik\varphi_1' + c_{44}'ikw_1 + e_{15}'ik\varphi_1\right] = 0 \\
&c_{33}w_1'' + c_{33}'w_1' + \left(\rho c^2 - c_{44} - \sigma_{11}^0\right)k^2w_1 \\
&\qquad + \left[(c_{13} + c_{44})iku_1' + e_{33}\varphi_1'' - e_{15}k^2\varphi_1 + c_{13}'iku_1 + e_{33}'\varphi_1'\right] = 0 \\
&\varepsilon_{33}\varphi_1'' + \varepsilon_{33}'\varphi_1' - \varepsilon_{11}k^2\varphi_1 \\
&\qquad + \left[e_{15}k^2w_1 - (e_{31} + e_{15})iku_1' - e_{33}w_1'' - e_{31}'iku_1 - e_{33}'w_1'\right] = 0
\end{aligned} \tag{5}$$

where the thermal stress deduced by the basic equilibrium equations is

$$\begin{aligned}
\sigma_{11}^0 = {}& (c_{11} + c_{12})(\hat{a} - a_{11}) - c_{13}a_{33} - 2\frac{2c_{13}e_{31}e_{33} + c_{13}^2\varepsilon_{33} - c_{33}e_{31}^2}{e_{33}^2 + c_{33}\varepsilon_{33}}\hat{a} \\
& + 2\frac{\varepsilon_{33}c_{13}^2 + c_{13}e_{31}e_{33}}{e_{33}^2 + c_{33}\varepsilon_{33}}a_{11} + \frac{\varepsilon_{33}c_{13}^2 + c_{33}c_{13}\varepsilon_{33}}{e_{33}^2 + c_{33}\varepsilon_{33}}a_{33} + \frac{e_{31}c_{33} - e_{33}c_{13}}{e_{33}^2 + c_{33}\varepsilon_{33}}p_3
\end{aligned} \tag{6}$$

in which, $\hat{a}$ denotes the thermal expansion coefficient of the substrate, and a_{11}, a_{33}, p_3 denotes the thermal expansion coefficients and the pyroelectric coefficient of the piezoelectric thin film, respectively.

Assume that the material properties of substrate vary with the temperature so weak that they can be treated as independent of temperature. Similarly, let subscript 2 denotes the physical quantity in substrate, and then the governing equations in the isotropic substrate are

$$\begin{aligned} \hat{c}_{44}u_2'' + (\hat{\rho}c^2 - \hat{c}_{11})k^2u_2 + (\hat{c}_{11} - \hat{c}_{44})ikw_2' = 0 \\ \hat{c}_{11}w_2'' + (\hat{\rho}c^2 - \hat{c}_{44})k^2w_2 + (\hat{c}_{11} - \hat{c}_{44})iku_2' = 0 \\ \varphi_2'' - k^2\varphi_2 = 0 \end{aligned} \tag{7}$$

Finally, the electrical potential φ_0 in the air above the cover layer should satisfy the Laplace equation, i.e., for $z < -h_0$:

$$\varphi_0'' - k^2\varphi = 0 \tag{8}$$

Additionally, the following boundary conditions, interface continuity conditions and attenuation conditions should be satisfied.

Traction free boundary condition: $\sigma_z = 0$ and $\tau_{xz} = 0$ at $z = -h$;

Electrical boundary conditions: electrical short $\varphi_1 = 0$ or electrical open $\varphi_1 = \varphi$ and $D_{z1} = D_{z0}$ at $z = -h$;

The continuity conditions: $w_1 = w_2$, $u_1 = u_2$, $\tau_{xz1} = \tau_{xz2}$, $\sigma_{z1} = \sigma_{z2}$, $\varphi_1 = \varphi_2$ and $D_{z1} = D_{z2}$ at $z = 0$.

The attenuation conditions: for $z \to \infty$, $u_2, w_2, \varphi_2 \to 0$ and for $z \to -\infty$, $\varphi_0 \to 0$.

