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Research Article

Analytical Optimization of Piezoelectric Circular Diaphragm Generator

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This paper presents an analytical study of the piezoelectric circular diaphragm microgenerator using strain energy method. Piezoelectrics are the intelligent materials that can be used as transducer to convert mechanical energy into electrical energy and vice versa. The aim of this paper is to optimize produced electrical energy from mechanical pressure. Therefore, the circular metal plate equipped with piezoelectric circular patch has been considered with simply and clamped supports. A comprehensive modeling, parametrical study and the effect of the boundary conditions on the performance of the microgenerator have been investigated. The system is under variable pressure from an oscillating pressure source. Results are presented for PZT and PMN-PT piezoelectric materials with steel and aluminum substrates. An optimal value for the radius and thickness of the piezoelectric layer with a special support condition has been obtained.

1. Introduction

Energy harvesting from environmental sources such as solar, thermal, and mechanical has been the center of interest of some researchers [1–3]. Piezoelectric material can be used as a mechanism to convert mechanical energy into electrical energy and vice versa. If a piezoelectric element is attached to a structure, it is strained as the structure deforms and converts a portion of the mechanical energy into electrical energy that can be harvested through a shunt network. Piezoelectric-based energy harvester can be used as power generator for mobile and low-power consuming devices [4–17]. Also, these devices present one possible solution to convert ambient vibrations into usable power either to replace the batteries especially in implanted medical devices or to enhance them [18–20]. A hybrid device using magnetic and ultrasonic energies through the magnetostriction and piezoelectric vibrators has been suggested by Suzuki et al. [21, 22]. Ramsay et al. [9, 23] investigated the feasibility of harvesting energy from internal activities in the human body using piezoelectric transducers for microelectromechanical systems applications. This proposed self-powered device provides an in-body power supply.

However, the boundary conditions significantly affect the results [24], several methods have been investigated for vibration energy harvesting using piezoelectric materials without any pointing to these effects. This paper is attempting to address this issue (support conditions) as well as the parametrical study. An analytical approach based on strain energy evaluation is presented in order to model the unimorph piezoelectric circular diaphragm. The source of varying pressure can be the variations of blood pressure, moving vehicles, heartbeat, and other variable pressure sources. The paper has been organized as follows. Section 2 describes the modeling of the system as well as the strain energy calculation. Section 3 depicts the results. Finally, conclusions are provided in Section 4.

2. Electromechanical Model of Microgenerator

The energy harvester device is the circular metal plate equipped with piezoelectric circular patch with two boundary

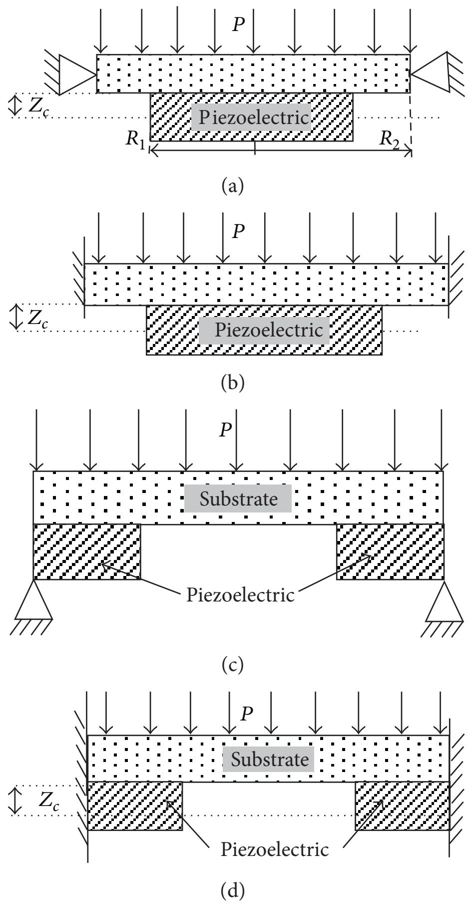

Figure 1: Piezoelectric energy harvester diaphragm.

conditions, simple and clamped supports (Figure 1). The system deflects under applied external pressure and consequently the electrical charge is generated by the piezoelectric diaphragm. Then, this electrical energy can be harvested by a shunt circuit.

The expression of total strain energy in order to calculate the generated energy is required. Therefore, at first, we are going to calculate these equations. The equations of deflection of axially symmetrical plate under uniform pressure p are given by

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d}{dr}\left(\frac{1}{r}\frac{d}{dr}\left(r\frac{dw}{dr}\right)\right)\right)=\frac{p}{D}, \tag{1}$$

$$M_r=-D\left(\frac{d^2w}{dr^2}+\frac{\nu}{r}\frac{dw}{dr}\right),$$
$$M_\theta=-D\left(\frac{1}{r}\frac{dw}{dr}+\nu\frac{d^2w}{dr^2}\right), \tag{2}$$

$$Q_r=-D\frac{d}{dr}\left(\frac{1}{r}\frac{d}{dr}\left(r\frac{dw}{dr}\right)\right), \tag{3}$$

where w is the plate deflection, r is the radial coordinate, M_r and M_θ are the moments in the radial and tangential directions, respectively, υ is the poison ratio (assumed to be the same for both layers), Q_r is the shear force, and D is the flexural rigidity of the plate. The generated energy by piezoelectric material is calculated using strain energy method in four cases as follows.

2.1. Simply Support. In this case (Figure 1(a)), the plate is divided into two parts: one is the inner section, where $r \le R_1$ and the other is the outer section, where $R_1 < r \le R_2$. Equations (1)–(3) can be applied for both the inner and outer sections. Inner section is a piezoelectric multilayer plate and outer section is a nonpiezoelectric annular plate. Boundary conditions are as follows:

$$\begin{gathered}
w_{r=R_2}=0, \qquad w^{(i)}_{r=R_1}=w^{(o)}_{r=R_1},\\
M_r\big|_{r=R_2}=0, \qquad \left.\frac{\partial w^{(i)}}{\partial r}\right|_{r=R_1}=\left.\frac{\partial w^{(o)}}{\partial r}\right|_{r=R_1},\\
\left.\frac{\partial w^{(i)}}{\partial r}\right|_{r=0}=0, \qquad Q^{(i)}_r\big|_{r=R_1}=Q^{(o)}_r\big|_{r=R_1},\\
M^{(i)}_r\big|_{r=R_1}=M^{(o)}_r\big|_{r=R_1}.
\end{gathered} \tag{4}$$

The subscripts (i) and (o) indicate inner multilayer and outer annular plate, respectively. Deflections of the inner and outer sections are found as

$$\begin{gathered}
w_1=c_0r^4+c_1r^2+c_2 \quad \text{inner section } r\le R_1,\\
w_2=c_6r^4+c_3r^2+c_4\ln r+c_5 \quad \text{outer section } R_1<r<R_2,
\end{gathered} \tag{5}$$

where the coefficients of c_i have been given in Appendix A.

