Appendix A
List of Abbreviations

CMOS Complementary metal-oxide-semiconductor
DC Direct electric current
ECF Electromechanical coupling factor
FC Ferroelectric ceramic
GA Genetic algorithm
KNN-T \((K_{0.562}Na_{0.438})(Nb_{0.768}Ta_{0.232})O_3\)
KNN-TL \(Li_x(K_{0.501}Na_{0.499})_{1-x}[(Nb_{0.660}Ta_{0.340})O_3\]
MEMS Micro-electro-mechanical system
MOGA Genetic algorithm for multiple objectives
PCR Piezoelectric ceramic from Rostov-on-Don (Russia)
PE-\(n\) Auxetic polyethylene, nine modifications \((n = 1, 2, \ldots, 9)\)
PIN-\(x-y\) Relaxor-ferroelectric solid solutions of \(xPb(In_{1/2}Nb_{1/2})O_3 - yPb\cdot(Mg_{1/3}Nb_{2/3})O_3 - (1-x-y)PbTiO_3\)
PMN-\(x\)PT Relaxor-ferroelectric solid solutions of \((1-x)Pb(Mg_{1/3}Nb_{2/3})O_3 - xPbTiO_3\)
PVDF Polyvinylidene fluoride
PZN-\(y\)PT Relaxor-ferroelectric solid solutions of \((1-x)Pb(Zn_{1/3}Nb_{2/3})O_3 - xPbTiO_3\)
PZT Piezoelectric ceramic of the Pb(Zr, Ti)O_3 type
SC Single crystal
SIMP Solid isotropic material with penalisation
SOMA Self-organisation migrating algorithm
Appendix B
Electromechanical Constants of Components

To analyse the energy-harvesting characteristics of piezoelectric materials and to predict the effective properties and related parameters of a piezo-active composite, we use full sets of electromechanical constants of components. A systematisation of data on the components is given in Table B.1.

Table B.1 Electromechanical constants of components at room temperature

<table>
<thead>
<tr>
<th>Component</th>
<th>Composition</th>
<th>Set of constants</th>
<th>Table number</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC</td>
<td>PMN–0.33PTa</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>PMN–0.30PTd</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>PMN–0.28PTa</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>PMN–0.28PTa,b,c</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>PMN–0.42PTb</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
<td>2.15</td>
</tr>
<tr>
<td></td>
<td>PZN–0.08PTa</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
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</tr>
<tr>
<td></td>
<td>PZN–0.07PTa</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>PZN–0.045PTa</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>PIN–0.24–0.49b</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>KNN–Ta</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
<td>2.12</td>
</tr>
<tr>
<td></td>
<td>KNN–TLa</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
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<tr>
<td></td>
<td>BaTiO3b</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
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<tr>
<td></td>
<td>BaTiO3d</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>PbTiO3b</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
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</tr>
<tr>
<td></td>
<td>α-ZnS</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
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</tr>
<tr>
<td></td>
<td>CdS</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
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</tr>
<tr>
<td></td>
<td>CdSe</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
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<tr>
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<td>ZnO</td>
<td>$s_{ab}^E$, $d_{ij}$ and $e_{pp}^\sigma$</td>
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<table>
<thead>
<tr>
<th>Component</th>
<th>Composition</th>
<th>Set of constants</th>
<th>Table number</th>
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<tr>
<td>FC</td>
<td>Compositions with perovskite-type structure (BaTiO₃, PZT, PCR, ZTS, modified PbTiO₃, PMN-0.35PT, etc.)</td>
<td>$s_{ab}$, $d_{ij}$ and $\varepsilon_{pp}$</td>
<td>1.2</td>
</tr>
<tr>
<td>Modified PbTiO₃</td>
<td></td>
<td>$s_{ab}$, $d_{ij}$ and $\varepsilon_{pp}$</td>
<td>1.2</td>
</tr>
<tr>
<td>(Pbₐ₀.₈₀Ca₀.₂₀)TiO₃</td>
<td></td>
<td>$s_{ab}$, $d_{ij}$ and $\varepsilon_{pp}$</td>
<td>3.10</td>
</tr>
<tr>
<td>(Pb₀₇₅Ca₀₂₅)TiO₃</td>
<td></td>
<td>$s_{ab}$, $d_{ij}$ and $\varepsilon_{pp}$</td>
<td>3.10</td>
</tr>
<tr>
<td>Polymer</td>
<td>Araldite</td>
<td>$s_{ab}$ and $\varepsilon_{pp}$</td>
<td>2.7</td>
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<td></td>
<td>Polyurethane</td>
<td>$s_{ab}$ and $\varepsilon_{pp}$</td>
<td>2.7</td>
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<tr>
<td></td>
<td>Elastomer</td>
<td>$s_{ab}$ and $\varepsilon_{pp}$</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Auxetic polyethylene</td>
<td>$s_{ab}$ and $\varepsilon_{pp}$</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>PVDF</td>
<td>$s_{ab}$, $d_{ij}$ and $\varepsilon_{pp}$</td>
<td>3.5</td>
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</tbody>
</table>