Solution of the Problem

For piezoelectric thin film in the graded temperature field, the material parameters are functions of depth. Suppose that the material parameters and thermal stress can be expressed as power series forms:

$$M_m = \sum_{n=0}^{\infty} \alpha_n^m \left(\frac{z}{-h}\right)^n \tag{9}$$

where $M_m, m = 1\sim 11$ represents $c_{11}, c_{13}, c_{33}, c_{44}, e_{15}, e_{33}, e_{31}, \varepsilon_{33}, \varepsilon_{11}, \rho$, and σ_{11}^0, respectively, and the coefficients α_n^m can be determined by the relations between the functions and their Taylor expansions. In view of the material grading relations given by (9), the solutions of Eqs. (5) can be assumed to take similar forms:

$$u_1 = \sum_{n=0}^{\infty} s_n \left(\frac{z}{-h}\right)^n, \quad w_1 = i\sum_{n=0}^{\infty} t_n \left(\frac{z}{-h}\right)^n, \quad \varphi_1 = i\sum_{n=0}^{\infty} r_n \left(\frac{z}{-h}\right)^n \tag{10}$$

Substituting (9) and (10) into Eqs. (5) and equating the coefficients of $(-z/h)^n$, we obtain recursive equations for s_n, t_n, and r_n as:

$$\sum_{i=0}^{n} F_{1i} = 0, \quad \sum_{i=0}^{n} F_{2i} = 0, \quad \sum_{i=0}^{n} F_{3i} = 0 \tag{11}$$

where

$$\begin{aligned} F_{1i} = {} & (n-i+1)\big[(n-i+2)\alpha_i^4 s_{n-i+2} + (i+1)\alpha_{i+1}^4 s_{n-i+1} + kh\big(\alpha_i^2 + \alpha_i^4\big)t_{n-i+1} \\ & + kh\big(\alpha_i^5 + \alpha_i^7\big)r_{n-i+1}\big] + (kh)^2\big(\alpha_i^{10}c^2 - \alpha_i^1 - \alpha_i^{11}\big)s_{n-i} \\ & + kh(i+1)\big[\alpha_{i+1}^4 t_{n-i+1} + \alpha_{i+1}^5 r_{n-i+1}\big] \end{aligned}$$

$$F_{2i} = (n-i+1)\big[(n-i+2)\big(\alpha_i^3 t_{n-i+2} + \alpha_i^6 r_{n-i+2}\big) + (i+1)\big(\alpha_{i+1}^3 t_{n-i+1} + \alpha_{i+1}^6 r_{n-i+1}\big) - kh\big(\alpha_i^2 + \alpha_i^4\big) s_{n-i+1}\big] + (kh)^2\big[\big(\alpha_i^{10} c^2 - \alpha_i^4 - \alpha_i^{11}\big) t_{n-i} - \alpha_i^5 r_{n-i}\big] - (kh)(i+1)\alpha_{i+1}^2 s_{n-i}$$

$$F_{3i} = (n-i+1)\big[(n-i+2)\big(\alpha_i^8 r_{n-i+2} - \alpha_i^6 t_{n-i+2}\big) + (i+1)\big(\alpha_{i+1}^8 r_{n-i+1} + \alpha_{i+1}^6 t_{n-i+1}\big) + kh\big(\alpha_i^7 + \alpha_i^5\big) s_{n-i+1}\big] + (kh)^2\big(\alpha_i^9 r_{n-i} + \alpha_i^5 t_{n-i}\big) + (kh)(i+1)\alpha_{i+1}^7 s_{n-i}$$

To decouple the undetermined coefficients, the following matrix is constructed.

$$(s_{0j}, s_{1j}, t_{0j}, t_{1j}, r_{0j}, r_{1j}) = I \tag{12}$$

where $j = 1{\sim}6$ and I is a 6×6 unit matrix. Accordingly, Eq. (10) can be rewritten as:

$$u_1 = \sum_{j=1}^{4} C_j \sum_{n=0}^{\infty} s_{nj} \left(\frac{z}{-h}\right)^n, \quad w_1 = i \sum_{j=1}^{4} C_j \sum_{n=0}^{\infty} t_{nj} \left(\frac{z}{-h}\right)^n,$$
$$\varphi_1 = i \sum_{j=1}^{4} C_j \sum_{n=0}^{\infty} t_{nj} \left(\frac{z}{-h}\right)^n \tag{13}$$

where the constants C_j $(j = 1{\sim}6)$ are to be determined. For $n = 0$ and 1, both s_{nj}, t_{nj}, and r_{nj} are defined by (12); for other values of n, s_{nj} and t_{nj} can be determined by solving Eqs. (11), while in these equations, s_n, t_n, and r_n are replaced by s_{nj}, t_{nj}, and r_{nj}.