The flexural rigidities for the inner and outer sections are as follows [25]:

$$D_t=\frac{XZ-Y^2}{X},$$
$$D=\frac{EI}{1-\upsilon^2}=\frac{h_m^3}{12s_m\left(1-\upsilon^2\right)}, \tag{6}$$

where

$$X=\sum_{k=1}^{2}\frac{E_K}{1-\nu_k^2}\left(z_k-z_{k-1}\right),$$
$$Y=\sum_{k=1}^{2}\frac{E_K}{1-\nu_k^2}\left(\frac{z_k^2-z_{k-1}^2}{2}\right), \tag{7}$$
$$Z=\sum_{k=1}^{2}\frac{E_K}{1-\nu_k^2}\left(\frac{z_k^3-z_{k-1}^3}{3}\right),$$

where z_k is the distance from kth layer to the first layer in any multilayer plate and E_K is the young modulus of the kth layer. I is the cross-section moment of inertia, h_m is the thickness of substrate layer, and s_m is the elastic compliance constant. Strain energy for the piezoelectric layer is

$$dU_p=\frac{1}{2}\left(\varepsilon_r\sigma_r+\varepsilon_\theta\sigma_\theta+D_3E_3\right) \tag{8}$$

and for the substrate layers

$$dU_m = \frac{1}{2}\left(\varepsilon_r\sigma_r + \varepsilon_\theta\sigma_\theta\right). \quad (9)$$

The strain equations for piezoelectric material are as follows [26]:

$$\begin{aligned}\varepsilon_r &= s_{11}^E\left(\sigma_r - \nu\sigma_\theta\right) - d_{31}E_3,\\ \varepsilon_\theta &= s_{11}^E\left(\sigma_\theta - \nu\sigma_r\right) - d_{31}E_3,\\ D_3 &= -d_{31}\left(\sigma_r + \sigma_\theta\right) + \varepsilon_{33}^T E_3,\end{aligned} \quad (10)$$

where σ, ε_{33}^T, d_{31}, D_3, and E_3 are the stress, piezoelectric permittivity, piezoelectric constant, charge density, and electric field in 3-direction (z), respectively. The radial direction is taken to be the 1-direction, and tangential direction is the 2-direction. The subscripts r and θ are used instead of 1 and 2, respectively. Substituting of the third equation of (10) into (8) leads to

$$dU_p = \frac{1}{2}\left(\varepsilon_r\sigma_r + \varepsilon_\theta\sigma_\theta - d_{31}\left(\sigma_r + \sigma_\theta\right)E_3 + \varepsilon_{33}^T E_3^2\right). \quad (11)$$

The stress equations for the piezoelectric material can be written as

$$\begin{aligned}\sigma_r &= \frac{1}{s_{11}^E\left(1-\nu^2\right)}\left(\varepsilon_r + \nu\varepsilon_\theta + (1+\nu)d_{31}E_3\right),\\ \sigma_\theta &= \frac{1}{s_{11}^E\left(1-\nu^2\right)}\left(\nu\varepsilon_r + \varepsilon_\theta + (1+\nu)d_{31}E_3\right)\end{aligned} \quad (12)$$

and for the nonpiezoelectric material are

$$\begin{aligned}\sigma_r &= \frac{1}{s_m\left(1-\nu^2\right)}\left(\varepsilon_r + \nu\varepsilon_\theta\right),\\ \sigma_\theta &= \frac{1}{s_m\left(1-\nu^2\right)}\left(\nu\varepsilon_r + \varepsilon_\theta\right),\end{aligned} \quad (13)$$

where s_{11}^E is the elastic compliance of piezoelectric material. The equations of curvature and moment (2) can be used for correlating of stress and strain to the applied pressure. The relation of strain and curvature in polar coordinate are as follows:

$$\begin{aligned}&\begin{aligned}\varepsilon_{ri} &= -\rho_{ri}\left(z - z_c\right)\\ \varepsilon_{\theta i} &= -\rho_{\theta i}\left(z - z_c\right)\end{aligned} \quad 0 \le r \le R_1,\\ &\begin{aligned}\varepsilon_{ro} &= -\rho_{ro}\left(z - z_c\right)\\ \varepsilon_{\theta o} &= -\rho_{\theta o}\left(z - z_c\right)\end{aligned} \quad R_1 \le r \le R_2,\end{aligned} \quad (14)$$

where ρ_r and ρ_θ are the radial and tangential curvatures, respectively, and z_c is the distance between neutral surface and interface of piezoelectric and substrate layer (Figure 1) that can be written as

$$z_c = \frac{u_1}{u_2}, \quad (15)$$

where

$$\begin{aligned}u_1 &= s_{11}^E R_2 h_m^2 - s_m R_1 h_p^2,\\ u_2 &= 2\left(s_{11}^E R_2 h_m + s_m R_1 h_p\right),\end{aligned} \quad (16)$$

where h_p is the thickness of piezoelectric layer. Moment equations for the inner and outer regions can be written as

$$\begin{aligned}M_{ri} &= \int_0^{h_p}\sigma_{rpi}\left(z - z_c\right)dz + \int_{-h_m}^0\sigma_{rmi}\left(z - z_c\right)dz,\\ M_{\theta i} &= \int_0^{h_p}\sigma_{\theta pi}\left(z - z_c\right)dz + \int_{-h_m}^0\sigma_{\theta mi}\left(z - z_c\right)dz,\\ M_{ro} &= \int_{-h_m}^0\sigma_{rmo}\left(z - z_c\right)dz,\\ M_{\theta o} &= \int_{-h_m}^0\sigma_{\theta mo}\left(z - z_c\right)dz.\end{aligned} \quad (17)$$

Substituting of (12) and (13) into the moment (17) leads to

$$\begin{aligned}M_{ri} &= \int_0^{h_p}\left(\frac{\varepsilon_{ri} + \nu\varepsilon_{\theta i}}{\left(1-\nu^2\right)s_{11}^E} + \frac{(1+\nu)d_{31}E_3}{\left(1-\nu^2\right)s_{11}^E}\right)\left(z - z_c\right)dz\\ &\quad + \int_{-h_m}^0\left(\frac{\varepsilon_{ri} + \nu\varepsilon_{\theta i}}{\left(1-\nu^2\right)s_m}\right)\left(z - z_c\right)dz,\\ M_{\theta i} &= \int_0^{h_p}\left(\frac{\nu\varepsilon_{ri} + \varepsilon_{\theta i}}{\left(1-\nu^2\right)s_{11}^E} + \frac{(1+\nu)d_{31}E_3}{\left(1-\nu^2\right)s_{11}^E}\right)\left(z - z_c\right)dz\\ &\quad + \int_{-h_m}^0\left(\frac{\nu\varepsilon_{ri} + \varepsilon_{\theta i}}{\left(1-\nu^2\right)s_m}\right)\left(z - z_c\right)dz,\\ M_{ro} &= \int_{-h_m}^0\left(\frac{\varepsilon_{ro} + \nu\varepsilon_{\theta o}}{\left(1-\nu^2\right)s_m}\right)\left(z - z_c\right)dz,\\ M_{\theta o} &= \int_{-h_m}^0\left(\frac{\nu\varepsilon_{ro} + \varepsilon_{\theta o}}{\left(1-\nu^2\right)s_m}\right)\left(z - z_c\right)dz.\end{aligned} \quad (18)$$