*a[001]-poled domain-engineered SC
*bSingle-domain SC
*c[011]-poled domain-engineered SC
*dPolydomain SC, calculated values
*ePiezo-passive material
*fCalculated values
Appendix C
Performance of Poled Ferroelectric Ceramics

The characteristics of poled FCs are often associated with their electromechanical constants, and full sets of such constants [1–6] are of interest to determine the potential applications of FCs [7–10]. In addition to the full sets of electromechanical constants, we also use combinations of them to describe the electromechanical coupling, piezoelectric anisotropy, figures of merit, electromechanical transformations, etc. The combinations of electromechanical constants are also of value to characterise piezo-active composites based on either FCs or relaxor-ferroelectric SCs. For instance, (2.6)–(2.8), (3.14), (3.15), (3.17), and (3.18), contain effective parameters that are related to the effective electromechanical properties of the piezo-active composites. Table C.1 contains the parameters that strongly depend on the piezoelectric properties of FCs and, therefore, should be taken into account when selecting FC materials for piezoelectric energy-harvesting, transducer and hydroacoustic applications.

Table C.1  Factors of the anisotropy of piezoelectric coefficients $\xi_{d_{3j}}$, ratios of electromechanical constants $e_{33}l_{33}^E$ (in $10^{-10}$ C/N), $d_{33}l_{33}^E$ and $d_{31}l_{11}^E$ (in C/m$^2$), ratios of coefficients of electromechanical transformation $r_N$, and ratios of specific acoustic powers $r_{pow}$ at the longitudinal and transversal piezoelectric responses of perovskite-type FCs at room temperature

<table>
<thead>
<tr>
<th>FC</th>
<th>$\xi_{d_{3j}}$</th>
<th>$e_{33}l_{33}^E$</th>
<th>$d_{33}l_{33}^E$</th>
<th>$d_{31}l_{11}^E$</th>
<th>$r_N$</th>
<th>$r_{pow}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaTiO$_3$ (I)</td>
<td>-2.42</td>
<td>1.15</td>
<td>21.4</td>
<td>-9.24</td>
<td>-2.32</td>
<td>6.12</td>
</tr>
<tr>
<td>BaTiO$_3$ (II)</td>
<td>-2.44</td>
<td>1.20</td>
<td>20.0</td>
<td>-8.57</td>
<td>-2.34</td>
<td>6.22</td>
</tr>
<tr>
<td>(Ba$<em>{0.917}$Ca$</em>{0.083}$)TiO$_3$</td>
<td>-2.53</td>
<td>0.900</td>
<td>15.4</td>
<td>-6.42</td>
<td>-2.40</td>
<td>6.75</td>
</tr>
<tr>
<td>TBK-3</td>
<td>-2.48</td>
<td>0.817</td>
<td>14.4</td>
<td>-5.90</td>
<td>-2.41</td>
<td>6.26</td>
</tr>
<tr>
<td>TBKS</td>
<td>-3.27</td>
<td>0.543</td>
<td>8.06</td>
<td>-2.52</td>
<td>-3.19</td>
<td>11.0</td>
</tr>
<tr>
<td>NBS-1</td>
<td>-2.68</td>
<td>1.48</td>
<td>16.5</td>
<td>-6.85</td>
<td>-2.41</td>
<td>7.99</td>
</tr>
<tr>
<td>ZTS-19</td>
<td>-2.44</td>
<td>1.60</td>
<td>18.1</td>
<td>-8.34</td>
<td>-2.17</td>
<td>6.70</td>
</tr>
<tr>
<td>ZTS-24</td>
<td>-2.28</td>
<td>0.806</td>
<td>15.2</td>
<td>-7.96</td>
<td>-1.91</td>
<td>6.21</td>
</tr>
<tr>
<td>ZTSNV-1</td>
<td>-2.09</td>
<td>1.68</td>
<td>21.3</td>
<td>-11.0</td>
<td>-1.93</td>
<td>4.74</td>
</tr>
<tr>
<td>PZT-4</td>
<td>-2.35</td>
<td>1.31</td>
<td>18.7</td>
<td>-10.1</td>
<td>-1.85</td>
<td>7.00</td>
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</table>

