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REVIEW ARTICLE

Piezoelectric devices for ocean energy: a brief survey

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Abstract Piezoelectric materials directly convert strain energy into electric energy and vice versa and are commonly used in sensing and actuating applications. They have been employed in mediums frequently undergoing vibrations, allowing harnessing of power at a small scale. Ideas of using the piezoelectric effect as a power take-off mechanism for ocean energy emerged in the 1970s and are still at a developing stage. This article overviews recent development on the application of the piezoelectric processes to the ocean field and provides a building block for future research work of ocean engineers who are interested in such possibilities. A brief discussion on the selection of the piezoelectric materials for different ocean-engineering applications is presented. Significant research projects on ocean-energy extraction through the use of these materials are then described and discussed with special scrutiny on the viability of proposed designs and their experimental or numerical validation. Various harvesting techniques in an ocean environment are categorized and compared. The challenges ahead and the outlook for success in this area are outlined.

Keywords Piezoelectricity · Ocean engineering · Energy harvesting · Piezoelectric materials · Energy scavenging · Waves · Electromechanical coupling

1 Introduction

Many large-scale technologies have been developed over the years to capture renewable energy. These include wind turbines, photovoltaic power plants, geothermal power stations, among others. Still, as shown in Fig. 1,[1] in the USA as an example, only 9 % of the energy consumption in 2012 was attributed to renewable sources (Energy Worldnet 2013). Further, while many of the land-based technologies are maturing, those involved in the marine environment are just emerging. The low percentage in renewable-energy sources is associated with the high cost of extraction technologies and the unavailability of the resources during all times of the year. Extensive research is continually being conducted to enhance the feasibility and usage of these large-scale efforts. In fact, it is expected that by 2040 (Institute For Energy Research 2012), the share of the fossil fuels will decrease by 4 % along with a 4 % increase in renewable-energy shares.

Besides the large-scale energy sources, smaller-scale energy sources that would end up being wasted and unused are abundant. They are in the surroundings, such as vibrating machines, shock absorbers, and flow turbulence (Priya 2007). Such ambient energy, if captured and transformed into useful electrical energy, can power nearby electronic equipment. Although such power sources provide only a small amount of power, they can be vital in many applications, particularly those involving self-powered devices.

Among the different types of available ambient-energy sources explained in (Nechibvute et al. 2012), vibrational energy is the most attractive one because of its abundance and easy accessibility. It is kinetic energy that can be converted into electric energy using piezoelectric, electromagnetic, or electrostatic principles. Piezoelectric transducers, being smaller and lighter, are usually favored over the other

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[1] Note from reference: sum of components in Fig. 1 may not equal 100 % because of independent rounding. Source of component values: US Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1 (April 2013), preliminary 2012 data.

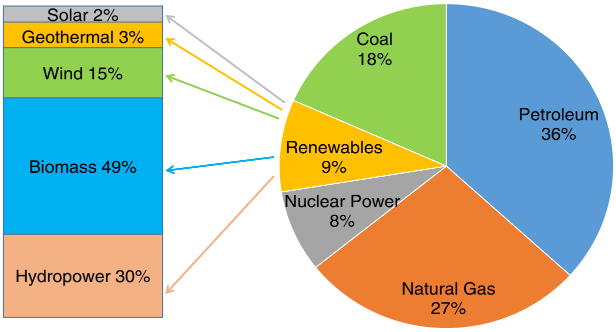

Fig. 1 Energy consumption of USA in 2012 (Energy Worldnet 2013)

means. They also have energy generation density that is three times higher (Priya 2007). Also, piezoelectric materials can be easily integrated into a system, having no moving parts, thus not requiring frequent maintenance. Further, they have the favorable ability of directly converting applied strain energy into electric energy, and producing power at voltage levels that can be easily conditioned (Nechibvute et al. 2012).

Power harvesting through piezoelectricity (Erturk and Inman 2011) is emerging as one of the most important ambient-energy scavenging methods. The scavenging devices are traditionally embedded in a vibrating host structure that can endure substantial excitations. Recent research, however, is directed to media that have prevalent fluctuations themselves. Priya et al. (2005), for example, developed a piezoelectric windmill to extract the energy from wind currents. The mill consists of piezoelectric bimorph cantilevers that are arranged along its circumference. The design makes use of the camshaft gear mechanism to induce oscillations on the piezoelectric patches, and hence generates power.[2]

In this survey article, we review the harvesting of ocean energy using piezoelectric materials. The questions of interest are:
What are the applications? What are the viable designs? What is the order of magnitude of the power output? What are the challenges in such developments?

Section 2 gives a short summary of the main concepts of piezoelectricity that are needed for the later sections. The piezoelectric effect is explained along with the important properties of piezoelectric materials, and the linear constitutive relations of piezoelectricity. Section 3 is devoted to the modeling of piezoelectric generators and to the power extraction techniques. Section 4 presents a comparison between the two most commonly used piezoelectric materials in the ocean field. In Sect. 5, the major accomplishments in ocean-energy extraction using piezoelectric means are categorized and described. Comparisons of these extraction techniques are made in Sect. 6, followed by concluding remarks on the prospects of this area. Because of space limitations, the review is not meant to be exhaustive, but more of selective highlights of a growing area.

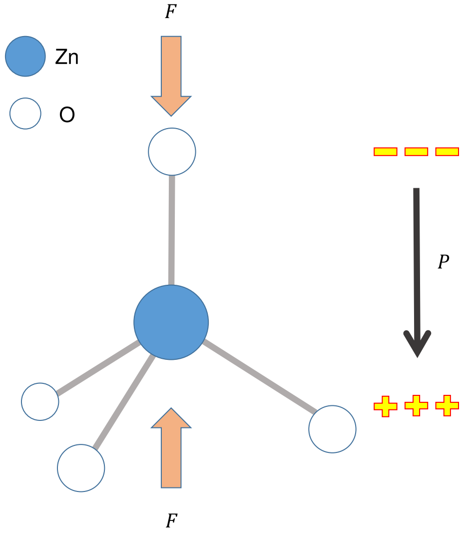

Fig. 2 Formation of a dipole moment P in Zincite (Safari and Akdogan 2008)

2 Physics of piezoelectricity

2.1 Piezoelectric effect

When a piezoelectric material is stressed, its atomic structure changes causing the formation of a dipole moment,[3] which results in a voltage difference across the material. This is called the direct piezoelectric effect, first discovered by Curie and Curie (1880). Shortly, Lippmann deduced that the same material can also undergo a process called the converse piezoelectric effect, where the material deforms when electrically polarized[4] (Cady 1964). Figure 2 illustrates the formation of a dipole moment in the piezoelectric material Zincite, where the legs of the tetrahedral spread upon the application of a compressive force F. This leads to the movement of the Zn ion closer to the three-O base, which results in the electric polarization P shown (Safari and Akdogan 2008). Also, upon the application of an electric field,[5] the material will contract or elongate depending on the direction of the field.

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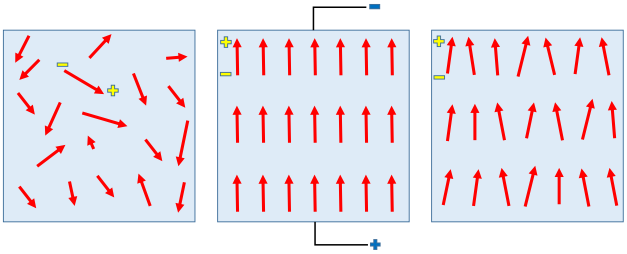
[2] Analysis of the performance of the piezoelectric windmill can be found in (Priya 2005). Using 10 piezoelectric bimorph transducers of the size $60 \times 20 \times 0.5$ mm^3, a power of 7.5 mW is generated at a wind speed of 10 mph across a matching load resistor of 6.7 kΩ.

[3] A dipole moment μ forms when two oppositely electrically charged particles of charge q are separated by a distance d. It is equal to $\mu = qd$.

[4] Electric polarization refers to the volumetric density of dipole moments (University of Cambridge 2007). It is induced by the application of an external electric field to insulators or dielectric materials. Unit: Coulomb/m^2.

[5] Unit: N/Coulomb.



Random Orientation of Polar Domains

Application of Electric Field

Remanent Polarization

Fig. 3 Poling process

Below a specific transformation temperature called 'The Curie Temperature T_c', some piezoelectric materials exhibit relative displacements between their atoms, which leads to the existence of permanent dipole moments within their crystal structures. These piezoelectric materials are called pyroelectrics. If such spontaneous polarization can be reversed by an external electric field, the crystal is called ferroelectric.