By substituting of (14) into (18), the curvature can be found as follows:

$$\begin{aligned}\rho_{ri} &= \frac{1}{I_1\left(1-\nu^2\right)}\left(M_{ri} - \nu M_{\theta i}\right) + I_2E_3,\\ \rho_{\theta i} &= \frac{1}{I_1\left(1-\nu^2\right)}\left(M_{\theta i} - \nu M_{ri}\right) + I_2E_3,\\ \rho_{ro} &= \frac{1}{I_3\left(1-\nu^2\right)}\left(M_{ro} - \nu M_{\theta o}\right),\\ \rho_{\theta o} &= \frac{1}{I_3\left(1-\nu^2\right)}\left(M_{\theta o} - \nu M_{ro}\right),\end{aligned} \quad (19)$$

where the coefficients of I_i have been given in Appendix A.

The total strain energy is the combination of the inner and outer strain energies as follows:

$$U = \int_0^{R_1}\int_0^{2\pi}\int_0^{h_p} dU_{pi}\, dzr\, d\theta\, dr + \int_0^{R_1}\int_0^{2\pi}\int_{-h_m}^{0} dU_{mi}\, dzr\, d\theta\, dr + \int_{R_1}^{R_2}\int_0^{2\pi}\int_{-h_m}^{0} dU_{mo}\, dzr\, d\theta\, dr. \quad (20)$$

The first and second terms are for the inner region and the third term is for the outer region. Substituting of (9) and (11) into (20) and using the previous equations of (2), (5), (12)–(14), and (19) lead to

$$U = L_1 E_3^2 + L_2 E_3 + L_3, \quad (21)$$

where L_1, L_2, and L_3 are the constants as given in Appendix A.

It should be mentioned that M_r and M_θ in (19) have been replaced by (2) whose deflection has been replaced by (5). Replacing of electric field E_3 by V/h_p, where V is the piezoelectric voltage, (21) can be simplified as

$$U = \alpha V^2 + \beta V + \gamma, \quad (22)$$

where $= L_1/h_p^2$, $\beta = L_2/h_p$, and $\gamma = L_3$. The term αV^2 represents the electrical energy stored on the capacitance of the piezoelectric material due to an externally applied voltage, which does not exist in this case. γ represents the mechanical energy, and βV is the converted energy from mechanical deformation to electrical energy, which can be harvested. The aim is to maximize this term. The total electrical charge Q_t can be obtained by differentiating of (22) with respect to voltage V:

$$Q_t = \frac{\partial U}{\partial V} = 2\alpha V + \beta. \quad (23)$$

Thus, β is the charge generated (Q_{gen}) by the applied pressure. From the terms $2\alpha V$ and $Q = C_{\text{free}} V$ for the capacitance, it can be concluded that

$$C_{\text{free}} = 2\alpha. \quad (24)$$

Then

$$V_{\text{gen}} = \frac{Q_{\text{gen}}}{C_{\text{free}}}, \quad (25)$$

and then

$$V_{\text{gen}} = \frac{\beta}{2\alpha}, \quad (26)$$

where C_{free} is the open-circuit piezocapacitance V_{gen} is the voltage generated by the applied pressure p. Therefore, the electrical energy that is generated by the applied external pressure p is

$$U_{\text{gen}} = \frac{Q_{\text{gen}} V_{\text{gen}}}{2}, \quad (27)$$

and then

$$U_{\text{gen}} = \frac{\beta^2}{4\alpha}. \quad (28)$$

2.2. Clamped Support. In this case, a similar method as in Section 2.1 is applied only with different boundary conditions (Figure 1(b)). The support in this case is clamped, and the boundary conditions are as follows:

$$w_{r=R_2} = 0, \quad \left.\frac{\partial w^{(o)}}{\partial r}\right|_{r=R_2} = 0, \quad w^{(i)}_{r=R_1} = w^{(o)}_{r=R_1},$$
$$\left.\frac{\partial w^{(i)}}{\partial r}\right|_{r=R_1} = \left.\frac{\partial w^{(o)}}{\partial r}\right|_{r=R_1}, \quad \left.\frac{\partial w^{(i)}}{\partial r}\right|_{r=0} = 0,$$
$$\left.Q_r^{(i)}\right|_{r=R_1} = \left.Q_r^{(o)}\right|_{r=R_1}, \quad \left.M_r^{(i)}\right|_{r=R_1} = \left.M_r^{(o)}\right|_{r=R_1}. \quad (29)$$

Deflections of the inner and outer sections are found as follows:

$$w_1 = c_0 r^4 + c_1 r^2 + c_2 \quad \text{inner section } r \le R_1,$$
$$w_2 = c_6 r^4 + c_3 r^2 + c_4 \ln r + c_5 \quad \text{outer section } R_1 < r < R_2, \quad (30)$$

where c_i are the coefficients similar to those in (5) with A_1 and A_2 as the following

$$A_1 = \frac{b_{19} b_4 - b_{18} b_{16}}{b_{20} b_{16} - b_{19} b_{17}},$$
$$A_2 = \frac{-\left(b_{18} + b_{20} A_1\right)}{b_{19}}, \quad (31)$$

where the coefficients of b_i have been given in Appendix A.

The equation of energy in this case is similar to (21) with the same constants of L_1, L_2, and L_3. Thus, the remaining calculations are similar to those in Section 2.1 from (22) to (28).