Equations (7) are constant coefficient ordinary differential equations. Considering the attenuation conditions, the mechanical displacements and the electric potential functions in the substrate can be solved as follows.

$$u_2 = [C_7 \exp(-k\hat{b}_1 z) + \hat{b}_2 C_8 \exp(-k\hat{b}_2 z)]$$
$$w_2 = i[\hat{b}_1 C_7 \exp(-k\hat{b}_1 z) + C_8 \exp(-k\hat{b}_2 z)] \tag{14}$$
$$\varphi_2 = iC_9 \exp(-kz)$$

where $C_j (j = 7{\sim}9)$ are the undetermined constants, $\hat{b}_1 = \sqrt{1 - c^2/\hat{c}_d^2}$, $\hat{b}_2 = \sqrt{1 - c^2/\hat{c}_{sh}^2}$, $\hat{c}_d = \sqrt{\hat{c}_{11}/\hat{\rho}}$, and $\hat{c}_{sh} = \sqrt{\hat{c}_{44}/\hat{\rho}}$.

Furthermore, the electric potential in the air solved by Eq. (8) can be expressed as

$$\varphi_0 = C_{10} \exp(kz) \tag{15}$$

where C_{10} is an undetermined constant.

Substituting Eqs. (13), (14), and (15) into the boundary conditions and continuity conditions for the electrical open case, we then obtain a set of homogeneous linear algebraic equations for determining C_i $(i = 1{\sim}10)$. The sufficient and necessary condition for the existence of a non-trivial solution is that the determinant of the coefficient matrix vanishes. For the electrical open case, there exists:

$$\left|Q_{ij}^o\right| = 0, i, j = 1{\sim}10 \tag{16}$$

where

$$Q_{11}^{o}=1,\ Q_{17}^{o}=1,\ Q_{18}^{o}=b_2,\ Q_{23}^{o}=1,\ Q_{27}^{o}=b_1,\ Q_{28}^{o}=1,\ Q_{35}^{o}=1,\ Q_{39}^{o}=1,$$
$$Q_{41}^{o}=c_{13}^{0}kh,\ Q_{44}^{o}=-c_{33}^{0},\ Q_{46}^{o}=-e_{33}^{0},\ Q_{47}^{o}=\left(\hat{c}_{11}-2\hat{c}_{44}-\hat{c}_{11}\hat{b}_1^2\right)kh,$$
$$Q_{48}=2\hat{c}_{44}\hat{b}_2kh,\ Q_{52}^{o}=c_{44}^{0},\ Q_{53}^{o}=-c_{44}^{0}kh,\ Q_{55}^{o}=-e_{15}^{0}kh,\ Q_{57}=2\hat{c}_{44}\hat{b}_1kh,$$
$$Q_{68}=-\hat{c}_{44}\left(1+\hat{b}_2^2\right)kh,\ Q_{61}^{o}=e_{13}^{0}kh,\ Q_{64}^{o}=-e_{33}^{0},\ Q_{66}^{o}=-\varepsilon_{33}^{0},\ Q_{69}^{o}=\hat{\varepsilon}_{33}kh,$$
$$Q_{7m}^{o}=\sum_{l=0}^{n}c_{13}^{h}s_{lm}kh-c_{33}^{h}(l+1)t_{(l+1)m}-e_{33}^{h}(l+1)r_{(l+1)m},\ m=1\sim 6,$$
$$Q_{8m}^{o}=\sum_{l=0}^{n}c_{44}^{h}(l+1)s_{(l+1)m}-c_{44}^{h}t_{lm}kh-e_{33}^{h}(l+1)r_{(l+1)m},\ m=1\sim 6,$$
$$Q_{9m}^{o}=\sum_{l=0}^{n}r_{lm},\ m=1\sim 6,\ Q_{910}^{o}=1,$$
$$Q_{10m}^{o}=\sum_{l=0}^{n}e_{31}^{h}s_{lm}kh-e_{33}^{h}(l+1)t_{(l+1)m}+\varepsilon_{33}^{h}(l+1)r_{(l+1)m},\ m=1\sim 6,\ Q_{1010}^{o}=\varepsilon_0,$$

All the other terms are equal to zero and the superscript 0 and h denotes the bottom and upper surfaces of PVDF layer, respectively.

