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Piezoelectric generators for biomedical and dental applications: Effects of cyclic loading

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Abstract This paper presents the results of a study of the effect of cyclic loading parameters on the performance of piezo crystals. The output power of the crystals was observed to increase with parameters such as the cyclic frequency and the dynamic load range. However, the output power also decreased with increasing mean load. The efficiency of the crystal was calculated based on the mechanical energy applied to the piezo crystal. The ratio of the electrical output to mechanical energy input was taken as the efficiency of the crystal. This ratio was seen to increase with the cycling frequency, and also with the dynamic load range. However, increasing mean load caused the efficiency to drop significantly. The implications of the results are discussed for possible applications implanted bioMEMS and microelectronics systems.

1 Introduction

The conversion of kinetic energy to electrical energy has been investigated by a number of researchers for electrical power generation [1–6]. Within this framework, piezoelectric materials have been investigated as essential elements for high-power pulse generation [1–6]. Electrical energy is generated when an applied force overcomes internal inductance or capacitance of a material. For a piezoelectric material, the internal fields are stored in the ohmic lattice of the material. Mechanical deformation of the material (by the applications of static or dynamic loads) generates the output voltage required to power the piezoelectric pulse generator. Experiments have been performed by Xu et al. [7], who applied quasi-static or dynamic stress to lead zirconia titanate (PZT) piezoelectric ceramics. They reported that dynamic and quasi-static loading produced equal magnitudes of output voltage. They also reported that the dynamic loading produced a unidirectional voltage, while the quasi-static case generated a bi-directional voltage.

However, Engel et al. [5] have reported different results for similar experiments performed on piezoelectric systems under dynamic and quasi-static systems. They discovered that the dynamic loading yielded a much higher output voltage (up to 10 times more) than the quasi-static case. They compared their experimental measurements of power generation with predictions from simulations. Their theory suggests that the material thickness to cross sectional area: ratio (TAR = hpiezo/A) can be used to maximize output power. A higher TAR results in a higher output voltage, while a lower output current. In an effort to maximize output power, the voltage and current have to be maximized. The overall effect of thickness to area ratio (TAR) will be dominated by the larger contribution of voltage to the product of voltage and current. In other words, piezoelectric power output increases with increasing TAR.

Two models have been proposed to explain the behavior of piezoelectric generators [5]. The first is a mechanical model that provides information on the displacement (deformation) of the material due to applied force and thus the generated voltage, while the second is an electrical model that is used to identify electrical conditions that are needed to generate maximum current [5]. These models provide insights into how loading/deformation can result in piezoelectric power generation under static loading conditions. However, models that explain the possible ranges of responses under cyclic

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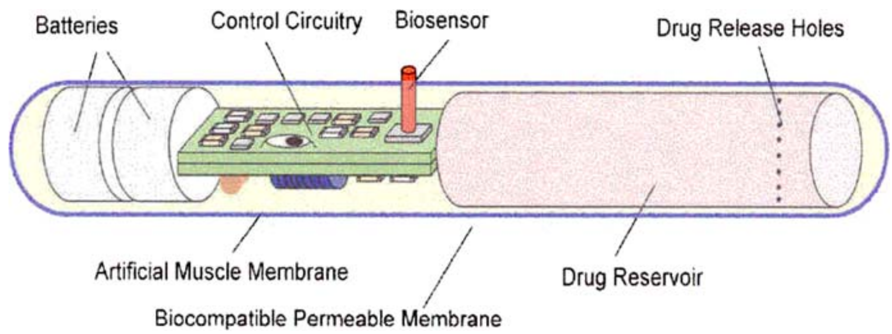

Fig. 1 Schematic of a drug delivery system (adapted from Madou [8])

loading are yet to be developed. Furthermore, although significant voltages may be generated by loading piezoelectric crystals, prior work [1–7] has shown that the overall power that is generated is relatively small. This suggests potential applications in small structures that have only limited power requirements.

One of the potential biomedical applications of piezoelectric generators is in implantable drug delivery systems, such as the bio-micro-electro-mechanical systems (BioMEMS) structure shown in Fig. 1 [8]. Although such a device has been proposed as a system that can deliver drugs locally to diseased cells and organs [8], the powering of such devices poses some significant technological challenges. One approach, which is shown in Fig. 1, is to use conventional thin film batteries and power capacitors [8, 9]. These are commercially available [9], and are known to generate sufficient power for bioMEMS (Table 1). However, they are difficult to recharge within the body.

