Chapter 6
Improving Piezoelectric Sensitivity

After the game, the king and the pawn go into the same box.
United we stand, divided we fall.

Proverbs

Abstract The piezoelectric sensitivity of the composite is described in terms of four types of the piezoelectric coefficients, d_{ij}^*, e_{ij}^*, g_{ij}^*, and h_{ij}^*. The role of each type of the piezoelectric coefficients and its merit in determining the PS in composites with various microgeometric features are discussed. Diagrams that link electric and mechanical fields and contain the four types of the piezoelectric coefficients are represented for the direct and converse piezoelectric effects. Examples of orders-of-magnitude of the aforementioned piezoelectric coefficients are given for modern composites based on single crystals. Some ways for improving the piezoelectric sensitivity of the composites are discussed.

6.1 Piezoelectric Coefficients and Ways to Improve Piezoelectric Sensitivity of Modern Composites

The monograph has described the role of the microgeometry and electromechanical properties of composites in forming their PS. As follows from (1.4) to (1.11) and results from Chaps. 2 to 5, the PS of a composite can be described in terms of four types of the piezoelectric coefficients, d_{ij}^*, e_{ij}^*, g_{ij}^*, and h_{ij}^*. The links between the variables from (1.4) to (1.11) by the direct and converse piezoelectric effect are shown in Figs. 6.1 and 6.2, respectively. Hereby we highlight the role of each type of the piezoelectric coefficients and its merit in determining the PS in composites with various microgeometric features. The schematics shown in Figs. 6.1 and 6.2 are mnemonic and suggest the sign that precedes the piezoelectric coefficient from (1.4) to (1.11). If we go from the left side to right side along the upper (or ascending) line, the piezoelectric coefficient is to be taken with a plus. In contrast, in a case of the

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bottom (or descending) line, the piezoelectric coefficient is to be taken with a minus. For instance, the electric displacement D_k as a result of an external mechanical strain ξ_l at the direct piezoelectric effect is determined in (1.5), and the piezoelectric coefficient e_{kl} that links D_k and ξ_l is taken with a plus (see also the line that links ξ and D in Fig. 6.1). The second item in the right part of (1.5) shows the link between the electric field E_r and electric displacement D_k, and at $E_r = 0$ we have the piezoelectric effect that is described by the first item in the right part of (1.5), and the PS is characterised by e_{kl}. The electric field E_k produced due to a mechanical stress σ_l is described in terms of (1.9), and the piezoelectric coefficient g_{kl} in this case is taken with a minus (see also the line that links σ and E in Fig. 6.1). The minus sign in (1.9) originates from experimental results on polarisation charges [1] at surfaces of a piezoelectric sample: these charges generate the electric field $\boldsymbol{E}$ in the direction that is opposite to the piezoelectric polarisation $\boldsymbol{P}$ of the sample. Alternatively, we deal with the electric field $\boldsymbol{E}$ of a large dipole whose orientation is caused by the stress field at the direct piezoelectric effect. The minus sign in (1.4) is concerned with the converse piezoelectric effect at constant mechanical strain, i.e., in the deformed sample. In this case, the piezoelectric coefficient e_{fp} from (1.4) enables us to find a mechanical stress σ that leads to a non-deformed state of the sample ($\xi = 0$) in the external electric field $\boldsymbol{E}$. This $\boldsymbol{E}$ field differs from that generated by the polarisation charges at the direct piezoelectric effect in the previous case. It is obvious that the PS associated with the piezoelectric coefficient e_{kl} differs from the PS described in terms of d_{kl} or g_{kl}.