Synthetic piezoelectric materials such as ferroelectric ceramics with a much improved piezoelectric response are manufactured by numerous companies nowadays for specific actuating or sensing applications. Below T_c, the manufactured ferroelectric ceramics consist of randomly oriented crystals each having a certain dipole moment orientation. If a mechanical stress is applied to the ceramic, some domains will experience an increase in their dipole moments while others will experience a decrease. Overall, there is no net increase in polarization, which will make the ceramic piezoelectrically inactive. However, these ceramics can be made piezoelectrically active through the process of poling, where a constant electric field is applied to "force" all the dipole moments to align in one direction. After the poling treatment, the element gains a permanent polarization called the remanent polarization. This way, the ceramic will have one polarization direction along which a voltage develops upon an applied stress. The poling process of piezoelectric ceramics is shown in Fig. 3. Electrodes are usually installed on the faces that are perpendicular to the polarization direction. In Fig. 3, for example, electrodes would be connected to the two horizontal faces because the polarization is in the vertical direction.

The piezoelectric effect in a poled ceramic is illustrated in Fig. 4. When the ceramic is compressed, the dipole moment will decrease, which will generate a voltage of the same polarity as the poling voltage. On the other hand, if tension is applied, a voltage opposite to that of the poling voltage will be generated. Hence, it is obvious that if a periodic tension/compression cycle is applied, an AC voltage will be generated. Regarding the converse effect, if a voltage having the same polarity as the poling voltage is applied, the element will lengthen, while reversing the voltage will shorten the element (APC 2011).

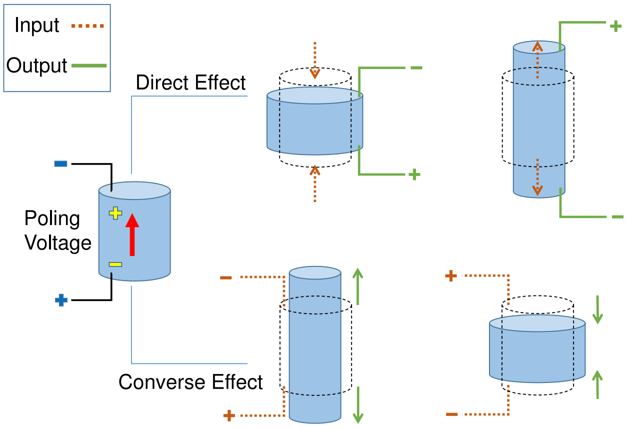


Fig. 4 Direct and converse effects in piezoelectric ceramic

2.2 Linear constitutive equations and electromechanical coupling

The fundamental piezoelectric equations involve different types of quantities: electric field and polarization, which are vectors, elastic stress and strain which are second-order tensors and the piezoelectric coefficients which relate the two. Many theories were formulated to describe the relations between the stress T, the strain S, the polarization P, and the electric field E. In 1949, however, the Institute of Radio Engineers gave preference to the use of the electric displacement[6] D of a dielectric as a variable, rather than the polarization P (Cady 1964).

There are multiple forms of piezoelectric equations (Standards Committee of the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society 1987). The choice of a specific equation depends on the geometrical, mechanical and electrical circumstances, the boundary conditions, and the electrode arrangement. The form that is mostly used in ocean-engineering applications will be presented first:

$$\sum_{i}^{6} s_{hi}^{E} T_i + \sum_{m}^{3} d_{mh} E_m = S_h \tag{1}$$

$$\sum_{k}^{3} \epsilon_{mk}^{T} E_k + \sum_{h}^{6} d_{mh} T_h = D_m \tag{2}$$

where s_{hi}^{E} are the elastic compliances[7] at constant electric field and ϵ_{mk}^{T} are the dielectric permittivities[8] at constant stress. d_{mh} are the piezoelectric strain coefficients.[9] They

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[6] It is related to the electric field and polarization by $D = \epsilon_0 E + P$ where ϵ_0 is the vacuum permittivity constant and is equal to $8.8541878176 \times 10^{-12}$ Farad/m (Mehta 2009). Unit: Coulomb/m^2.

[7] It is the strain generated per unit stress. Unit: m^2/N.

[8] It is the measure of the resistance that is encountered when forming an electric field in a medium. Unit: Farad/m.

[9] Unit: m/V.

represent the strain in the h-direction caused by an electric field applied in the m-direction. Conversely, they also represent the electrical displacement created in the m-direction by a stress applied in the h-direction.

Equation (1) represents the converse piezoelectric effect. The strain is expressed as the sum of a term associated with stress and another associated with an electric field. Note that, the equation reduces to Hook's law for anisotropic materials for the case of $E = 0$. Equation (2) represents the direct piezoelectric effect. The first term is the contribution from an electric field E towards the electric displacement, while the second term is the contribution from stress. In the case where there is no stress, this equation reduces to the known relationship between the electric field and electric displacement.

The subscripts h and i in the elastic compliance s^E_{hi} denote the directions of strain and stress, respectively. Similarly, m and k in the dielectric permittivity ϵ^T_{mk} represent the directions of the electric displacement and the electric field, respectively. As to the important piezoelectric coefficients d_{mh}, m indicates the field direction, while h represents the strain direction. Unlike the elastic compliances and the dielectric permittivities, d_{mh} is different from d_{hm}. For example, if d_{12} of a certain piezoelectric material is different from zero, then an electric polarization in the x direction[10] is associated with a normal stress in the y direction. However, if d_{21} is not zero, then an electric polarization in the y direction is associated with a normal stress in the x direction. For a more detailed understanding of the definitions of constants, the reader is referred to (Cady 1964).

Another form of piezoelectric equations that is sometimes employed expresses the stress T and the electric displacement D in terms of the strain S and the electric field E.

$$\sum_{i}^{6} c^E_{hi} S_i - \sum_{m}^{3} e_{mh} E_m = T_h \tag{3}$$

$$\sum_{k}^{3} \epsilon^S_{mk} E_k + \sum_{h}^{6} e_{mh} S_h = D_m \tag{4}$$

where c^E_{hi} are the elastic coefficients[11] at constant electric field and ϵ^S_{mk} are the dielectric permittivities at constant strain. e_{mh} are the piezoelectric stress coefficients[12] and they represent the electric displacement created in the m-direction by a given strain in the h-direction. They also represent the stress in the h-direction caused by an applied electric field in the m-direction. The meaning of the subscripts of the piezoelectric stress coefficients e_{mh} is similar to that of the piezoelectric strain coefficients d_{mh} explained earlier.

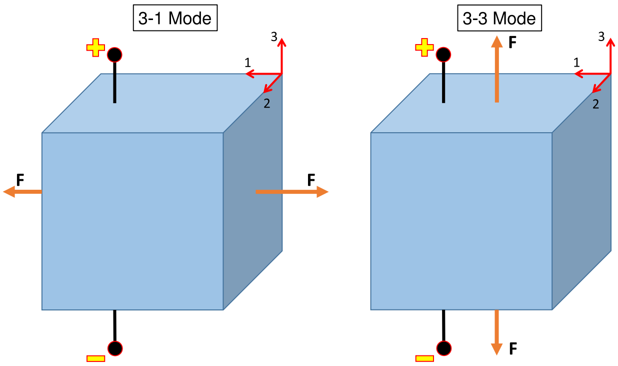

Fig. 5 3-1 and 3-3 coupling modes

As mentioned in Sect. 2.1, piezoelectric materials are usually manufactured through a process called poling so that their piezoelectric response favors certain direction. As will be seen later in Sect. 5, all of the piezoelectric materials used for ocean-energy extraction rely on either one of the two coupling modes shown in Fig. 5. In 3-1 coupling mode, the stress is applied in a perpendicular direction to that of poling. For the 3-3 coupling mode, however, the applied stress and the poling of the piezoelectric material have the same direction (Cook-Chennault et al. 2008). Hence, the two piezoelectric coefficients d_{31} and d_{33} are of particular importance in the current discussion.

The case of the 3-1 coupling mode will be explained briefly and an important parameter regarding the energy extraction efficiency will be derived. Restricting the mechanical and electrical quantities to the 1 and 3 directions, respectively, Eqs. (1) and (2) reduce to:

$$S_1 = s^E_{11} T_1 + d_{31} E_3$$
$$D_3 = \epsilon^T_{33} E_3 + d_{31} T_1$$

The two equations above can be combined together by eliminating E_3, to get:

$$S_1 = s^E_{11} \left(1 - K^2_{31}\right) T_1 + \frac{d_{31}}{\epsilon^T_{33}} D_3, \text{ with } K^2_{31} = \frac{d^2_{31}}{\epsilon^T_{33} s^E_{11}} \tag{5}$$

In a similar manner, a factor K_{33} for the 3-3 coupling mode can be derived:

$$K^2_{33} = \frac{d^2_{33}}{\epsilon^T_{33} s^E_{33}} \tag{6}$$

In general, K_{ij} is called the electromechanical coupling coefficient[13] and it represents the effectiveness with which piezoelectric elements convert energy between the mechanical and

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[10] As usual, x, y and z directions correspond to 1, 2 and 3, respectively.

[11] Unit: N/m^2.

[12] Unit: Coulomb/m^2.