For the electrical short case, Eq. (15) and C_{10} is superfluous, thus the dispersion equation is:

$$\left|Q_{ij}^{sh}\right|=0 \tag{17}$$

where the coefficient matrix $[Q_{ij}^{sh}]$ is 9×9, with $Q_{ij}^{sh}=Q_{ij}^{o},\ \ i,j=1\sim 9$.

Numerical Results and Discussions

Summarizing from the published results [1–3], it can be assumed that the relations between the material parameters of the PVDF thin layer and temperature are linear. The material parameters are summarized in Table I,

Other material properties are as follows:

PVDF: thermal expansion coefficient: $a_{11}=2\times 10^{-4}$/K, $a_{33}=2.5\times 10^{-4}$/K, pyro-electric coefficient $p_3=4\times 10^{-3}\,\text{C/m}^2\text{K}$.

Silicon substrate: $E=112.4\,\text{GPa}$, $\nu=0.28$, $\rho=2329\,\text{kg/m}^3$, $a=2\times 10^{-8}$/K where E and ν are elastic modulus and Poisson ratio and the parameters in Eqs. (7) can be obtained. The phase velocity in the electrical open case is discussed in the numerical example.

Frequency Dispersion in the Uniform Temperature Field

Figure 2 shows the dispersion curves of surface wave of the layered structure in different uniform temperature field without the thermal stress. Due to the thermal properties of PVDF, the dispersion curves of generalized Rayleigh wave vary with temperature. For the first mode, the phase velocity equals to the velocity of Rayleigh waves $\hat{c}_R$ in substrate half space when $k\to 0$, while it decreases with kh increasing. It can be found that the phase velocity decreases rapidly at higher temperature. For the other modes, the phase velocity

Table 1
Material constants of PVDF dependence on temperature

Material constants	Elastic constants ($\times 10^{10}$N/m^2)					Piezoelectric constants (C/m^2)			Dielectric constants ($\times 10^{-10}$F/m)		Density (kg/m^3)
$T_0 = 20^\circ$C	C_{11}	C_{12}	C_{13}	C_{33}	C_{44}	e_{31}	e_{33}	e_{15}	ε_{11}	ε_{33}	ρ
	3.8	1.9	1.0	1.2	0.7	0.025	−0.027	0.0	0.655	0.673	1780
$T = T_0 + \Delta T$	$1 + l_1 \Delta T$					$1 + l_2 \Delta T$			$1 + l_3 \Delta T$		$1 + l_4 \Delta T$
$p(T)/p(T_0)$	$l_1 = -0.008$					$l_2 = 0$			$l_3 = 0.01$		$l_4 = -0.00025$

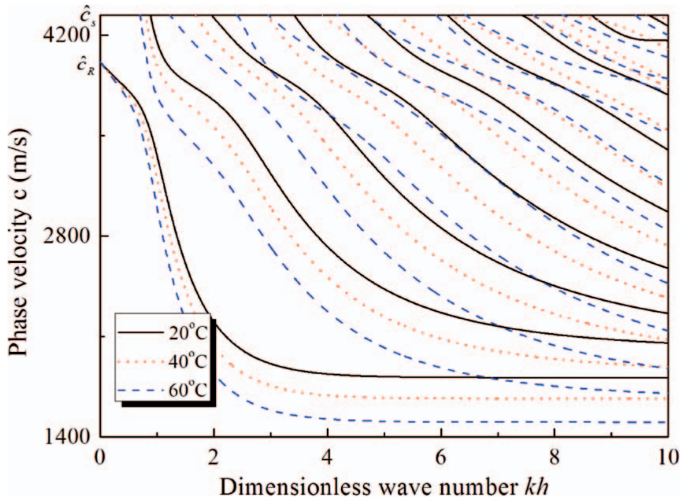


Figure 2. Dispersion curves of the surface wave in the PVDF layered structure at different temperatures. (See Color Plate I)

less than $\hat{c}_s$ (bulk shear velocity of substrate) also decreases with temperature. The results show that the mode number increases with temperature. For example, for the case when kh ranges from 0 to 10 as shown in Fig. 2, there exists nine modes at 20°C, eleven modes at 40°C, and twelve modes at 60°C. For different temperature, the difference of phase velocity in the first mode becomes more obvious when kh varies from 0 to 4.