Figure 6.2 suggests that a similar link between E and ξ is described in terms of the piezoelectric coefficient d at the converse piezoelectric effect. The different signs of the piezoelectric coefficients for mechanical strain ξ and stress σ (see the right part of Fig. 6.2) can be concerned with elastic properties of an anisotropic piezoelectric medium. For example, the strain ξ_p at the converse piezoelectric effect is described by one of the items, d_{fp} E_f from (1.6) or g_{fp} D_f from (1.9), and the link between E_f and D_f is described by the dielectric permittivity, see (1.5). The

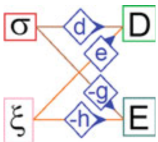

Fig. 6.1 Inter-relations between mechanical (left side) and electric (right side) variables at the direct piezoelectric effect. E, electric filed; D, electric displacement; ξ, mechanical strain; σ, mechanical stress

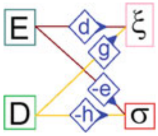

Fig. 6.2 Inter-relations between electric (left side) and mechanical (right side) variables at the converse piezoelectric effect. E, electric filed; D, electric displacement; ξ, mechanical strain; σ, mechanical stress

remaining items in the right parts of (1.6) and (1.8) are the strains $s^E_{pq}\sigma_q$ and $s^D_{pq}\sigma_q$ which depend on the elastic properties. The similar character of the strains $s^E_{pq}\sigma_q$ and $s^D_{pq}\sigma_q$ is consistent with the similar character of the piezoelectric strains $d_{fp}\ E_f$ and $g_{fp}\ D_f$. The mechanical stress σ_p caused by the converse piezoelectric effect is associated with the items $(-e_{fp}E_f)$ and $(-h_{fp}D_f)$ from (1.4) to (1.10), respectively. In this case, the link between E_f and D_f is described in terms of (1.9). The contributions $c^E_{pq}\xi_q$ and $c^D_{pq}\xi_q$ to σ_p from (1.4) to (1.10), respectively, are similar because of the similar anisotropy of elastic moduli c^E_{pq} and c^D_{pq} of the piezoelectric medium. This is consistent with the similar anisotropy of the piezoelectric coefficients e_{fp} and h_{fp}.

The PS caused by the piezoelectric coefficient e_{kl} differs from the PS described in terms of the piezoelectric coefficient h_{kl}. In fact, the PS of each piezoelectric can be described in terms of four types of the piezoelectric coefficients shown in (1.4)–(1.11) and Figs. 6.1 and 6.2. As is known from studies on effective piezoelectric properties of composites (see, for instance, work [2]), the piezoelectric coefficients d_{kl} are widely used in averaging procedures applied to various connectivity patterns. The piezoelectric coefficients e_{kl} are also involved in averaging procedures [3] to find the effective properties of composites, however the number of such procedures described in the literature is relatively small. As follows from the literature, the piezoelectric coefficients g_{kl} and h_{kl} are seldom involved in similar averaging procedures. One of the reasons is concerned with the full sets of electromechanical constants that contain g_{kl} and h_{kl}, see (1.8)–(1.11). In these sets, the elastic properties are represented by the elastic compliances s^D_{pq} and elastic moduli c^D_{pq}, see (1.8) and (1.10), respectively. However the elastic compliances s^E_{pq} or elastic moduli c^E_{pq} are often found by means of experimental methods because conditions for measurements of s^D_{pq} and c^D_{pq} in piezoelectric media [1, 4, 5] are complicated in comparison to conditions for measurements of s^E_{pq} and c^E_{pq}.

Our present study enables us to state that the piezoelectric coefficients d_{ij}^* and g_{ij}^* are widely used to describe the PS of composites, and improving its PS is of value for many sensor, actuator, transducer, and other piezotechnical applications. The piezoelectric coefficients g_{ij}^* are of importance mainly at the direct piezoelectric effect. The piezoelectric coefficients e_{ij}^* and h_{ij}^* are less often desired for piezotechnical applications [4–6]. This is accounted for by changes in the mechanical strain ξ_{ik} and electric displacement D_f [1] which can be detected in experiments on piezoelectrics [4, 5] with a lesser accuracy than changes in the mechanical stress σ_{ik} or electric field E_f.