[13] It is sometimes referred to as the piezoelectric coupling coefficient.

electrical states (APC 2011). K_{ij} can thus be interpreted as:

$$K_{ij}^2 = \frac{\text{mechanical energy stored}}{\text{electrical energy applied}} \text{ or, } \\ = \frac{\text{electrical energy stored}}{\text{mechanical energy applied}} \quad (7)$$

As it is the case with piezoelectric coefficients, the subscripts in K_{ij} denote the relative directions of electrical and mechanical quantities. For example, K_{31} in Eq. (5) of a piezoelectric material applies when a mechanical energy input in the 1-direction is converted and stored as electrical energy along the 3-direction, or when an electrical energy input in the 3-direction is converted and stored as mechanical energy along the 1-direction. A high value of the electromechanical coefficient is desirable since it leads to a high energy conversion efficiency. In fact, it is often regarded by many as a measure of the conversion efficiency, but one has to bear in mind that this coupling coefficient does not account for dielectric and mechanical losses which should be included in efficiency computations. The unconverted energy is not necessarily lost as heat and can be recovered in many cases. The true definition of the conversion efficiency is the ratio of the converted *useful* energy to the total energy input to the piezoelectric harvester.

Developing a general equation that governs the conversion efficiency of piezoelectric power harvesting devices is a tedious process because of the many different factors that affect the power generation process of these harvesters. The chosen material, electrode pattern, stress direction, poling direction, force application, and natural frequency all vary among the multiple harvester designs. These parameters can be altered to increase the conversion efficiency and the generated power from piezoelectric devices. This has been the subject of multiple research studies. For example, Umeda et al. (1996, 1997) studied the relationship between the conversion efficiency and piezoelectric properties of a device experiencing impact induced vibrations. Goldfarb and Jones (1999) investigated the effect of the operating frequency on the conversion efficiency of stack actuators fabricated from bulk piezoelectric materials. Sodano et al. (2005) compared the efficiencies of three different piezoelectric materials when excited at resonance. Richards et al. (2004) presented a general approach to determine the dependence of the conversion efficiency of a piezoelectric generator on its electromechanical coefficient K with specific values of the subscripts implied, and mechanical quality factor Q_{M}. The quality factor, as shown in Eq. (8) is a dimensionless parameter that represents the ratio of the stored energy to the dissipated one per cycle of oscillation.

$$Q_{\text{M}} = 2\pi \frac{\text{Energy stored per cycle}}{\text{Energy dissipated per cycle}} \quad (8)$$

A higher Q_{M} means that energy is dissipated from the system at a lower rate than the stored energy. The efficiency η was given by the above authors as:

$$\eta = \frac{0.5\left(\frac{K^2}{1-K^2}\right)}{\frac{1}{Q_{\text{M}}} + 0.5\left(\frac{K^2}{1-K^2}\right)} \quad (9)$$

From Eq. (9), it is readily apparent that an increase in K or Q_{M} increases the efficiency of conversion. This form of efficiency is used in making material selection to optimize the power harvesting ability of the piezoelectric device. A summary of the main research projects focusing on the determination of the conversion efficiency through different piezoelectric configurations can be found in Anton and Sodano (2007).

For a deeper and better understanding of the origin and complete set of piezoelectric equations, the reader is referred to Tiersten (1969), Ikeda (1990), and Yang (2005).

3 Piezoelectric generators

This section briefly presents the basic modeling of piezoelectric generators and the electric systems used to extract and store the generated electrical energy.

3.1 Modeling of piezoelectric generators

A piezoelectric generator consists of a piezoelectric element coupled to a mechanical structure. It is usually modeled as a mass coupled to a damper, a spring and a piezoelectric structure, typically when operating around its resonance frequency and experiencing linear movement (Guyomar et al. 2005; Shu and Lien 2006). Figure 6 shows the model of a generator having one degree of freedom (*DOF*) given by Richards et al. (2004). If this model is installed in the ocean, the forces exerted by the passing waves will excite the system. The oscillations of the mass induce stresses and strains in the piezoelectric element, which lead to the generation of an electric voltage that can be extracted through electrical equipment connected to the electrodes.

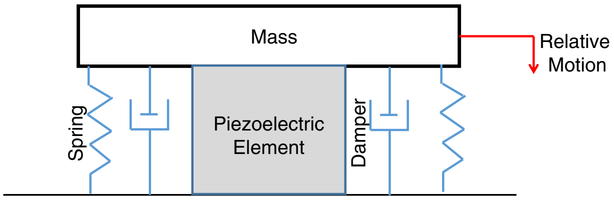

Fig. 6 Modeling of a piezoelectric power generator (1 *DOF*) (Richards et al. 2004)

Table 1 Conventional analogy between mechanical and electrical parts (Firestone 1933)

Mechanical element	Mass	Damping	Compliance
Electrical element	Inductance	Resistance	Capacitance

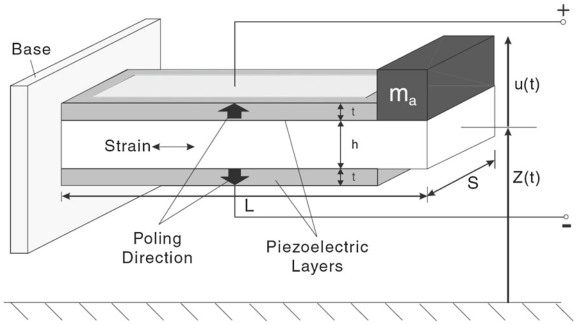

Fig. 7 A common piezoelectric-based power generator (Priya and Inman 2009) (reprinted by permission of Springer Science and Business Media)

When analyzing piezoelectric generators, it is more convenient to represent both the mechanical and electrical parts of the model with electric circuit elements. Table 1 shows the conventional analogy between mechanical and electrical parts.

A common generator is illustrated in Fig. 7,[14] where a cantilever beam, with a mass attached to its tip, will oscillate and develop bending stresses along the beam. If the piezoelectric parts are poled in the thickness direction, a voltage will be generated as shown in the figure. This was referred to as 3-1 coupling mode in Sect. 2.2.

The electrical-circuit analog representing such systems is shown in Fig. 8[15] (Roundy and Wright 2004). It is composed of a mechanical section, an electrical section, and a transformer. In the mechanical part of the circuit, the inductor, the resistor and the equivalent capacitor represent the equivalent mass of the system, the mechanical damping and the mechanical stiffness (or inverse of compliance), respectively. The stress generator σ_{in} represents the stresses induced by input vibrations and is analogous to a voltage source. The current in this part of the circuit is the strain rate in the material. In the electrical section, the capacitor represents the actual electrical capacitance of the piezoelectric bender. These two separate "domains" are coupled together through the transformer, which represents the piezoelectric coupling.

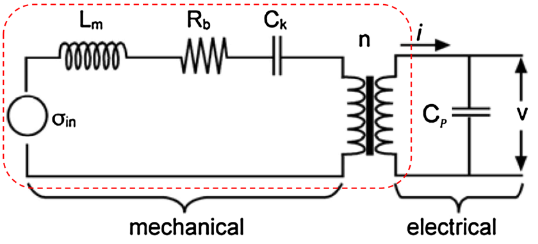

Fig. 8 Circuit representation of a piezoelectric generator (Roundy and Wright 2004) (© IOP Publishing. Reproduced by permission of IOP Publishing. All rights reserved)

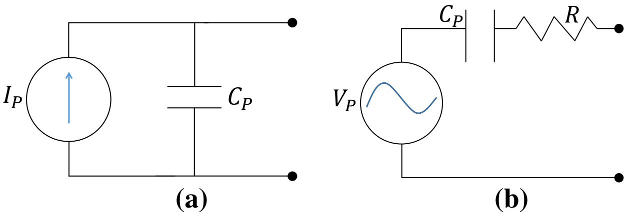

Fig. 9 Electrical AC equivalents of dashed part of Fig. 8: **a** a current source, **b** a voltage source

The number of turns of the transformer n is in terms of the piezoelectric strain coefficient d_{mh} of the material. When the values of the different material properties such as stiffness and density are known, the values of the circuit elements are also known. Hence, through applying the basic techniques of Kirchhoff's voltage and current rules, the output voltage of the piezoelectric material can be calculated when a certain stress σ_{in} is applied. Roundy and Wright (2004) can be referred to for more detailed analysis.

Alternatively, since the mechanical part of the system and the transformer are causing the generation of charges in the electrical part, they both can be lumped into a simple current source in parallel to the capacitor C_P as shown in Fig. 9a. This circuit can be transformed into a voltage source in series with the capacitor through Thevenin/Norton equivalent circuits. If the internal resistance of the piezoelectric material is to be taken into account below ultrasonic frequencies, a resistor should be added in series to the voltage source and the capacitor as shown in Fig. 9b (Park 2001).

3.2 Power extraction systems

If the electrical energy is to be collected and stored, an electrical load or power storage system has to be connected to the circuit. However, some processing is often needed before feeding the current to the load. Electronic equipment and power storage systems such as batteries require a direct current (DC). Since the piezoelectric generator, if behaving as a resonator, would act as a sinusoidal voltage source when implemented in the ocean, the generated AC current has to be processed and rectified for proper usage.