2.3. System with Annular Piezoelectric Plate and Simple Support. In this case (Figure 1(c)), the plate is divided into two parts: one is the inner section, where $r \le R_1$ and the other is the outer section, where $R_1 < r \le R_2$. Equations (1)–(3) can be applied for both the inner and outer sections. Outer section is a piezoelectric multilayer annular plate and inner section is a nonpiezoelectric plate. Boundary conditions are similar to (4). Deflections of the inner and outer sections can be found as

$$w_1 = c_0 r^4 + c_1 r^2 + c_2 \quad \text{inner section } r \le R_1,$$
$$w_2 = c_6 r^4 + c_3 r^2 + c_4 \ln r + c_5 \quad \text{outer section } R_1 < r < R_2, \quad (32)$$

where the coefficients of c_i have been given in Appendix B. The total energy is the combination of the inner and outer strain energies as follows:

$$U = \int_{R_1}^{R_2}\int_0^{2\pi}\int_0^{h_p} dU_{po}\, dzr\, d\theta\, dr + \int_{R_1}^{R_2}\int_0^{2\pi}\int_{-h_m}^{0} dU_{mo}\, dzr\, d\theta\, dr + \int_{0}^{R_1}\int_0^{2\pi}\int_{-h_m}^{0} dU_{mi}\, dzr\, d\theta\, dr. \quad (33)$$

Substituting of (9) and (11) into this equation and using the previous equations of (2), (12)–(14), (19), and (32) lead to

$$U = L_1 E_3^2 + L_2 E_3 + L_3, \quad (34)$$

where L_1, L_2, and L_3 are the constants as given in Appendix B. The remaining equations are similar to those in Section 2.1 from (22) to (28).

2.4. System with Annular Piezoelectric Plate and Clamped Support. In this case, a similar method as in Section 2.3 is applied only with different boundary conditions. (Figure 1(d)). The support in this case is clamped and the boundary conditions are similar to those in Section 2.2. Thus, the deflections of the inner and outer sections are similar to (30) with their constants of c_i similar to those in (32) with A_1 and A_2 as follows:

$$A_1 = \frac{b_{19}b_4 - b_{18}b_{16}}{b_{20}b_{16} - b_{19}b_{17}}, \qquad A_2 = \frac{-(b_{18} + b_{20}A_1)}{b_{19}}, \quad (35)$$

where the coefficients of b_i have been given in Appendix B. Equation of energy in this case is similar to (34) with the same constants of L_1, L_2, and L_3. The remaining equations are similar to those in Section 2.1 from (22) to (28).

3. Results and Discussions

In this paper, the strain energy solution is used in order to paramedical studies, effects of support conditions and substrate material on the generated power by the circular piezoelectric diaphragm. The substrate materials are the circular metal plate of aluminum and steel that are equipped with piezoelectric material. The excitation signal is a uniform pressure of 40 mmHg (5330 Pa) with 1 Hz frequency, which could arise from a blood pressure source. Table 1 summarizes materials' properties that are used in this section.

Figures 2 and 3 show the variations of generated energy versus the radius ratio (R_1/R_2) for each support condition. It can be seen that the generated energy has an optimum value related to piezoelectric plate radius R_1/R_2. Also, the effect of boundary conditions on the generated energy is evident. It can be concluded that harvested energy in the case of simple support is more than clamped support for the same conditions (same PZT piezoelectric thickness 350 μm, applied pressure 40 mmHg, and aluminum substrate material with 175 μm thickness). The piezoelectric material consumption in the case of simple support is less than clamped support because its optimum value of R_1/R_2 is smaller than clamped support (Figure 2). This optimum value of R_1/R_2 in Figure 3 for simple support is greater than clamped support. Thus, in this case, the piezoelectric material consumption is also less for simple support condition. In each curve, harvested energy with increase of piezoelectric material increases, but in contrast, the bending resistance increases as well, consequently resulting in less deflection and then less generated energy. By this way, each curve has an optimum value (maximum value).

Table 1: Piezoelectric and substrate materials properties.

ε_{33}^T ($\times 10^{-12}$)	S_{11}^E, S_m ($\times 10^{-12}$ m^{2}N^{-1})	ν	d_{31} ($\times 10^{-12}$ mV)	Materials
30090	16.5	0.3	−274	PZT-5H
48675	1.25	0.3	−1063	PMN-%33PT
—	0.14286	—	—	Aluminum
—	5	—	—	Steel

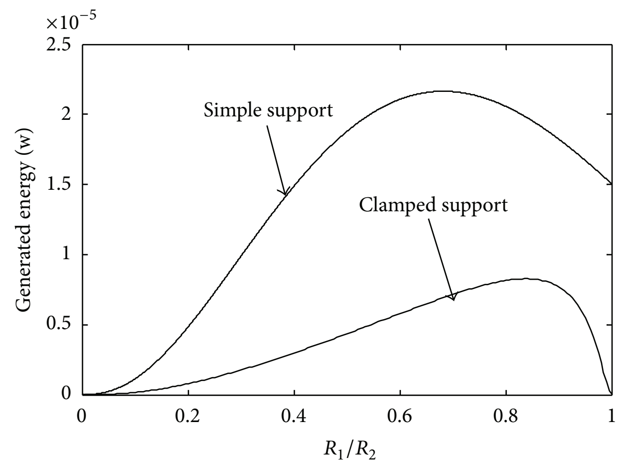

Figure 2: Generated energy for the simple and clamped supports according to the variations of piezoelectric plate radius (R_2 = 20 mm) (Sections 2.1 and 2.2).

Figure 4 shows the effect of piezoelectric thickness on the generated energy in the case of simple support condition (Section 2.1). It is observed that generated power has an optimum value related to piezoelectric thickness variations. It increases with increase of piezoelectric thickness, but in contrast the bending resistance increases as well, consequently resulting in less deflection and then less harvested energy. It should be mentioned that piezoelectric power is proportional to deflection. Thus, generated power should be in good agreement with the piezoelectric thickness and radius. The results have been calculated with the outer radius of 20 mm, AL substrate plate thickness of 175 μm, PZT material and

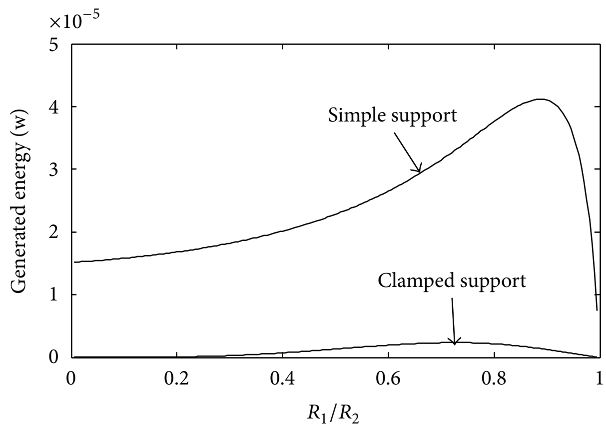

FIGURE 3: Generated energy for the simple and clamped supports according to the variations of piezoelectric plate radius (R_2 = 20 mm) (Sections 2.3 and 2.4).