Because the change of phase velocity looks obvious at $kh > 4$ for the first mode, we also discuss the change of phase velocity at $kh = 2\pi$ where the wavelength equals to the thickness of PVDF film, as shown in Fig. 3. We find that the phase velocity decreases almost linearly with temperature. The result gives us a theoretical guidance for the temperature compensation of the devices.

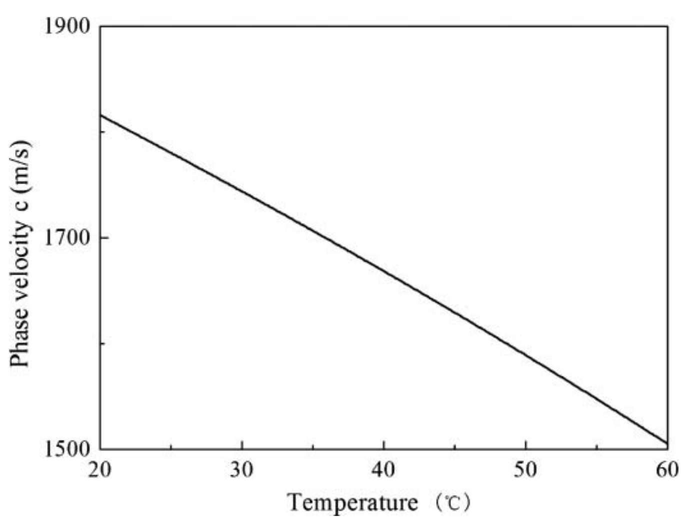


Figure 3. Phase velocity variation with temperature at $kh = 2\pi$ without considering thermal stress.

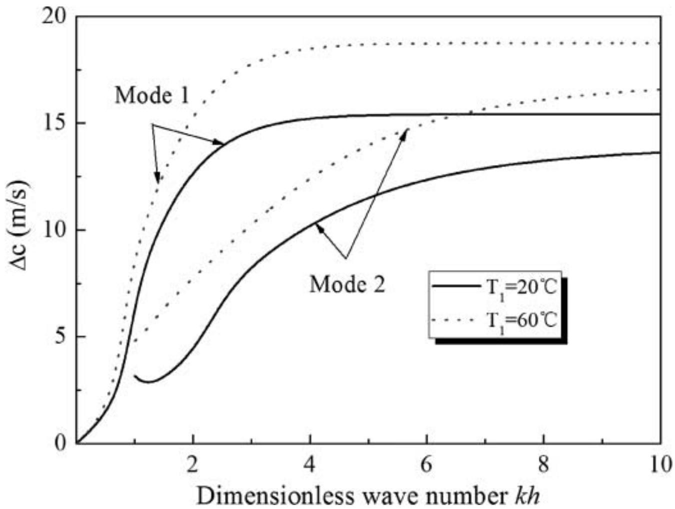


Figure 4. The variation of the phase velocity of the first two modes due to 100 Mpa prestress.

For the layered structure, due to the difference in thermal-elastic properties of each layer, the initial stress might exist in the cover thin film. Fig. 4 shows the difference of phase velocity under $\sigma_{11} = 100$ MPa in Eq. (5), where $\Delta c = c|_{\sigma_{11}^0=100Mpa} - c|_{\sigma_{11}^0=0}$. It is shown that the positive initial stress leads to the increase of the phase velocity. The variation in the higher temperature field is more obvious. The variation increases with the increase of dimensionless wavelength, while variation in the first mode becomes smooth when $kh > 3$.

However, for a certain structure, the initial stress must change with temperature. We select $T_r = 20°$C and $T_r = 60°$C and discuss the variation of phase velocity of the first mode at $T = 60°$C and $T = 20°$C, respectively, as shown in Fig. 5.