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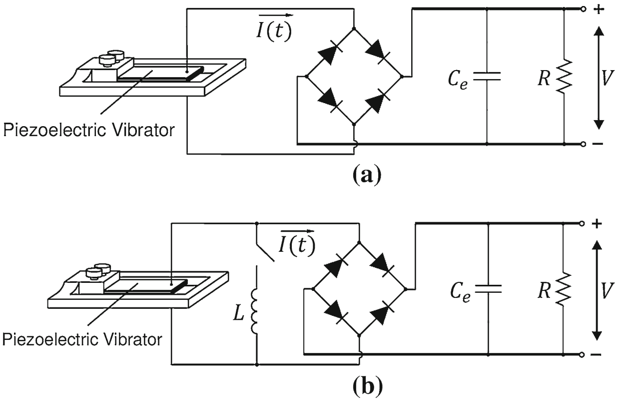
[14] This is Fig. 3.2, page 85 from Chapter 3 'Performance Evaluation of Vibration-Based Piezoelectric Energy Scavengers' written by Professor Yi-Chung Shu in the book Energy Harvesting Technologies by Priya and Inman (2009).

[15] Some labels were removed or changed from original figure to match notation of current work. Dashed line is added.



(a)

(b)

Fig. 10 Energy harvesting circuit: **a** *ST* (Priya and Inman 2009); **b** *SSHI* (Priya and Inman 2009) (reprinted by permission of Springer Science and Business Media)

The processing system consists of a full rectifier bridge made of four diodes, a filtering capacitor and a controller (Shu and Lien 2006). The AC signal passes through the rectifier bridge first where it is converted to a DC signal. The filtering capacitor usually has a large capacitance and it only contributes in smoothing out the DC voltage by eliminating the ripple voltage. Before storing the energy in a battery or supplying it directly to a load, the controller regulates the output voltage depending on the need of the specific application. This method is referred to as the 'Standard Technique' (*ST*) and is shown in Fig. 10a[16] where the controller and the battery are represented by a load resistor of value *R* (Priya and Inman 2009). Another technique of electrical energy harvesting with the name 'Synchronized Switch Harvesting on Inductor' (*SSHI*) that results in a significant increase in the electromechanical conversion capability of piezoelectric materials was developed by Guyomar et al. (2005). It is similar to *ST*, but has an extra inductor and switch added in parallel to the piezoelectric vibrator as shown in Fig. 10b.[17] The switch is only closed when the harvester is experiencing maximum vibrations. This way, the processing of the piezoelectric voltage will be synchronized with the extreme amplitudes of vibrations. A thorough comparison between the *ST* and *SSHI* techniques in both on and off resonance conditions of the piezoelectric harvester can be found in Guyomar et al. (2005), and Shu and Lien (2007).

The external circuit connected to the piezoelectric harvester has a great influence on the energy flow in the harvester. A detailed discussion concerning this effect can be found in Liang and Liao (2011). Also, Anton and Sodano (2007) presented a review of research studies that focus on improving the efficiency and power generation of piezoelectric harvesting devices through electric circuits and power storage media.

4 Materials for ocean-engineering applications

There are multiple piezoelectric materials of the form of small solid pieces or films that are being used in a variety of sensing and actuating applications. Among those materials, we list: Quartz, Berlinite, Gallium orthophosphate, Tourmaline, PZT, PVDF, and Barium Titanate (Piezomaterials 2007).

In this section, however, we restrict our attention to piezoelectric materials that are suitable for applications in the ocean. As will be seen later in Sect. 5, PZT and PVDF are the two most commonly used materials in ocean-energy extraction devices. PZT, called Lead Zirconate Titanate (Fujishima 2000) is a poled ferroelectric ceramic that has a perovskite structure. PVDF is a poled electroactive polymer with the name Polyvinylidene Fluoride and has an approximately 10 times larger piezoelectric response than most other polymers (Kawai 1969). The type of piezoelectric material selected for a power harvesting application has a tremendous influence on the performance of the harvester. PZT and PVDF have very different properties and one is usually favored over the other depending on the nature of the application at hand. Table 2 illustrates the most relevant properties of such materials. The values of these properties are obtained experimentally so they usually vary among different sources. The table numbers represent a rough average of the literature values.

As mentioned in Sect. 2.2, the 3-1 or 3-3 electromechanical coupling modes have been employed for all ocean-energy harvesting designs. The relevant parameters for these modes of coupling are included in the table for comparison. It is very clear from Table 2 that the coupling terms of PZT are greater than those of PVDF by a substantial amount, which means that PZT is capable of generating more power when subjected to the same stress as PVDF. However, PZT cannot withstand very high stresses given its low tensile strength,

Table 2 Properties of PZT and PVDF (Roundy 2003)

Property	PZT	PVDF	Units
d_{31}	320	20	10^{-12} m/V
k_{31}	0.44	0.11	CV/Nm
d_{33}	650	30	10^{-12} m/V
k_{33}	0.75	0.16	CV/Nm
Elastic modulus	5	0.3	10^{10} N/m^2
Tensile strength	2	5.2	10^7 N/m^2

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[16] This is Fig. 3.3(a), page 86 from Chapter 3 'Performance Evaluation of Vibration-Based Piezoelectric Energy Scavengers' written by Professor Yi-Chung Shu in the book Energy Harvesting Technologies by Priya and Inman (2009).

[17] This is Fig. 3.3(b), page 86 from Chapter 3 'Performance Evaluation of Vibration-Based Piezoelectric Energy Scavengers' written by Professor Yi-Chung Shu in the book Energy Harvesting Technologies by Priya and Inman (2009).

Table 3 Classification of piezoelectric ocean-energy harvesting methods

Energy source	Harvesting method	Material	Coupling mode
Water current	Flow-induced vibrations	PVDF	3-1 mode
Wave motion	Heaving and pitching bodies	PZT	3-3 mode
	Bodies fixed to ocean bottom	PVDF/PZT	3-1 mode
	Flexible membranes on ocean surface	PVDF	3-1 mode
Waves impact forces	Sloshing	PVDF	3-3 mode

unlike PVDF which exhibits a strength that is 2.6 times larger than that of PZT. The high tensile strength, low stiffness and high ductility of PVDF make it a very attractive material for applications where flexibility is needed. Although PZT has high piezoelectric coupling coefficients, its high stiffness and brittleness limit its implementation to few designs in the ocean-engineering field.

Every manufactured piezoelectric material has its own mechanical, thermal and electrical operational conditions that depend on its chemical composition. A thorough analysis of such topic is beyond the scope of this paper. Exceeding certain operational limits in general leads to the loss of some piezoelectric properties and sometimes to the total depolarization of the material. For example, piezoelectric ceramics are usually operated at temperatures well below their Curie Temperature, and are usually exposed to electric fields that do not exceed 0.5–1 kV/mm (Morgan Advanced Materials 2009).

Extensive research is continuously being conducted to improve the piezoelectric properties of PZT and PVDF, and to develop new piezoelectric materials suitable for energy harvesting. For example, the year 1984 marked the discovery of quasicrystals, which were later shown to have some piezoelectric effects. Significant progress has been made regarding their structural properties, and more work is being done to understand and investigate their physical properties (Hu et al. 1997; Altay and Dokmeci 2012; Fan 2013). Quasicrystals seem to have promising potential applications in technology that might include energy harvesting practices in the future.

Besides piezoelectric materials, other material types are being tested for energy harvesting applications. The most promising ones are the dielectric electroactive polymers (DEAP) which can sustain large deformations and have high energy conversion coefficients (Athanassoulis and Mamis 2013). Unfortunately, those materials are incompressible and behave viscoelastically, which prevent their modeling using the classical piezoelectric methods mentioned before. Several researchers studied the implementation of such materials in ocean-energy harvesting devices (Kornbluh et al. 2011; Chiba et al. 2013; Wang and Chen 2012).

5 Piezoelectric devices for ocean energy

Extraction of energy from the ocean using piezoelectric materials is still at an immature stage. Ideas that have been proposed and investigated are based on very wide-ranging and different concepts. The source of energy, the method of extraction and the type of piezoelectric materials used all vary among the designs of such generators. This technology is far from reaching a steady-state phase, where a specific model can be thought of as the most efficient and cost-effective. The purpose of this section is to cover some representative works that have been conducted and to familiarize the reader with the various piezoelectric generators being considered and developed. For a clearer presentation, the ideas are divided into different categories as shown in Table 3. The three sources that are exploited are water currents, wave motion, and waves' impact forces on structures. For each category, the energy is extracted through different means such as heaving bodies and flexible membranes. The material and the coupling mode that are usually employed for each harvesting method are also included in the table. Selected publications that represent the bulk of the research done on piezoelectric energy harvesting from ocean resources are covered. Few other papers also tackled this field of study, but are very similar in concept to the selected works, and would not be included in the present survey.