Factors that promote an improvement of the PS of the studied composites can be divided into the following groups:

(i) physical (concerned with electromechanical properties of components and with boundary conditions and distributions of internal electric and mechanical fields in composite materials),
(ii) microgeometric (the arrangement of the main piezoelectric component in the form of long rods, layers or inclusions along the poling direction to facilitate the poling of the composite, and formation of composite structures in the matrix component to achieve a large piezoelectric anisotropy), and
(iii) technological (providing favourable poling conditions, perfect bonding at interfaces, use of piezoelectric layers, rods, inclusions, etc. with almost equal properties, and formation of uniform porous structures in matrices of composite samples).

The methods to improve the PS of the composite with the appointed connectivity pattern and components are inseparably linked to the items (i)–(iii) and some, but not all, piezoelectric coefficients of the main component of the composite. The microgeometric factors from item (ii) are to be taken into account at forming the specific piezoelectric coefficient of the composite (d_{ij}^*, e_{ij}^*, g_{ij}^*, or h_{ij}^*). Since the maxima of the piezoelectric coefficients are found in various volume-fraction ranges even for a composite with a constant connectivity (see results in Chaps. 2–5), we should carefully consider both the microgeometry and properties of components. To the best of our knowledge, it is impossible to improve all the four types of the piezoelectric coefficients simultaneously because of features of the electromechanical coupling, microgeometry, piezoelectric anisotropy [2, 3, 6, 7], and other characteristics of the piezo-active composites.

Our results show that the modern composites based on the high-performance domain-engineered SCs are promising due to an improvement of piezoelectric coefficients, for instance, d_{3j}^* and g_{3j}^* or d_{3j}^* and e_{3j}^*. In Table 6.1 we show typical orders-of-magnitude of the piezoelectric coefficients of composites based on the [001]-poled domain-engineered SCs. There are examples of the high PS of the lead-free composites that are to be developed in the nearest future. Undoubtedly, an important stimulus to improve the PS of the composite is linked to applications [4–6] that are based on the effective properties and related parameters.

Table 6.1 Examples of improved PS of composites based on [001]-poled domain-engineered SCs

Connectivity	Main SC component	Remaining components	Piezoelectric coefficients, orders-of-magnitude	Section
2–2	PMN–0.33PT	Araldite	$d_{3j}^* \sim 10^3$ pC/N	2.1.2
		Elastomer	$g_{3j}^* \sim 10^3$ mV m/N	3.1
		Auxetic PE	$d_{33}^* \sim 10^3$ pC/N at $d_{31}^* \to 0$ or $d_{33}^* \sim 10^3$ pC/N at $d_{32}^* \to 0$	2.1.2
	PMN–0.28PT	Araldite	$d_{33}^* \sim 10^3$ pC/N, $d_{31}^* \sim 10^2$ pC/N and $d_{32}^* \sim 10^2$ pC/N	2.1.2
		Elastomer	$g_{3j}^* \sim 10^3$ mV m/N	3.1
		Auxetic PE	$d_{33}^* \sim 10^3$ pC/N at $d_{31}^* \to 0$ or $d_{33}^* \sim 10^2$ pC/N at $d_{32}^* \to 0$	2.1.2
	KNNTL:Mn	Araldite, polyurethane or elastomer	$g_{33}^* \sim 10^3$ mV m/N, $g_{31}^* \sim (10^2–10^3)$ mV m/N and $g_{32}^* \sim (10^2–10^3)$ mV m/N	3.1
		Araldite	$h_{33}^* \sim 10^{10}$ V/m, $h_{31}^* \sim 10^9$ V/m and $h_{32}^* \sim 10^9$ V/m	5.1
		Auxetic PE	$g_{33}^* \sim 10^3$ mV m/N at $g_{32}^* \to 0$ or $g_{33}^* \sim 10^2$ mV m/N at $g_{31}^* \to 0$	3.1
2–0–2	PMN–0.33PT	Modified $PbTiO_3$ FC and PE	$d_{33}^* \sim 10^3$ pC/N, $d_{31}^* \sim 10^2$ pC/N and $d_{32}^* \sim 10^3$ pC/N $d_h^* \sim (10^2–10^3)$ pC/N	2.7
	KNNTL:Mn	LBO SC and PE	$g_{33}^* \sim 10^3$ mV m/N, $g_{31}^* \sim 10^2$ mV m/N and $g_{32}^* \sim 10^2$ mV m/N	3.1
1–3	PMN–0.33PT	Araldite, polyurethane or elastomer	$d_{3j}^* \sim 10^3$ pC/N	2.2.2
		Auxetic PE	$d_{33}^* \sim 10^3$ pC/N at $d_{31}^* \to 0$	2.2.2
	KNNTL:Mn	Araldite, polyurethane or elastomer	$d_{3j}^* \sim 10^2$ pC/N	2.2.2
			$g_{33}^* \sim 10^3$ mV m/N and $g_{31}^* \sim (10^2 –10^3)$ mV m/N	3.2
			$h_{33}^* \sim 10^{10}$ V/m and $h_{31}^* \sim 10^8$ V/m	5.2
		Auxetic PE	$d_{33}^* \sim 10^2$ pC/N at $d_{31}^* \to 0$	2.2.2
			$g_{33}^* \sim 10^2$ mV m/N at $g_{31}^* \to 0$	3.2
			$h_{33}^* \sim 10^{10}$ V/m and $h_{31}^* \sim 10^8$ V/m	5.2