(continued)
### Table C.1 (continued)

<table>
<thead>
<tr>
<th>FC</th>
<th>(\zeta d_j)</th>
<th>(e_{33} k_{33}^E)</th>
<th>(d_{33} k_{33}^E)</th>
<th>(d_{31} s_{11}^E)</th>
<th>(r_N)</th>
<th>(r_{pow})</th>
</tr>
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<tbody>
<tr>
<td>PZT-5</td>
<td>−2.19</td>
<td>1.42</td>
<td>19.9</td>
<td>−10.4</td>
<td>−1.91</td>
<td>5.50</td>
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<tr>
<td>PZT-5H</td>
<td>−2.46</td>
<td>1.99</td>
<td>27.2</td>
<td>−11.9</td>
<td>−2.29</td>
<td>6.50</td>
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<tr>
<td>PZT-7A</td>
<td>−2.51</td>
<td>0.769</td>
<td>10.9</td>
<td>−5.63</td>
<td>−1.93</td>
<td>8.18</td>
</tr>
<tr>
<td>Navy Type VI</td>
<td>−2.16</td>
<td>1.99</td>
<td>28.6</td>
<td>−16.5</td>
<td>−1.73</td>
<td>5.81</td>
</tr>
<tr>
<td>PZ 27</td>
<td>−2.41</td>
<td>1.38</td>
<td>18.6</td>
<td>−10.3</td>
<td>−1.81</td>
<td>7.73</td>
</tr>
<tr>
<td>PZ 34</td>
<td>−15.1</td>
<td>0.540</td>
<td>4.55</td>
<td>−0.508</td>
<td>−8.96</td>
<td>3.84</td>
</tr>
<tr>
<td>PCR-1, hp</td>
<td>−2.32</td>
<td>0.835</td>
<td>13.8</td>
<td>−7.60</td>
<td>−1.82</td>
<td>6.85</td>
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<tr>
<td>PCR-7, hp</td>
<td>−2.18</td>
<td>2.34</td>
<td>35.3</td>
<td>−16.3</td>
<td>−2.17</td>
<td>4.78</td>
</tr>
<tr>
<td>PCR-7M, hp</td>
<td>−2.17</td>
<td>2.49</td>
<td>38.8</td>
<td>−20.0</td>
<td>−1.94</td>
<td>5.27</td>
</tr>
<tr>
<td>PCR-8, hp</td>
<td>−2.23</td>
<td>1.17</td>
<td>18.6</td>
<td>−10.4</td>
<td>−1.79</td>
<td>6.21</td>
</tr>
<tr>
<td>PCR-8, ct</td>
<td>−2.24</td>
<td>1.54</td>
<td>19.3</td>
<td>−9.40</td>
<td>−2.05</td>
<td>5.47</td>
</tr>
<tr>
<td>PCR-13, ct</td>
<td>−2.15</td>
<td>1.04</td>
<td>12.4</td>
<td>−6.25</td>
<td>−1.98</td>
<td>5.02</td>
</tr>
<tr>
<td>PCR-21, hp</td>
<td>−2.29</td>
<td>1.37</td>
<td>19.8</td>
<td>−9.24</td>
<td>−2.14</td>
<td>5.60</td>
</tr>
<tr>
<td>PCR-63, hp</td>
<td>−2.33</td>
<td>1.05</td>
<td>14.3</td>
<td>−6.12</td>
<td>−2.33</td>
<td>5.43</td>
</tr>
<tr>
<td>PCR-73, hp</td>
<td>−2.26</td>
<td>2.03</td>
<td>36.6</td>
<td>−21.2</td>
<td>−1.72</td>
<td>6.71</td>
</tr>
<tr>
<td>Pb(Zr0.54Ti0.46)O3</td>
<td>−2.49</td>
<td>0.796</td>
<td>10.3</td>
<td>−5.19</td>
<td>−1.95</td>
<td>7.91</td>
</tr>
<tr>
<td>Pb(Zr0.52Ti0.48)O3</td>
<td>−2.39</td>
<td>1.12</td>
<td>13.0</td>
<td>−6.78</td>
<td>−1.93</td>
<td>7.08</td>
</tr>
<tr>
<td>(Pb0.94Sr0.06)(Ti0.47Zr0.53)O3</td>
<td>−2.35</td>
<td>1.31</td>
<td>18.6</td>
<td>−10.0</td>
<td>−1.86</td>
<td>6.96</td>
</tr>
<tr>
<td>Modified PbTiO3 (I)</td>
<td>−10.6</td>
<td>0.511</td>
<td>6.63</td>
<td>−0.666</td>
<td>−9.95</td>
<td>120</td>
</tr>
<tr>
<td>(Pb0.9623La0.025)(Ti0.99Mn0.01)O3</td>
<td>−11.4</td>
<td>0.447</td>
<td>6.19</td>
<td>−0.576</td>
<td>−10.8</td>
<td>138</td>
</tr>
<tr>
<td>(Pb0.85Nd0.10)(Ti0.99 Mn0.01)O3</td>
<td>−10.5</td>
<td>0.535</td>
<td>7.81</td>
<td>−0.792</td>
<td>−9.88</td>
<td>117</td>
</tr>
<tr>
<td>(Pb0.855Nd0.11)(Ti0.94 Mn0.02In0.04)O3</td>
<td>−9.05</td>
<td>0.531</td>
<td>7.94</td>
<td>−0.945</td>
<td>−8.40</td>
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</tr>
<tr>
<td>PMN-0.35PT</td>
<td>−2.03</td>
<td>0.968</td>
<td>18.4</td>
<td>−10.1</td>
<td>−1.82</td>
<td>4.59</td>
</tr>
</tbody>
</table>