5.1 Water current

The United States Department of the Interior estimated in 2006 that only 0.1 % of the Gulf stream available energy is sufficient to supply the state of Florida with 35 % of its electrical needs (Minerals Management Service 2006). Many different prototypes have been developed such as current and marine turbines to harness this form of energy. Another way to extract such energy is to transform the vibrations present in the water into electrical energy through a generator placed in the current stream. This method is based on the coupling between flow-induced vibrations and piezoelectric patches.

5.1.1 Flow-induced vibrations

Two different types of flow-induced vibrations are used for energy harvesting. They are 'Vortex Induced Vibrations' (*VIV*) and 'Self-Excited Vibrations' (*SEV*). Designs based on *VIV* are the most common and will be discussed first, followed by a brief mention of designs that rely on *SEV* methods.

When a bluff body is placed in a water current, it will shed vortices with a frequency and size that depend on its characteristics (Yeung 2002). If for example, a piezoelectric membrane is placed behind the bluff body, it will interact with the shed vortices and will start oscillating. This will create bending stresses in the piezoelectric material, which will lead to voltage generation. Electrode segments can be implemented on the piezoelectric device to withdraw the voltage signal. Other harvesters that do not rely on piezoelectric materials were also developed to harvest energy through *VIV*. One such example is a device called VIVACE (Bernitsas et al. 2008).

Taylor et al. (2001) developed a device that was inspired by the bodies of eels and their motion. It consists of a bluff body and a flexible piezoelectric strip behind it. When subjected to water flow, the bluff body sheds vortices that create a pressure gradient on the piezoelectric polymer strip and make it oscillate in a motion similar to the undulating motion of the eel. The eel can be designed in such a way that its flapping frequency matches the frequency of the vortices trailing behind the bluff body. In this case, the maximum power transfer from the flow to the piezoelectric device is achieved. A prototype eel that was 9.5 in long (in the direction of the flow), 3 in wide, and 150 μm thick was designed and tested in a water tank, where the water flow was 0.5 m/s. Eight electrode segments were installed along the length of the eel to extract the current. A peak voltage close to 3 V was recorded during the experiments. According to the analysis performed by the authors, the mechanical to electrical power conversion efficiency[18] of such piezoelectric generator can reach 37 %. Although a power output was not given, the authors claim that the order of magnitude of the eel generated power can vary from mW to W depending on the varying parameters of the system such as flow velocity and size. The conceptual design of the energy harvesting eel was also considered and studied by Allen and Smits (2001).

Pobering and Schwesinger (2004) also presented a design for electricity generation that is similar to the aforementioned eel concept. It consists of a flag made of two embedded PVDF layers. The flag is fixed to a bar that causes the separation of incoming flow, which results in alternating vortices that travel along the top and bottom sides of the flag. This drives the fluttering of the flag, and consequently the electricity generation from the piezoelectric material because of charge separation. The authors estimated the power density of this design to be in the range of 11–32 W/m^2. The design is shown in Fig. 11.

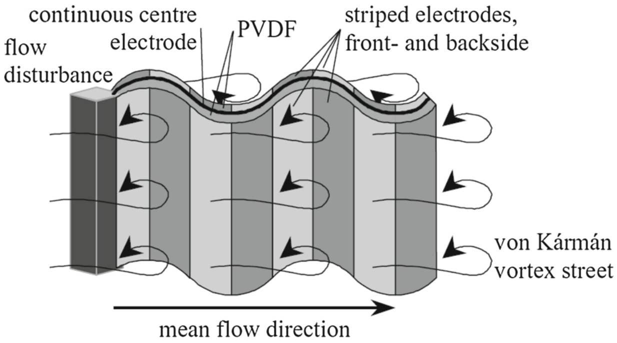

Fig. 11 Piezoelectric flag (© 2004 IEEE. Reprinted, with permission, from Pobering and Schwesinger (2004))

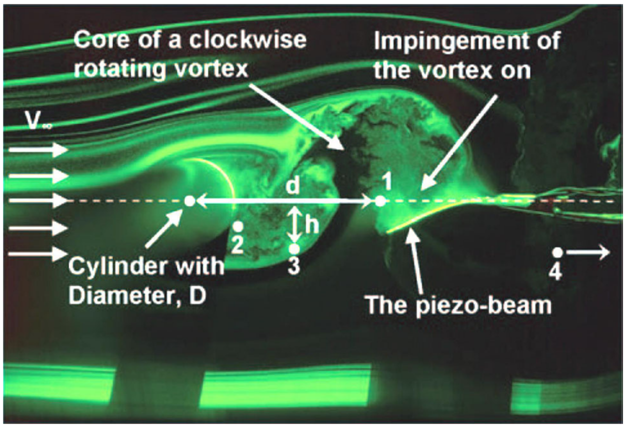

Fig. 12 Cantilever behind cylinder in flow (from page 3 of Akaydin et al. (2010), © Akaydin et al., reprinted by permission of SAGE)

Pobering and Schwesinger also studied the ability of a PZT cantilever bimorph to generate electricity from water currents. The power output was found to be 6.81 μW for a cantilever with a 5 mm length, 3 mm width, and 60 μm thickness. The authors proposed a micro-power plant consisting of a 3D array of the piezoelectric bimorphs. Although the concept has not been validated, they estimated that a power density of 68 W/m^3 can be delivered. According to the authors, this is twice the power density of available state of the art wind turbines.

Another study on piezoelectric cantilever beams was conducted by Akaydin et al. (2010) in City College of New York. The authors investigated the energy harvesting ability of a PVDF beam in unsteady turbulent air flows (Reynolds number >10,000). Two configurations were considered. In the first, shed vortices pass along the surfaces of the beam placed at an optimized location in the turbulent wake of a circular cylinder as presented in Fig. 12. In the second configuration, the beam is placed in a turbulent boundary layer where it oscillates because of the surrounding turbulence.

The authors developed a three-way coupled interaction numerical simulation that takes into account the aerodynamics, structural vibration, and electrical response of the piezoelectric generator. The structural response of the beam was modeled with one degree of freedom as in Fig. 6. In this case,

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[18] Ratio of the electrical energy dissipated by the connected electric circuit over the mechanical energy input to the piezoelectric material.

the electromechanical response for a purely resistive load R is given by:

$$m\ddot{y}_\mathrm{t} + c\dot{y}_\mathrm{t} + ky_\mathrm{t} - \Theta v = F \tag{10}$$

$$\Theta\dot{y}_\mathrm{t} + C\dot{v} = -\frac{v}{R} = I \tag{11}$$

where I is the generated current, v the developed voltage, y_t the tip displacement, and m, c and k are the mass, damping and stiffness of the beam, respectively. C is the capacitance and Θ is the electromechanical coupling coefficient[19] of the piezoelectric generator. F is the excitation force or the forcing term due to the varying pressure on the surface of the beam. The over-dot represents a time derivative. Experiments were conducted on this design in a wind tunnel of a 1.2 m × 1.2 m square cross section to validate the numerical results. The piezoelectric beam used had dimensions of 30 mm × 16 mm × 0.2 mm and was composed of two layers. One layer is made of PVDF and has a thickness equal to $t_\mathrm{p} = 28$ µm, and the other is made of a Mylar backing material of thickness $t_\mathrm{b} = 172$ µm. In the first set of experiments, the flow speed was chosen to be 7.23 m/s to achieve a matching between the Strouhal frequency and the first natural mode frequency of the beam (47.6 Hz). The maximum non-rectified power from the piezoelectric generator with a load resistor of 100 kΩ in the wake of the cylinder was found to be 4 mW. In the second set of experiments, the non-rectified power obtained from the boundary layer was 0.06 mW over a 10 MΩ resistance (Akaydin et al. 2010).

Based on the numerical simulations, the mechanical power given to the beam was around 60 µW and the power harvested and extracted was 7 µW, which results in a conversion efficiency of 11 %.

Research works have also been conducted to exploit the energy through *VIV*. For example, SARTI Research group from the electronics department of the Universitat Politècnica de Catalunya performed some experiments to evaluate a developed energy harvesting device based on *VIV* (Molino-Minero-Re et al. 2012). Also, Progeny systems corporation and the center for Energy Harvesting Materials and Systems at Virginia Tech worked on designing a sea floor power supply that can drive low-power electronics such as oceanographic sensors and health monitoring systems (Bezanson et al. 2010).

Most recently, there is an increasing interest in energy harvesting from fluid flows using the concept of *SEV*. Flexible bodies placed in a uniform steady flow attain self-excited vibrations when the relative speed of the flow exceeds a certain critical speed value for a given body characteristic length. *SEV* also occur if the characteristic length of the body is greater than a critical length for a given flow speed. If piezoelectric patches are installed in such conditions, called fluttering conditions, they can be utilized for energy harvesting applications (Akcabay and Young 2012).