If the reference temperature is lower than the working temperature, the thermal stress is negative. The negative thermal stress leads to the decrease of the phase velocity. Conversely,

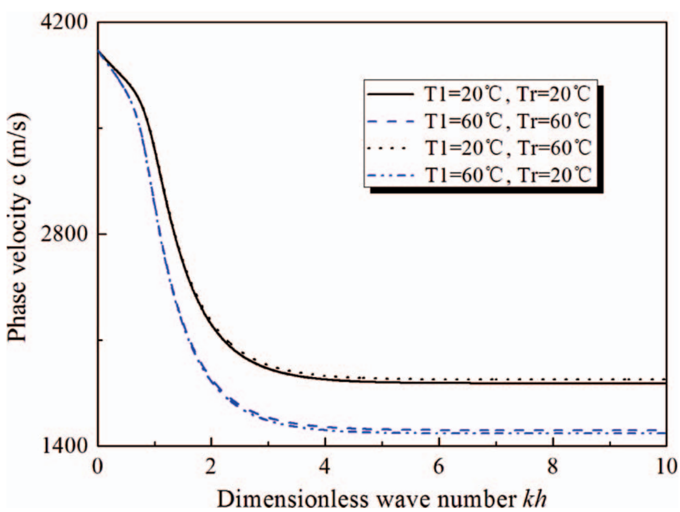


Figure 5. The phase velocity of the first mode for different reference temperatures. (See Color Plate II)

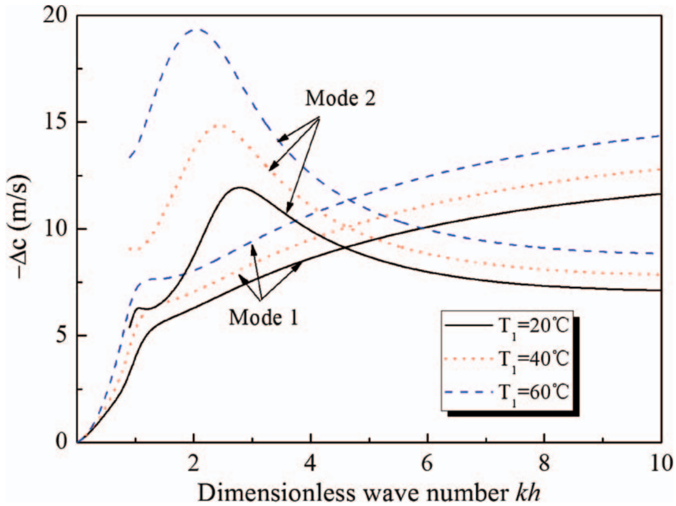


Figure 6. The variation of the phase velocity of the first two modes due to graded temperature. (See Color Plate III)

the phase velocity increases under positive thermal stress, namely, the reference temperature is higher than the working temperature. This result is useful in studying the temperature drift properties of the SAW devices.

Frequency Dispersion in the Graded Temperature Field

In engineering application, there might be temperature difference between the upper surface of the cover layer and the substrate. Figure 6 shows the variation of phase velocity Δc due to graded temperature field without considering the thermal stress, where $\Delta c = c|_{T2=T1+\Delta T} -$