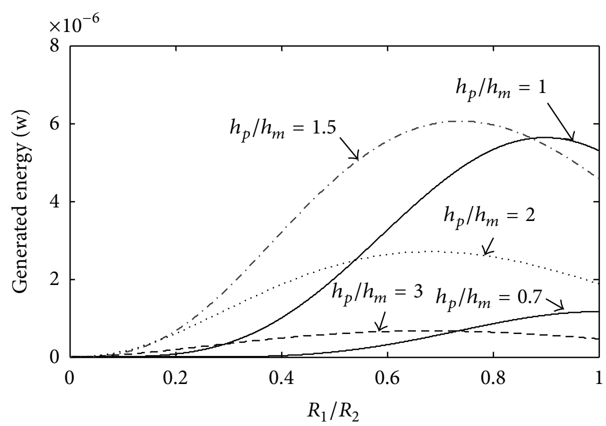

FIGURE 4: Effect of piezoelectric thickness on generated energy in the case of simple support (Section 2.1).

applied pressure of 5330 pa. The harvested energy for h_p/h_m = 1.5 and R_1/R_2 = 0.72 is maximum and equal to 6 μW.

Figure 5 shows the generated energy that is provided by different piezoelectric materials in the case of simple support condition (Section 2.1). To investigate this effect, two materials of PMN-PT and PZT have been considered. It is observed that generated power is sensitive to the type of piezoelectric material. In these results, the piezoelectric thickness is 350 μm with aluminum substrate material of 175 μm thickness.

Also, the material substrate affects the results. This has been shown in Figure 6 generated energy for the aluminum substrate is more than steel substrate. Since the aluminum stiffness is less than steel stiffness, its deflection is more and consequently it provided more generated energy.

4. Conclusions

An analytical model using strain energy method for piezoelectric circular diaphragm generator has been presented. A parametrical study to investigate the effects of various parameters on the generated power has been performed.

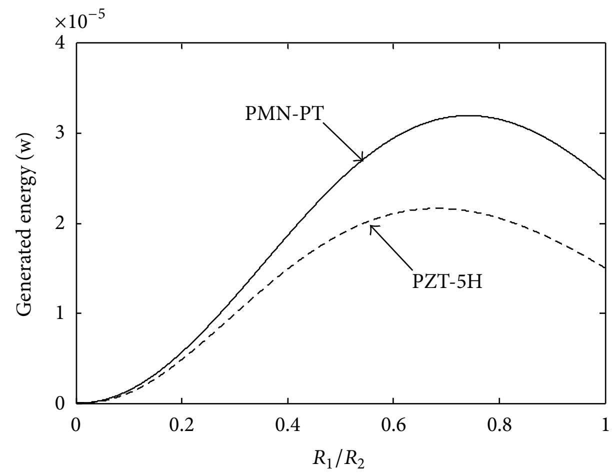

FIGURE 5: Effect of piezoelectric material on generated energy in the case of simple support (R_2 = 20 mm) (Section 2.1).

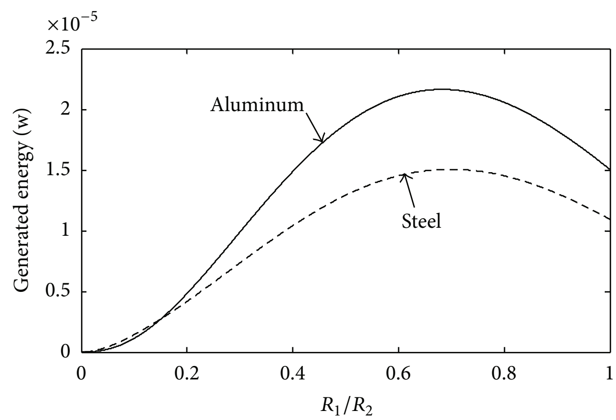

FIGURE 6: Effect of substrate material on generated energy with simple support conditions (Section 2.1).

With the proposed model, the generated power has been compared in four cases of simple and clamped supports conditions under uniformly distributed pressure. It was shown that the boundary conditions, material, and radius and thickness of piezoelectric layer and substrate material affect the results. Therefore, generated power should be in good agreement with the piezoelectric thickness and radius with a special support condition.

Appendices

A.

Coefficients of (5). Consider

$$\begin{gathered} c_0 = \frac{p}{64D_t}, \qquad c_1 = F_1, \\ c_2 = A_3 - b_3A_1 + b_2A_2 - b_2F_1 - b_1, \\ c_3 = A_2, \qquad c_4 = A_1, \\ c_5 = A_3, \qquad c_6 = \frac{p}{64D}, \end{gathered} \tag{A.1}$$

where

$$A_1 = \frac{b_4 b_{13} - b_{12} b_{16}}{b_{14} b_{16} - b_{13} b_{17}}, \qquad A_2 = \frac{-\left(b_{12} + b_{14} A_1\right)}{b_{13}},$$
$$A_3 = -\left(b_7 + b_8 A_2 + b_9 A_1\right), \qquad F_1 = \frac{-b_{15}}{b_{10}} A_2 - \frac{b_{11}}{b_{10}} A_1,$$
$$b_1 = \frac{pR_1^4}{64}\left(\frac{1}{D_t} - \frac{1}{D}\right), \qquad b_2 = R_1^2,$$
$$b_3 = -\ln R_1, \qquad b_4 = \frac{pR_1^3}{16}\left(\frac{1}{D_t} - \frac{1}{D}\right), \qquad b_5 = 2R_1,$$
$$b_6 = \frac{-1}{R_1}, \qquad b_7 = \frac{pR_2^4}{64D}, \qquad b_8 = R_2^2,$$
$$b_9 = \ln R_2, \qquad b_{10} = 2\left(1+\nu\right) D_t, \qquad b_{11} = \frac{D}{R_1^2}\left(1-\nu\right),$$
$$b_{12} = \frac{-p}{16}\left(3+\nu\right) R_2^2, \qquad b_{13} = -2D\left(1+\nu\right),$$
$$b_{15} = b_{13}, \qquad b_{14} = \frac{D}{R_2^2}\left(1-\nu\right),$$
$$b_{16} = \frac{-b_5\left(b_{15} + b_{10}\right)}{b_{10}}, \qquad b_{18} = \frac{p}{16D} R_2^3,$$
$$b_{19} = 2R_2, \qquad b_{20} = \frac{1}{R_2}. \tag{A.2}$$

Coefficients of (19). Consider

$$I_1 = \left(\left(s_m h_p^3 + s_{11}^E h_m^3\right) u_2^2 + 3\left(s_{11}^E h_m^2 - s_m h_p^2\right) u_1 u_2 + 3\left(s_{11}^E h_m - s_m h_p\right) u_1^2\right) \times \left(3\left(1-\nu^2\right) s_{11}^E s_m u_2^2\right)^{-1},$$
$$I_2 = \frac{d_{31}\left(h_p^2 u_2 - 2h_p u_1\right)}{2u_2\left(1-\nu\right) s_{11}^E},$$
$$I_3 = \frac{h_m^3 u_2^2 + 3h_m^2 u_1 u_2 + 3h_m u_1^2}{3u_2^2\left(1-\nu^2\right) s_m}, \qquad I_4 = \frac{-I_2}{I_1\left(1+\nu\right)}. \tag{A.3}$$