Doaré and Michelin published a sequence of papers in which they studied the energy harvesting from the fluttering of plates placed in axial flows through the use of piezoelectric materials (Doare and Michelin 2011; Michelin and Doare 2013; Doare et al. 2014). Also, Akcabay and Young (2012) examined the hydroelastic response and the energy harvesting potential of flexible piezoelectric beams in viscous flows when subjected to fluttering conditions, including the effects of viscous damping on destabilization.

5.2 Wave motion

Many prototypes have been developed to extract the energy in waves such as oscillating systems (Falnes 2002), cavity resonators, and pressure devices (McCormick 2013). In the context of this work, only those designs that harvest this source of energy based on piezoelectric techniques will be discussed. They mainly consist of heaving and pitching bodies, flexible membranes on ocean surface, and bodies fixed to the ocean bottom.

5.2.1 Heaving and pitching bodies

Heaving and pitching bodies constitute one of the most common and promising techniques in wave-energy extraction. Most of the electromechanical devices used are based on the concept of magnetic induction, some with sophisticated control strategies, for example, see (Yeung et al. 2011). In this survey, the usage of piezoelectric diaphragms will be investigated instead. The main challenge encountered in implementing piezoelectric devices as means of energy conversion via heaving and pitching bodies is the large difference between the ranges of natural frequencies of the piezoelectric materials and those of waves. The frequencies of waves are on the order of 10^{-1} Hz, whereas the natural frequencies of piezoelectric materials used in such applications, usually PZT, are around a few kHz. Thus, to have a meaningful and useful energy conversion system, this challenge has to be overcome in the design.

Murray and Rastegar (2009) developed a design with the goal of overcoming this challenge. The authors proposed a two-stage energy harvesting process, introduced by Rastegar et al. (2006), for a heaving buoy. The energy available in the low-frequency buoy motion is transformed into potential energy in the first stage, and then transferred to another system with a much higher natural frequency in the second stage. One example is shown in Fig. 13. The primary system is composed of a piston that oscillates vertically relative to a chassis as incoming low-frequency waves pass by. When oscillating at low frequency, the piston contacts and excites

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[19] This was referred to as K in Sect. 2.2.

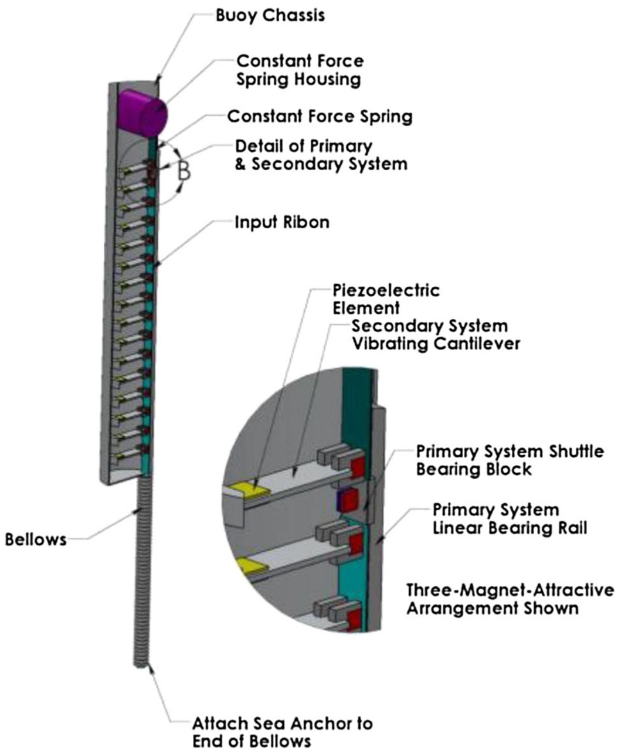

Fig. 13 Heaving-based harvester (Murray and Rastegar 2009) (reprinted by permission of SPIE)

fixed cantilevers (secondary system) that start vibrating at a high frequency close to that of PZT. The piezoelectric elements are located on the cantilever beams, which will lead to electrical energy generation. Preliminary computer simulations showed that the one-hour time-averaged power output[20] of a buoy of length $L = 36$ in and diameter $d = 3$ in is between 60 to 180 mW depending on the sea state.

Vinolo et al. (2013) developed a piezoelectric energy converter through the heaving and pitching motions of buoys. The generation process uses the motion of the waves to produce impact forces on piezoelectric diaphragms that are attached to the buoyant structures. The energy harvesting takes place inside a box, where four PZT disks are situated at its four corners and are struck by two spherical pendulum to resonate the PZT vibration. In a prototype at-sea experiment, a mere 9 mW was captured in Sea State 1 during a full day.

Okada et al. (2012) conducted some experiments on a floating wave-power generation device using piezoelectric elements. Other researchers considered the insertion of the piezoelectric parts into the mooring systems of the heaving or pitching bodies (Hausler and Stein 1987; Patel 2004, 2006). In this case, the cables used for mooring consist of piezoelectric high polymer film such as PVDF. The cyclic motion of the float induces strain in the cable, which will lead to electric charge generation. Large strain in the cable is needed for this method of energy extraction to be effective.

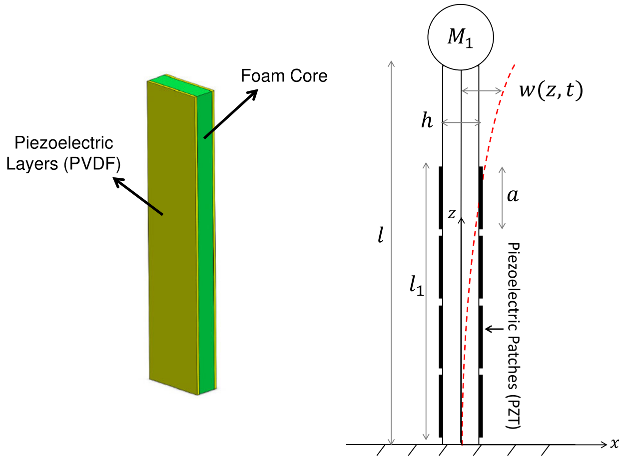

Fig. 14 Designs of Zurkinden et al. (2007) (*left*) and Xie et al. (2014) (*right*)

5.2.2 Bodies fixed to ocean bottom

Zurkinden et al. (2007) used the piezoelectric polymer PVDF to design a device based on a cantilever beam mounted on shallow sea bed, see Fig. 14. According to the authors, the power generated by the device can be on the order of mW or W depending on the mechanical system and the surrounding conditions. For the simulation performed, the cantilever beam was 30 mm long and made of a 3.75-mm-thick flexible foam core sandwiched between two 1.25-mm-thick piezoelectric polymer layers that span the whole body. Waves were generated in a 10-m-long channel with an amplitude of 0.03 m and a period $T = 1.1$ s. Results showed that the maximum displacement of the tip of the structure was 3.5 mm and the corresponding peak output voltage was 3.28 V.

Water particles have larger horizontal and vertical velocities closer to the surface. Hence, piezoelectric cantilever beams will experience larger bending next to the ocean's surface and will consequently generate more power. Unlike the presented work of Zurkinden et al. that only exploits the energy close to the bottom of the ocean, a study performed by Xie et al. (2014) investigates the potential of a power harvester consisting of a vertical cantilever column fixed to the ocean bottom and extending to the ocean surface. The energy harvesting is a result of the coupling between the PZT piezoelectric patches attached to the sides of the column and the longitudinal motion of the waves. The design is shown in Fig. 14.

M_1 is called the proof mass and is placed on top of the cantilever of length l, width b, thickness h, and mass m. The

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[20] The power was computed assuming an electric extraction efficiency of 33 %. The authors claim that this value is typically a minimum for systems of their device's type.

piezoelectric patches have length a, width b, thickness h_1, and span a total length of l_1 along the length of the cantilever. The deflection of the beam is denoted by $w(z,t)$ and the water depth is d. The authors adopted a formulation developed by Lee and Moon (1990) in their publication entitled ‘Modal sensors and actuators’ to find the generated charge Q and voltage V in the piezoelectric patches during the bending of the beam:

$$V = \frac{Q}{C}, \quad Q = -e_{31} b \frac{h + h_1}{2} \left[\frac{\partial w(z,t)}{\partial z} |_{z+a} - \frac{\partial w(z,t)}{\partial z} |_{z} \right] \tag{12}$$

where C is the capacitance of the piezoelectric material, and e is the piezoelectric stress coefficient of Eqs. (3) and (4). The RMS value of the power generated from a wave of period T can be obtained via:

$$p_e^{\mathrm{RMS}} = \left(\frac{1}{T} \int_0^T [p_e(t)]^2 \, \mathrm{d}t \right)^{1/2}, \qquad p_e(t) = \sum_{i=1}^{n} \left[\dot{Q}^i(t) V^i(t) \right] \tag{13}$$

where $p_e(t)$ is the overall generated electric power from the total number of patches n at time t (Xie et al. 2014).