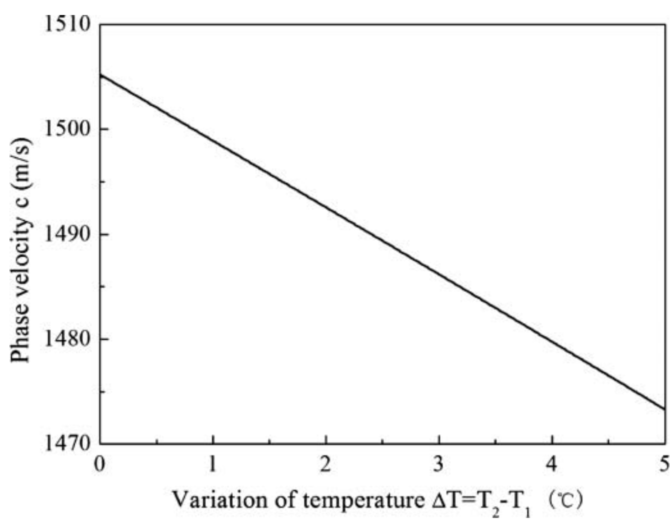
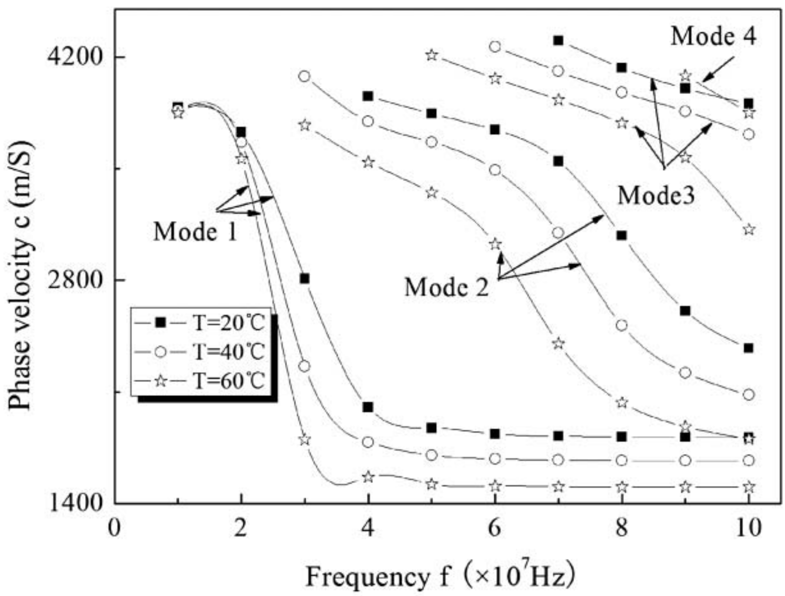
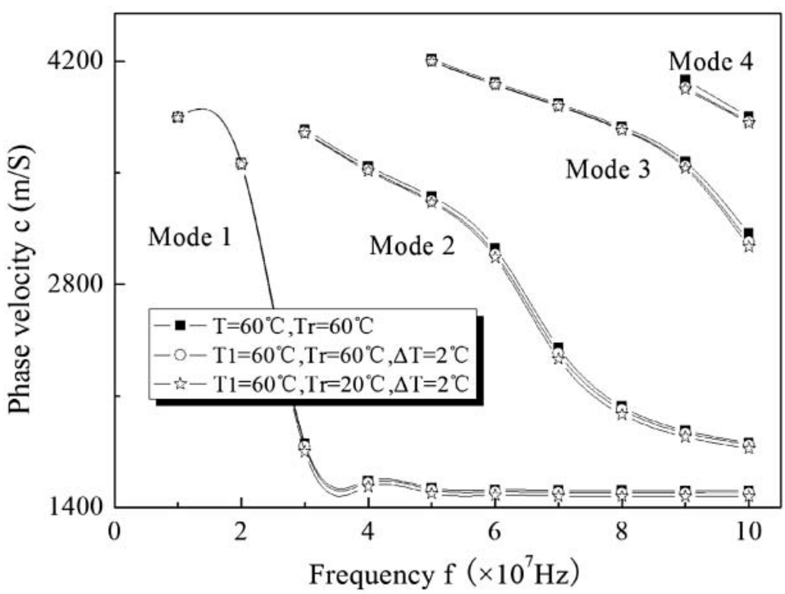


Figure 7. The influence of ΔT on the variation of the phase velocity.



(a) Phase velocity in uniform temperature with thermal stress omitted



(b) Phase velocity in graded temperature field

Figure 8. Phase velocity in some special cases.

$c|_{T2=T1}$ and $\Delta T = 2°C$. The value of Δc is minus means that if temperature in upper surface of PVDF is higher than that in substrate, it leads to the decrease of the phase velocity.

For a certain temperature gradient, the variation of phase velocity is more obvious. For the first mode, the larger the dimensionless wavelength is, the more sensitive the variation of phase velocity is. For the second mode, the variation of phase velocity is not monotone function of dimensionless wavelength, which reaches its maximum when *kh* is in the range of 2∼3. On the other hand, the temperature gradient should influence on the phase velocity. Figure 7 points out the relation between the variation of phase velocity in mode 1 and the temperature gradient ΔT at $T_1 = 60^{\circ}$C, $kh = 2\pi$. It can be seen again that the phase velocity decreases almost linearly with temperature when the wavelength equals to the thickness of PVDF film.