Coefficients of (21). Consider

$$L_1 = G_1 + G_4, \qquad L_2 = G_2 + G_5, \qquad L_3 = G_3 + G_6 + G_7, \tag{A.4}$$

where

$$\begin{aligned} G_1 &= \pi h_p R_1^2\left(\frac{\varepsilon_{33}^T}{2} - e_4 d_{31}\right) + \pi H_1\left(k_9 - e_3 d_{31}\right) R_1^2 + \pi H_2 k_6 R_1^2, \\ G_2 &= \pi H_1 R_1^4\left(\frac{k_8 + k_{13} - \left(e_2 + e_5\right) d_{31}}{4}\right) + \pi H_1\left(k_7 - e_1 d_{31}\right) + \pi H_2 R_1^4\left(\frac{k_4 + k_{11}}{4}\right) + \pi H_2 k_3 R_1^2, \end{aligned} \tag{A.5}$$

$$\begin{aligned} G_3 &= \pi H_2 k_1 R_1^2 + \pi H_2 R_1^4\left(\frac{k_2 + k_{10}}{4}\right) + \pi H_2 R_1^6\left(\frac{k_5 + k_{12}}{6}\right), \\ G_4 &= \pi H_3 q_6 R_1^2, \\ G_5 &= \pi H_3 q_3 R_1^2 + \pi H_3 R_1^4\left(\frac{q_4 + q_8}{4}\right), \\ G_6 &= \pi H_3 q_1 R_1^2 + \pi H_3 R_1^4\left(\frac{q_2 + q_7}{4}\right) + \pi H_3 R_1^6\left(\frac{q_5 + q_9}{6}\right), \\ G_7 &= 2\pi H_3\left[\left(\frac{x_1 + x_6}{2}\right) V_5 + \left(\frac{x_2 + x_7}{2}\right) V_3 + \left(\frac{x_3 + x_8}{2}\right) V_4 + \left(\frac{x_4 + x_9}{2}\right) V_1 + \left(\frac{x_5 + x_{10}}{2}\right) V_2\right], \end{aligned} \tag{A.6}$$

where

$$x_1 = -\left(B_1 g_1 + B_2 g_3 + B_3 g_2\right), \qquad x_2 = -\left(B_1 g_2 + B_2 g_1\right),$$
$$x_3 = -\left(B_1 g_3 + B_3 g_1\right), \qquad x_4 = -\left(B_2 g_2\right),$$
$$x_5 = -\left(B_3 g_3\right), \qquad x_6 = -\left(B_1 g_1 + B_4 g_5 + B_5 g_4\right),$$
$$x_7 = -\left(B_1 g_4 + B_4 g_1\right), \qquad x_8 = -\left(B_1 g_5 + B_5 g_1\right),$$
$$x_9 = -\left(B_4 g_4\right), \qquad x_{10} = -\left(B_5 g_5\right),$$
$$H_1 = h_p\left(\frac{h_p}{2} - z_c\right), \qquad H_2 = \frac{\left(h_p - z_c\right)^3 - z_c^3}{3},$$
$$H_3 = \frac{\left(h_m + z_c\right)^3 - z_c^3}{3},$$
$$q_1 = -\left(B_6 f_1\right), \qquad q_2 = -\left(B_7 f_1 + B_6 f_2\right),$$
$$q_3 = -\left(I_4 f_1 + B_6 f_3\right), \qquad q_4 = -\left(B_7 f_3 + I_4 f_2\right),$$
$$q_5 = -B_7 f_2, \qquad q_6 = -I_4 f_3,$$
$$q_7 = -\left(B_8 f_1 + B_6 f_4\right), \qquad q_8 = -\left(I_4 f_4 + B_8 f_3\right),$$
$$q_9 = -B_8 f_4, \qquad k_1 = -\left(B_6 e_1\right),$$
$$k_2 = -\left(B_7 e_1 + B_6 e_2\right), \qquad k_3 = -\left(I_4 e_1 + B_6 e_3\right),$$
$$k_4 = -\left(B_7 e_3 + I_4 e_2\right), \qquad k_5 = -B_7 e_2$$
$$k_6 = -I_4 e_3, \qquad k_7 = -\left(B_6 e_4\right),$$
$$k_8 = -\left(B_7 e_4\right), \qquad k_9 = -\left(I_4 e_4\right),$$
$$k_{10} = -\left(B_8 e_1 + B_6 e_5\right), \qquad k_{11} = -\left(I_4 e_5 + B_8 e_3\right),$$
$$k_{12} = -\left(B_8 e_5\right), \qquad k_{13} = -\left(B_8 e_4\right),$$
$$g_1 = -BB_1\left(1+\nu\right), \qquad g_2 = -B\left(B_2 + \nu B_4\right),$$

$$g_3 = -B(B_3 + \nu B_5), \qquad g_4 = -B(B_4 + \nu B_2)$$
$$g_5 = -B(B_5 + \nu B_3), \qquad f_1 = -BB_6(1+\nu),$$
$$f_2 = -B(B_7 + \nu B_8), \qquad f_3 = -BI_4(1+\nu),$$
$$f_4 = -B(B_8 + \nu B_7), \qquad e_1 = -AB_6(1+\nu),$$
$$e_2 = -A(B_7 + \nu B_8), \qquad e_3 = -AI_4(1+\nu),$$
$$e_4 = Ad_{31}(1+\nu), \qquad e_5 = -A(B_8 + \nu B_7),$$
$$A = \frac{1}{s_{11}^E(1-\nu^2)}, \qquad B = \frac{1}{s_m(1-\nu^2)},$$
$$B_1 = I_6 a_4(1-\nu), \qquad B_2 = I_6(a_5 - \nu a_6),$$
$$B_3 = I_6(a_7 - \nu a_8), \qquad B_4 = I_6(a_6 - \nu a_5),$$
$$B_5 = I_6(a_8 - \nu a_7), \qquad B_6 = a_1 I_5(1-\nu),$$
$$B_7 = I_5(a_2 - \nu a_3), \qquad B_8 = I_5(a_3 - \nu a_2),$$
$$a_1 = -2c_1 D_t(1+\nu), \qquad a_2 = -4c_0 D_t(3+\nu),$$
$$a_3 = -4c_0 D_t(1+3\nu), \qquad a_4 = -2c_3 D(1+\nu),$$
$$a_5 = -4c_6 D(3+\nu), \qquad a_6 = -4c_6 D(1+3\nu),$$
$$a_7 = c_4 D(1-\nu), \qquad a_8 = c_4 D(\nu-1),$$
$$V_1 = \frac{1}{6}\left(R_2^6 - R_1^6\right), \qquad V_2 = \frac{1}{2R_1^2} - \frac{1}{2R_2^2},$$
$$V_3 = \frac{1}{4}\left(R_2^4 - R_1^4\right), \qquad V_4 = \ln\frac{R_2}{R_1},$$
$$V_5 = \frac{1}{2}\left(R_2^2 - R_1^2\right), \qquad I_5 = \frac{1}{I_1(1-\nu^2)},$$
$$I_6 = \frac{-BD}{I_3}. \tag{A.7}$$

B.