The performance of such harvester was investigated for different sea wave motions. It was found that the generated power increased non-linearly with the length of the cantilever and was smaller for larger wavelength-to-depth ratios. The mathematical model developed by the authors showed that when a wave with a height and wavelength of 2 and 15 m, respectively, hits a structure with $M_1/m = 3$, $h = 0.05$ m, $h_1 = 0.001$ m, $b = 1$ m, $d = l = 3$ m, $a = 0.1$ m and $l_1 = \frac{2}{3} l$, the RMS generated electric power can reach 55 W.

5.2.3 Flexible membranes

The concept of the Pelamis, a flexing and bending attenuator-type wave-energy absorber, can be extended to an entire flexible piezoelectric membrane. A high degree of flexibility is required for such applications, so PVDF is favored over PZT.

In fact, Koola and Ibragimov (2003) introduced a novel concept called ‘the wave carpet’, consisting of a large flexible sheet that acts as a terminator and attenuator device and is installed in deep water. It was designed as a very large floating structure with dynamic positioning systems. The power take-off mechanism, however, was not thoroughly discussed in this paper, but piezoelectric generators seem appropriate for such application. Because of the large designed area of the carpet (order of km^2) and the low efficiency of PVDF, a substantial number of piezoelectric elements would need to be used to make the concept viable. Besides, some cancelation effects between the electric outputs of the multiple PVDF elements might take place, so the external extraction electric circuit should be connected in a way to avoid such cancelations and to extract most of the energy being generated.

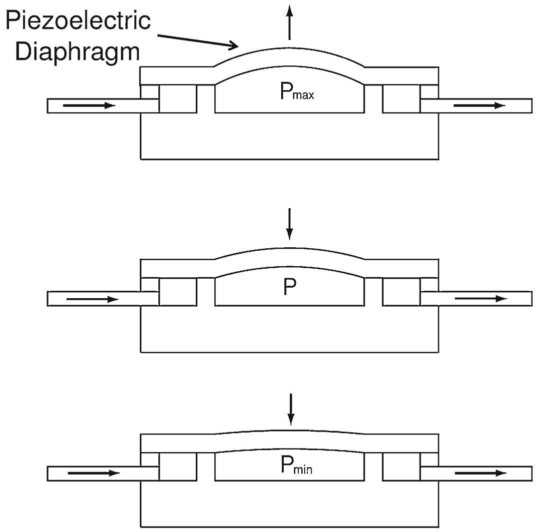

Fig. 15 Piezoelectric device operation (Wang and Ko 2010) (© IOP Publishing. Reproduced by permission of IOP Publishing. All rights reserved)

Wang and Ko (2010) developed a piezoelectric energy harvesting device based on flow-induced vibrations. A flow source is connected to a flow channel with a flexible diaphragm on top (see Fig. 15). The flow source generates an oscillating liquid pressure in the channel, which drives the diaphragm to oscillate. This situation resembles a ‘wave carpet’ on the ocean surface oscillating with the waves passing underneath. If a piezoelectric film is attached to the diaphragm, the strain will cause electrical charge to accumulate on the electrodes, with a resulting voltage difference across the sheet. The authors’ experiments showed that the output open circuit voltage was 2.2 V and the power generated was 0.2 μW when the amplitude of the excitation pressure was 1.196 kPa and the oscillation frequency was 26 Hz. The concept is viable.

Mutsuda et al. (2010, 2011, 2012, 2013) published a sequence of papers in four successive Offshore Mechanics and Arctic Engineers (OMAE) conferences from 2010 to 2013. The work in the first two papers was mostly experimental to test the feasibility of a manufactured flexible device with multiple PVDF polymers in generating electric power from the the ocean-energy sources mentioned above: wave motion, water currents, etc. The device, called FPED, which stands for flexible piezoelectric device, consists of a soft substrate (non-piezoelectric) such as silicon or rubber and a number of embedded PVDF layers. Later work of Mutsuda et al. concentrated on a design called Elastic Floating

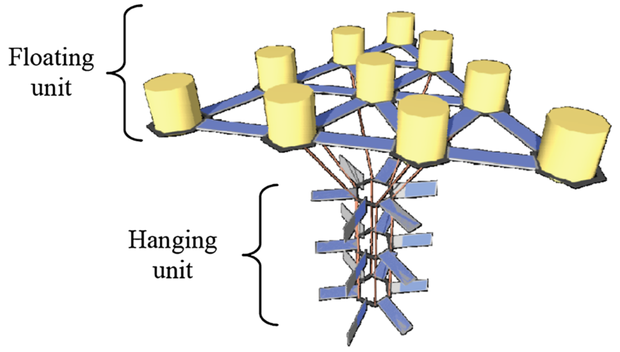

Fig. 16 EFHAS (Mutsuda et al. 2012) (reprinted by permission of ASME)

Unit with Hanging Structures (EFHAS), which harvests the energy present on and beneath the ocean surface (Fig. 16).

The floating unit extracts the energy resources present on the ocean surface such as wave bending motion and wave breaking. The hanging unit is suspended from the floating one and can consist of many levels. Experiments have been conducted to prove the ability of EFHAS to generate electric power, with more performance data given in Mutsuda et al. (2013).

5.3 Wave impact

Ocean structures are carefully designed to withstand the huge loads from wave impacts. The modeling issue of such phenomena is a separate field by itself (McConnell et al. 2004). Such large forces exerted by waves on the structures can prove to be beneficial rather than merely destructive. If piezoelectric patches are implemented on the impacted surface, they can utilize the induced pressure for electricity generation.

5.3.1 Sloshing

The sloshing of waves on tank walls and ocean structures has been a subject of study for many years. Apart from the resulting structural damage, sloshing can also affect the stability of dynamic systems (Wu et al. 1998). Many sloshing situations arise, where the use of piezoelectric elements seems plausible and useful. Piezoelectric sheets can be fixed on the walls of large fluid tanks in motion such as liquid fuel tanks in aircraft, or on offshore structures such as oil platforms.

Athanassoulis and Mamis (2013) studied a piezoelectric sheet's ability to extract electrical energy directly from the impingement of incident waves on vertical cliffs (see Fig. 17).[21] The two main advantages offered by such piezoelectric harvesters are the extraction of useful energy and the damping of internal sloshing loads.

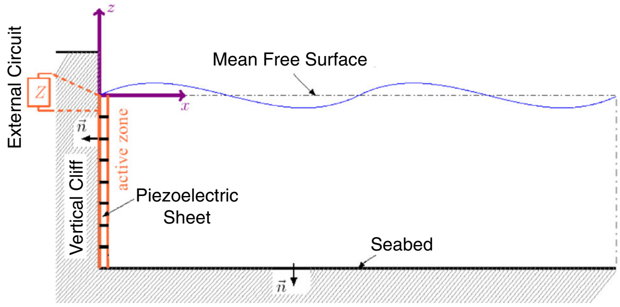

Fig. 17 Hydrodynamic-piezoelectric system (Athanassoulis and Mamis 2013) (reprinted by permission of Techno Press)

In their work, the "barrier sheet" was formed by vertical arrays connected in parallel, each one consisting of series-connected piezoelectric elements. The sheet was also connected to an external AC circuit so as to take off power from the impinging waves. The 3-3 coupling mode was adapted where the resulting polarization vector and the applied stress both act in the x-direction. In this case, Eqs. (3) and (4) reduce to:

$$T_3 = c_{33}^{E} S_3 - e_{33} E_3$$
$$D_3 = e_{33} S_3 + \epsilon_{33}^{S} E_3$$

The excitation stress T_3, applied on the piezoelectric element, is equal to the negative of the hydrodynamic pressure p. This stress gives rise to a voltage gradient between the two electrode faces of the piezoelectric elements. The coupled problem between the hydrodynamic, piezoelectric and external extraction circuit systems was solved, where a closed-form solution for the energy harvesting system's efficiency[22] that is optimized with respect to the external resistive load was obtained. Figure 18[23] shows the efficiency variation with respect to two dimensionless parameters that combine the hydrodynamic, piezoelectric and circuit characteristics affecting the energetic coupling of the system.

Only the physical meaning of each parameter will be given here because of the complexities of the expressions. Both parameters are products of a hydrodynamic factor and a piezoelectric one. The first parameter $\frac{\sigma}{\Pi}$ is a function of the electromechanical coupling factor K explained in Sect. 2.2. The higher this coupling factor is, the higher the efficiency. The second parameter $\bar{\omega}$ includes the flexibility of the piezo-

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[21] Some labels were removed from original figure for clarity.

[22] It is the ratio of the electrical energy harvested by the piezoelectric sheet and external circuit over the total input energy contained in the incident wave. It is expressed as $1 - |W|^2_{\text{opt}}$, where W is the reflection coefficient off the cliff.

[23] Some labels were removed or changed from original figure to match notation of current work.