Discussions

From the numerical results given, we note that the material thermo-electro-elastic properties, thermal stress, and the temperature gradient affect the phase velocity of the surface wave propagating in the layered structure. To investigate the dominant factors, we list the phase velocity in some special cases in Fig. 8, where the frequency $f = \omega/2\pi$ is fixed and the thickness of PVDF film is assumed to be 20 μm.

If we only consider the material thermo-electro-elastic properties in uniform temperature field, namely, $\sigma_{11}^{0} = 0$, the phase velocity decreases obviously, and the mode number increases with the increase of temperature, the same as what we mentioned before. For example, there exist 2 modes at 20°C and 3 modes at 40°C and 60°C when the frequency equals to 30 MHz. Comparing the results in uniform temperature field and graded temperature field, we note that the effect of the temperature gradient is less than that of the uniform temperature field because the former only varies in a small range and the latter changes in a large range. Furthermore, the thermal stress, which depends on the reference temperature, also affects the phase velocity but its effect is not as obvious as that of the temperature field. We know that only material thermo-electro-elastic properties influence the propagation properties strongly, implies that the material thermo-electro-elastic properties are the dominant factors of the temperature properties of these devices, while the graded temperature and thermal stress are the subsidiary factors.

Conclusions

Effects of thermo-electro-elastic properties, thermal stress, and the temperature gradient on the surface wave propagating behaviors are discussed. Increase of temperature in the uniform temperature field, increase of temperature at the upper surface of the piezoelectric cover layer, and exert of a minus thermal stress can lead to the decrease of the phase velocity of the surface wave and the increase of the mode number. Thermo-electro-elastic properties are the dominant factors which influence the thermal properties of the SAW devices, while the thermal stress and the graded temperature field are the subsidiary factors. Results presented are of great importance in the applications of temperature compensation for SAW devices and for non-destructive test utilizing SAW effects.

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References

1. R. Singh, R. P. Tandon, R. D. P. Sinha, and S. Chandra, Low frequency ac conduction and dielectric relaxation in PVDF films. *ISAF '94, Proceedings of the Ninth IEEE International Symposium on Applications of Ferroelectrics*, 504–507 (1994).
2. H. Q. Zhu and J. D. Zhang, Measurement of the material complex constant and thermal properties of piezoelectric polymer PVDF. *Applied Acoustics (in Chinese)* **1**, 25–28 (1992).
3. W. N. Dos Santos, C. Y. Iguchi, and J. R. Gregorio, Thermal properties of poly (vinilidene fluoride) in the temperature range from 25 to 210°C. *Polym. Test.* **27**, 204–208 (2008).
4. J. S. Yang, Equations for small fields superposed on finite biasing fields in a thermoelectroelastic body. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **50**, 187–192 (2003).
5. J. Yang, Propagation of straight-crested waves in an electroelastic plate under biasing fields. *Acta Mech.* **196**, 113–122 (2008).
6. X. G. Tian and Y. P. Shen, Finite element analysis of thermoelastic behavior of piezoelectric structures under finite deformation. *Acta. Mech. Solida. Sin.* **15**, 312–322 (2002).
7. H. Liu, Z. B. Kuang, Z. M. Cai, T. J. Wang, and Z. K. Wang, Propagation of surface acoustic waves in prestressed anisotropic layered piezoelectric structures. *Acta. Mech. Solida. Sin.* **16**, 16–23 (2003).
8. H. Liu, Z. B. Kuang, and Z. M. Cai, Propagation of Bleustein-Gulyaev waves in a prestressed layered piezoelectric structure. *Ultrasonics* **41**, 397–405 (2003).
9. F. Jin, Z. K. Wang, and K. Kishimoto, The propagation behavior of Bleustein-Gulyaev waves in a pre-stressed piezoelectric layered structure. *Int. J. Nonlin. Sci. Num.* **4**, 125–138 (2003).
10. Z. H. Qian, F. Jin, K. Kishimoto, and T. J. Lu, Propagation behavior of love waves in a functionally graded half-space with initial stress. *Int. J. Solids. Struct.* **46**, 1354–1361 (2009).
11. X. S. Cao, F. Jin, and Z. K. Wang, On dispersion relations of Rayleigh waves in a functionally graded piezoelectric material (FGPM) half-space. *Acta Mech.* **200**, 247–261 (2008).