(continued)

Table 6.1 (continued)

Connectivity	Main SC component	Remaining components	Piezoelectric coefficients, orders-of-magnitude	Section
1–2–2	PMN–0.33PT	Araldite and PE	$d_{33}^* \sim 10^3$ pC/N and $d_{31}^* \sim 10^2$ pC/N	2.2.3
		Araldite and polyurethane	$e_{33}^* \sim 10^1$ C/m^2 and $e_{31}^* \sim (10^{-2}–10^{-1})$ C/m^2	4.2
1–3–0	PMN–0.33PT	Porous polyurethane	$d_{33}^* \sim 10^3$ pC/N and $d_{31}^* \sim (10^1–10^3)$ pC/N	2.2.4
		Porous araldite	$d_h^* \sim (10^2–10^3)$ pC/N	2.7
	PMN–0.28PT	Porous araldite	$e_{33}^* \sim 10^1$ C/m^2	4.2
1–0–3	PMN–0.33PT	Modified $PbTiO_3$ FC and PE	$d_{33}^* \sim 10^3$ pC/N and $d_{31}^* \sim (10^1–10^3)$ pC/N	2.2.5
	KNNTL:Mn	Modified $PbTiO_3$ FC and PE	$d_{33}^* \sim 10^2$ pC/N and $d_{31}^* \sim (10^1–10^2)$ pC/N	2.2.5
			$g_{33}^* \sim (10^2–10^3)$ mV m/N and $g_{31}^* \sim (10^2–10^3)$ mV m/N	3.2
0–3	KNNTL:Mn	PVDF	$g_{33}^* \sim 10^2$ mV m/N, $g_{31}^* \sim (10^1–10^2)$ mV m/N	3.4
	PMN–0.33PT	Modified $PbTiO_3$ FC	$e_{33}^* \sim 10^1$ C/m^2 and $e_{31}^* \sim (10^{-2}–10^0)$ C/m^2	4.3
		PMN–0.35PT FC	$e_{33}^* \sim 10^1$ C/m^2 and $e_{31}^* \sim 10^0$ C/m^2	4.3
0–3–0	PMN–0.33PT	Porous araldite	$g_{33}^* \sim 10^2$ mV m/N and $g_{31}^* \sim (10^1–10^2)$ mV m/N	3.4

To finish the present monograph, we would like to quote work [8]: “As niche applications become more prevalent in the future, composites and displacement-amplifying techniques and materials will proliferate in a continuing effort to widen the force–displacement envelope of performance. These devices, too, will become smarter and smarter as the applications demand”.

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