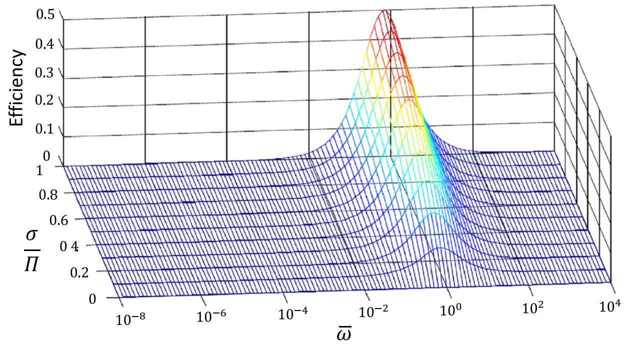

Fig. 18 Variation of efficiency with the two non-dimensional parameters (Athanassoulis and Mamis 2013) (reprinted by permission of Techno Press)

electric material. The authors concluded that the flexibility of existing piezoelectric materials should increase by three orders of magnitudes, in order for efficient wave-energy harvesting to occur through the cliff mounted piezoelectric sheet. In other words, it is a challenge for the material scientists to increase the flexibility of piezoelectric materials, in order for the efficiency of such piezoelectric harvesting techniques to improve. Interestingly, in contrast, if a heaving-floater system with a specific shape called "The Berkeley Wedge" is used as the barrier,[24] a perfect energy absorber results, absorbing the wave and capturing the full energy. There is a resulting reduction of force, but not necessarily the pitching moment (Madhi et al. 2014).

6 Discussion and comments

A short discussion commenting on and comparing the previously explained energy harvesting methods is presented below, along with Table 4 that summarizes some key points.

The first method discussed in this article is based on flow-induced vibrations. Different designs such as eel, flag, and cantilever generators are presented. This energy method is very important for powering underwater sensors, robots, etc., especially in regions where moving water is always present. It would be particularly applicable to electrical devices moving underwater. Such harvesters are actually exploiting only a very small fraction of the energy potential of water flows because of their low hydrodynamic efficiency.[25] Perhaps, adding a passive control system to these harvesters where they can be automatically oriented to the direction of the flow will improve the effectiveness of this technique. Further, more flow energy can be captured by building a farm composed of many of these energy harvesters, with special attention given to the positioning of the array components and interference effects to achieve maximum energy output. The harvesters should be designed to have their natural frequency very close to that of the surrounding vibrations. This will result in a resonant phenomenon, where power output increases significantly. Because of their continuous exposure to sea water, these harvesters should be able to withstand corrosion.

Heaving and pitching bodies are well known to be commonly used for wave-energy extraction applications. Different designs involving the usage of piezoelectric materials as power take-off mechanisms using such motion were presented. This energy conversion method is mostly used to build self-contained power sources, where batteries or any other limited storage technology inside buoys can be replaced or supplemented by this harvesting method. The main challenge here is the large difference between the low frequency of the waves and the high natural frequency of PZT, which is typically used for such applications. A two-stage energy harvesting system was presented by Murray and Rastegar (2009) as a solution. Here, the low-frequency energy of the waves is transferred to a mass that excites piezoelectric elements with high frequency vibrations. If physical contact can be avoided during the transfer, frictional losses will be reduced. Thus, magnetic or other field forces seem more suitable than impact-type forces for such applications (Anton and Sodano 2007).

As discussed in Sect. 5, ocean-energy harvesting methods through piezoelectric materials required the use of either lead zirconate titanate (PZT) or polyvinylidene fluoride (PVDF). However, in the case of bodies fixed to the ocean bottom, as explained in Sect. 5.2.2, PZT and PVDF are both potentially suitable. In the work of Zurkinden et al. (2007), PVDF was embedded in a bottom-fixed cantilever, whereas Xie et al. (2014) used PZT patches attached to the surface of the cantilever. PZT has higher coupling coefficients and will lead to higher power generation. However, its stiffness limits its range of applications. With the considered harvesting technique, the charge generation in the piezoelectric material is due to the bending of the cantilever, which requires low stiffness. Hence, flexibility and strength should be considered as an important design factor, especially near the ocean surface where bending stresses increase owing to the larger velocities of water particles. The wave and water current loads should be incorporated in the design as well to know whether or not the yield strength of PZT is high enough to endure such applications. In harsh environments, PVDF should be favored over PZT even if its electromechanical coupling is lower. One potential application of such harvesting technique is its use for seismic activity monitoring near the ocean bottom.

Piezoelectric membranes were also covered as a potential method for wave-energy extraction. Two employments of these membranes were considered. The first is placing

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[24] http://techtransfer.universityofcalifornia.edu/NCD/23530.html.

[25] Ratio of mechanical energy transmitted to the piezoelectric material to the total mechanical energy present in the flow.

Table 4 Summary of piezoelectric methods for ocean-energy harvesting

Harvesting method	Power order	Power density	Applications	Challenges	Recommendations
Flow-induced vibrations	mW to W	15 W/m^2	Powering of moving underwater electronic devices such as UWV's and robots	Low hydrodynamic efficiency	Passive control system, use of multiple devices
Heaving and pitching bodies	mW	5 W/m^2	Powering of buoys, powering of sensors used for ocean surveillance, salinity measurements, etc	Large gap between low wave frequency and high natural frequency of PZT	Transformation of low-frequency vibrations to high frequency through two-stage systems, use of field forces rather than impact forces in two-stage systems
Bodies fixed to ocean bottom	mW to W	13 W/m^2	Electricity collection and transmission to nearby offshore platforms, seismic activity monitoring	Mechanical design and material selection	Compromise between electromechanical coupling and required flexibility and strength
Flexible membranes on ocean surface	µW to mW	20 mW/m^2	Wave dampers around wind turbines and offshore structures, power transmission to nearby ocean structures and floating harbors	Very large devices needed (order of km^2), accommodation of waves with multiple frequencies and directions	Use of multiple piezoelectric elements, external extraction circuits designed effectively to avoid cancelation effects in the generated voltage
Sloshing on flexible sheets	µW	Not available	Power transmission to ocean structures, wave load dampers on bodies such as cliffs, offshore structures, and ships	Required flexibility not present in currently available piezoelectric materials, low efficiency	Fabrication of new piezoelectric materials with higher degree of flexibility

the piezoelectric sheet on the surface of the ocean where charges are generated as the membrane flexes because of the passing waves. Clearly, PVDF is the suitable material for this application since flexibility is needed. This is actually a disadvantage because for a worthy energy conversion process to occur, the piezoelectric sheets have to cover a large and wide area of the ocean surface. Further, the membrane should be designed to accommodate the random and different wave frequencies and directions. The second employment was using the piezoelectric sheets to extract the energy associated with the wave loads. However, as mentioned previously in Sect. 5.3.1, piezoelectric materials with the needed flexibility are not available yet. Thus, it is in the materials scientists' hands to improve the mechanical properties of piezoelectric materials. Although such devices are less efficient and feasible than others, they offer two big advantages: Low maintenance resulting from the lack of any translational or rotational parts, and the potential usage as wave load dampers around offshore structures such as oil platforms or wind turbines.

For the harvesters that rely on the usage of PVDF layers such as the eel, flag, and flexible membranes, the location of these layers is an important design factor. They are usually embedded in the core of the harvester and have to be placed far from the neutral axis of the body to maximize the bending stresses on them and consequently increasing the power output. Normally, the body consists of a non-active flexible layer such as Silicon sandwiched between two PVDF layers. However, a central layer that is too thick can stiffen the harvester, which is not desired in ocean-energy harvesting applications. Hence, an optimized configuration of the thickness of non-active and piezoelectric layers should be achieved in the design process.

Table 4 presents a summary of the harvesting techniques explained above. The second column of the table 'Power Order' shows the order of magnitude of the power that can be generated through the different energy harvesting techniques.[26] For the sake of comparison, the values presented by various publications were used to obtain a rough estimate of the average power density of the different devices. These values are tabulated in the third column entitled 'Power Density' and represent wattage per area (m^2) of piezoelectric material. Note that, µW, mW and W stand for micro-Watt, milli-Watt and Watt, respectively.

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[26] This power order is based on the results of the reviewed research works.

7 Conclusions

In this article, we recall the physical principles and quantitative description of the piezoelectric materials. We categorized the types of materials that would be relevant to ocean-energy applications. We surveyed energy harvesting methods utilizing piezoelectric means based on energy sources coming from fluctuating flow, wave motion, and wave impacts. The assessments and prospective potentials of the addressed devices are evaluated in Sect. 6, with their performance and limitations summarized in Table 4. In all, developments in this area have not reached a state where devices based on the direct piezoelectric effect can be manufactured and deployed for the sole purpose of generating electrical energy and transferring it back to land. Rather, piezoelectric materials can be an integral part of larger systems in the ocean, and can act as power sources for low-power electronics such as salinity and temperature sensors. High efficiency is not the main target of these devices. More importantly, these are sustainable and relatively maintenance-free devices, which will enhance the operability of many ocean systems, present day and forthcoming.

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