Coefficients of (32). Consider

$$c_0 = \frac{p}{64D}, \qquad c_1 = F_1,$$
$$c_2 = A_3 - b_3 A_1 + b_2 A_2 - b_2 F_1 - b_1,$$
$$c_3 = A_2, \qquad c_4 = A_1, \qquad c_5 = A_3, \qquad c_6 = \frac{p}{64D_t}, \tag{B.1}$$

where

$$A_1 = \frac{b_4 b_{13} - b_{12} b_{16}}{b_{14} b_{16} - b_{13} b_{17}}, \qquad A_2 = \frac{-(b_{12} + b_{14} A_1)}{b_{13}},$$
$$F_1 = \frac{-b_{15}}{b_{10}} A_2 - \frac{b_{11}}{b_{10}} A_1, \qquad A_3 = -(b_7 + b_8 A_2 + b_9 A_1),$$
$$b_1 = \frac{-pR_1^4}{64}\left(\frac{1}{D_t} - \frac{1}{D}\right), \qquad b_2 = R_1^2, \qquad b_3 = -\ln R_1,$$
$$b_4 = \frac{-pR_1^3}{16}\left(\frac{1}{D_t} - \frac{1}{D}\right), \qquad b_5 = 2R_1,$$
$$b_6 = \frac{-1}{R_1}, \qquad b_7 = \frac{pR_2^4}{64D_t}, \qquad b_8 = R_2^2,$$
$$b_9 = \ln R_2, \qquad b_{10} = 2(1+\nu)D,$$
$$b_{11} = \frac{D_t}{R_1^2}(1-\nu), \qquad b_{12} = \frac{-p}{16}(3+\nu)R_2^2,$$
$$b_{13} = -2D_t(1+\nu), \qquad b_{14} = \frac{D_t}{R_2^2}(1-\nu),$$
$$b_{15} = b_{13}, \qquad b_{16} = \frac{-b_5(b_{15} + b_{10})}{b_{10}},$$
$$b_{17} = \frac{b_6 b_{10} - b_5 b_{11}}{b_{10}}, \qquad b_{18} = \frac{p}{16D} R_2^3,$$
$$b_{19} = 2R_2, \qquad b_{20} = \frac{1}{R_2}. \tag{B.2}$$

Coefficients of (34). Consider

$$L_1 = G_1 + G_4, \qquad L_2 = G_2 + G_5, \qquad L_3 = G_3 + G_6 + G_7, \tag{B.3}$$

where

$$\begin{aligned}
G_1 &= 2\pi h_p V_5\left(\frac{\varepsilon_{33}^T}{2} - e_5 d_{31}\right) + 2\pi H_1(k_{13} - e_4 d_{31})V_5 \\
&\quad + 2\pi H_2 k_9 V_5, \\
G_2 &= 2\pi H_2 k_4 V_5 + \pi H_2(k_5 + k_{17})V_3 + \pi H_2(k_6 + k_{18})V_4 \\
&\quad + 2\pi H_1(k_{10} - e_1 d_{31})V_5 \\
&\quad + \pi H_1(k_{11} + k_{21} - (e_2 + e_6)d_{31})V_3 \\
&\quad + \pi H_1(k_{12} + k_{22} - (e_3 + e_7)d_{31})V_4, \\
G_3 &= \pi H_2\left[(k_1 + k_{14})V_5 + (k_2 + k_{15})V_3\right. \\
&\quad \left. + (k_3 + k_{16})V_4 + (k_7 + k_{19})V_1 + (k_8 + k_{20})V_2\right], \\
G_4 &= 2\pi H_3 q_9 V_5, \\
G_5 &= 2\pi H_3 q_4 V_5 + \pi H_3(q_5 + q_{13})V_3 + \pi H_3(q_6 + q_{14})V_4, \\
G_6 &= \pi H_3\left[(q_1 + q_{10})V_5 + (q_2 + q_{11})V_3 + (q_3 + q_{12})V_4\right. \\
&\quad \left. + (q_7 + q_{15})V_1 + (q_8 + q_{16})V_2\right], \\
G_7 &= \pi H_3\left[x_1 R_1^2 + (x_2 + x_4)\frac{R_1^4}{4} + (x_3 + x_5)\frac{R_1^6}{4}\right],
\end{aligned} \tag{B.4}$$