**Notes**

1. Parameters shown in the 2nd–7th columns were calculated using the full sets of electromechanical constants of poled FCs [1–6] at room temperature.
2. FC samples of the PCR type have been manufactured using either the conventional technology (ct) or hot pressing (hp).
3. The anisotropy of the piezoelectric coefficients \(d_j\) is characterised by \(\zeta d_j\), and this factor is taken into account [6, 8] to provide the effective transformation of energy along the poling axis \(OX\).
4. The \(e_{33}/s_{33}^E\) ratio is of value when selecting piezoelectric components to promote large values of squared figures of merit \(Q^E_k\) and \(Q^E_{33}\) of the 1–3-type composites (see Sect. 3.3.1).
5. The \(d_{33} k_{33}^E\) and \(d_{31} s_{11}^E\) ratios are to be taken into account when selecting piezoelectric materials for transducers. Coefficients of electromechanical transformation \(N_j\) linearly depend [7] on \(d_{3j}/s_{ij}^E\) and the geometric size of the parallelepiped (piezoelectric transducer element), where \(j = 1\) and \(3\) (see Sect. 3.7).
6. According to (3.17), the ratio of the specific acoustic powers [7] related to the longitudinal and transversal piezoelectric responses of the poled FC sample is represented as \(r_{pow} = (\zeta d_j)^2 s_{33}^E s_{11}^E\), i.e., depends on the piezoelectric and elastic anisotropy factors (see Sect. 3.7).
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