where

$$
\begin{gathered}
x_1 = -(B_6 g_1), \qquad x_2 = -(B_7 g_1 + B_6 g_2), \\
x_3 = -(B_7 g_2), \qquad x_4 = -(B_8 g_1 + B_6 g_3), \\
x_5 = -(B_8 g_3), \qquad q_1 = -(B_1 f_1 + B_2 f_3 + B_3 f_2), \\
q_2 = -(B_1 f_2 + B_2 f_1), \qquad q_3 = -(B_1 f_3 + B_3 f_1), \\
q_4 = -(B_1 f_4 + I_4 f_1), \qquad q_5 = -(B_2 f_4 + I_4 f_2), \\
q_6 = -(B_3 f_4 + I_4 f_3), \qquad q_7 = -(B_2 f_2), \\
q_8 = -(B_3 f_3), \qquad q_9 = -I_4 f_4, \\
q_{10} = -(B_1 f_1 + B_4 f_6 + B_5 f_5), \qquad q_{11} = -(B_1 f_5 + B_4 f_1), \\
q_{12} = -(B_1 f_6 + B_5 f_1), \qquad q_{13} = -(B_4 f_4 + I_4 f_5), \\
q_{14} = -(B_5 f_4 + I_4 f_6), \qquad q_{15} = -(B_4 f_5), \\
q_{16} = -(B_5 f_6), \qquad k_1 = -(B_1 e_1 + B_2 e_3 + B_3 e_2), \\
k_2 = -(B_1 e_2 + B_2 e_1), \qquad k_3 = -(B_1 e_3 + B_3 e_1), \\
k_4 = -(B_1 e_4 + I_4 e_1), \qquad k_5 = -(B_2 e_4 + I_4 e_2), \\
k_6 = -(B_3 e_4 + I_4 e_3), \qquad k_7 = -(B_2 e_2), \\
k_8 = (-B_3 e_3), \qquad k_9 = -(I_4 e_4), \\
k_{10} = -(B_1 e_5), \qquad k_{11} = -(B_2 e_5) \\
k_{12} = -(B_3 e_5), \qquad k_{13} = -(I_4 e_5), \\
k_{14} = -(B_1 e_1 + B_4 e_7 + B_5 e_4), \qquad k_{15} = -(B_1 e_6 + B_4 e_1), \\
k_{16} = -(B_1 e_7 + B_5 e_1), \qquad k_{17} = -(B_4 e_4 + I_4 e_6), \\
k_{18} = -(B_5 e_4 + I_4 e_7), \qquad k_{19} = -(B_4 e_6), \\
k_{20} = -(B_5 e_5), \qquad k_{21} = -(B_4 e_5), \qquad k_{22} = k_{20}, \\
g_1 = -B B_6 (1 + \nu), \qquad g_2 = -B (B_7 + \nu B_8), \\
g_3 = -B (B_8 + \nu B_7), \\
f_1 = -B B_1 (1 + \nu), \qquad f_2 = -B (B_2 + \nu B_4), \\
f_3 = -B (B_3 + \nu B_5), \qquad f_4 = -B I_4 (1 + \nu), \\
f_5 = -B (B_4 + \nu B_2), \qquad f_6 = -B (B_5 + \nu B_3), \\
e_1 = -A B_1 (1 + \nu), \qquad e_2 = -A (B_2 + \nu B_4), \\
e_3 = -A (B_3 + \nu B_5), \qquad e_4 = -A I_4 (1 + \nu), \\
e_5 = A d_{31} (1 + \nu), \qquad e_6 = -A (B_4 + \nu B_2), \\
e_7 = -A (B_5 + \nu B_3), \qquad A = \frac{1}{s_{11}^E (1 - \nu^2)}, \\
B = \frac{1}{s_m (1 - \nu^2)}, \\
B_1 = I_5 a_4 (1 - \nu), \qquad B_2 = I_5 (a_5 - \nu a_6), \\
B_3 = I_5 (a_7 - \nu a_8), \qquad B_4 = I_5 (a_6 - \nu a_5), \\
B_5 = I_5 (a_8 - \nu a_7), \qquad B_6 = a_1 I_6 (1 - \nu), \\
B_7 = I_6 (a_2 - \nu a_3), \qquad B_8 = I_6 (a_3 - \nu a_2), \\
a_1 = -2 c_1 D (1 + \nu), \qquad a_2 = -4 c_0 D (3 + \nu), \\
a_3 = -4 c_0 D (1 + 3\nu), \qquad a_4 = -2 c_3 D_t (1 + \nu), \\
a_5 = -4 c_6 D_t (3 + \nu), \qquad a_6 = -4 c_6 D_t (1 + 3\nu), \\
a_7 = c_4 D_t (1 - \nu), \qquad a_8 = c_4 D_t (\nu - 1).
\end{gathered} \tag{B.5}
$$

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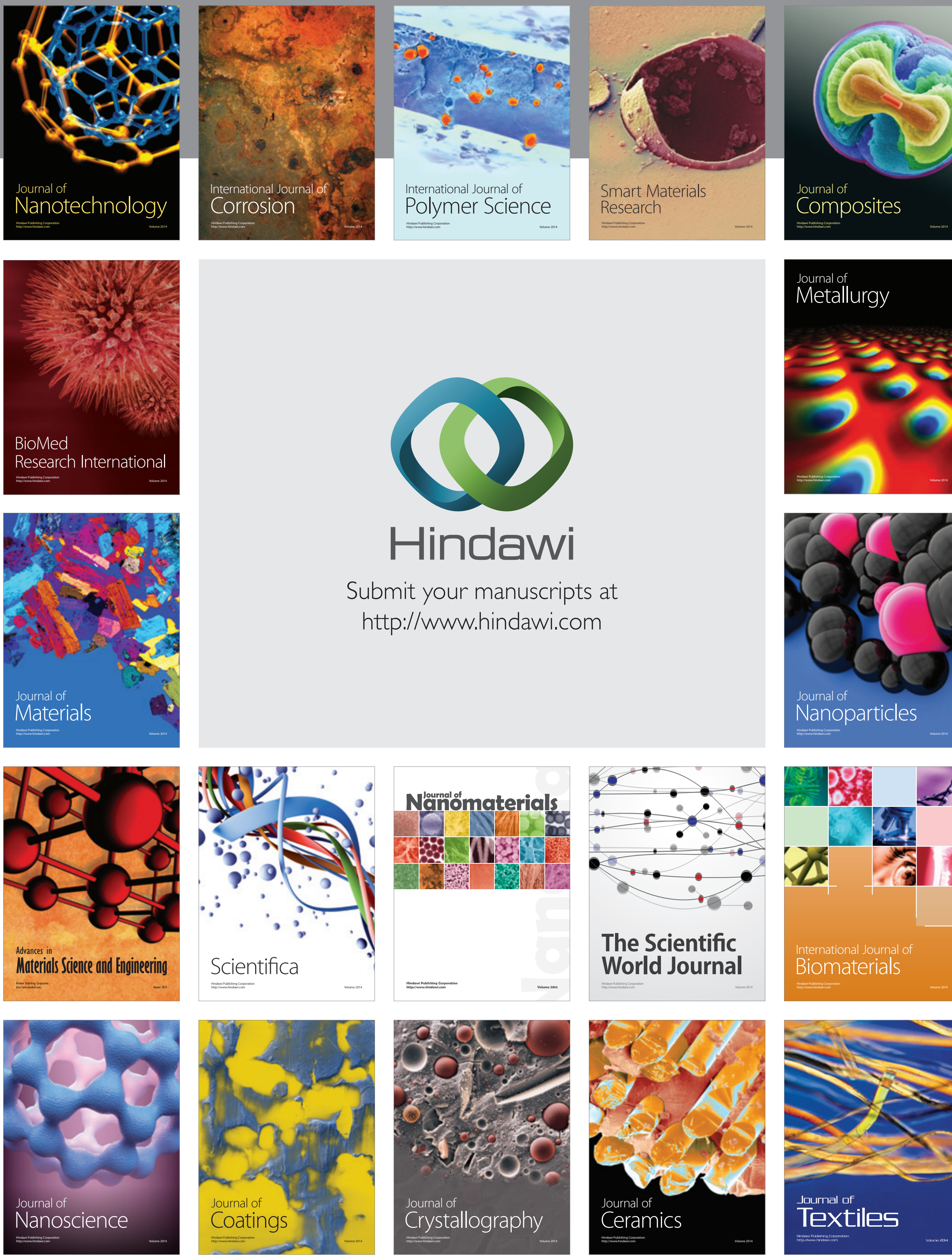

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