An alternative approach is to use a piezoelectric generator to recharge and/or power drug delivery systems such as the one shown in Fig. 1. This is attractive because the systems can then be recharged by mechanical energy from moving fluids or solids within the body. Simple back-of-the-envelope calculations show that the kinetic energy from moving blood is insufficient to generate the required power levels in piezoelectric thin film generators with appropriate sizes for bioMEMS structures [10].

In contrast, the significant mechanical energy associated with occlusal contact (typical maximum loads between 100-200N) may be in the regime that is sufficient for the generation of adequate power generation for applications in bioMEMS and microelectronics systems. With adequate electrical isolation, the piezoelectric generators may be inserted between the coping of a dental crown and the metal abutment, as shown in Fig. 2, which is adapted from Ref. [11]. Such a system could tap the mechanical energy that is provided annually by ~1 million contact cycles

Table 1 Power generated from small capacitors and thick/thin film batteries (data obtained from Ref. [8])

Power capacitor	4 μJ/mm^3	1 μW for 4 h
Thick film battery	1 J/mm^3	270 μW for 1 h
Thin film battery	2.5 J/mm^3	0.7 mW for 1 h

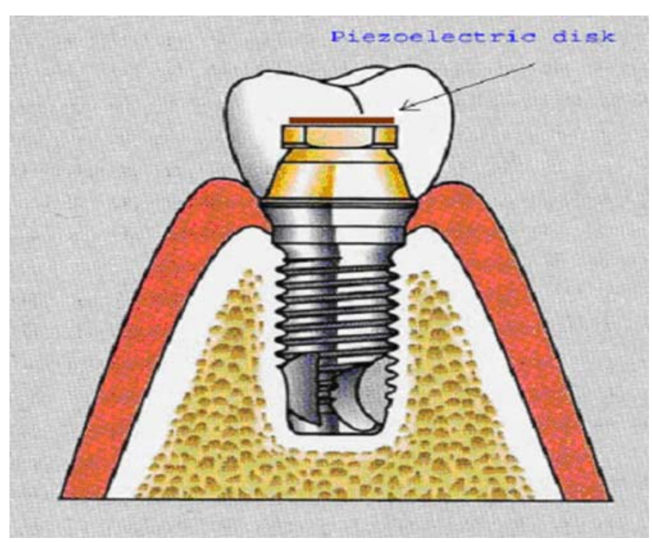

Fig. 2 Possible location of a piezoelectric layer, in between the coping of a dental crown and the metal abutment of an implant

[11] and bruxism [12]. However, the potential electromechanical response of such a system has not been fully explored.

This paper presents the results of an experimental study of the piezoelectric power generation that can be achieved under cyclic loading conditions that simulate the range of loads and cyclic frequencies that are relevant to normal occlusal activity. The experiments are performed on a piezoelectric crystal using a micro-tester that was developed originally for the testing of MEMS structures [13]. The studies explore the effects of cyclic loading at different frequencies and load ranges, with different applied resistances at the output. The possible implications of the results are then discussed for applications in piezoelectric power generation from occlusal contacts.

2 Experimental procedure

The piezoelectric crystals that were used in this study were obtained from Staveley Sensors Inc., East Hartford, CT. The characteristics of the crystals are tabulated in Table 2. They had a diameter of 25 and a thickness of 6.3 mm. The crystals were sandwiched between two Al blocks to acquire or impart electric signal to them. One Al block was then placed in load train, insulated from other components by a ZrO_2 block. The ZrO_2 was housed in an Al block connected to load cell, which was mounted on an *x*-*y* stage. The other Al block covering the piezo crystal was connected to a piezoelectric actuator made by Polytec PI, Inc. (MA, USA).

The piezoelectric actuator was powered by a wave function generator that produced sinusoidal signals, with different frequencies, different amplitudes, and different offsets. The signal from the wave function generator was then sent to a PI amplifier and then fed to the PI piezoelectric actuator.

A range of frequencies from 0.1 to 30 Hz were chosen for the first set of tests conducted at a cyclic load amplitude of 52 N and a constant mean load of 30 N. One set of experiments was carried out, with a varying load range of 27 to 54 N, at a constant mean load 36 N. Another set of tests was performed at a constant load range of 53 N but at a varying mean load of 3.7 N to 4.4 N. The set up is shown in Fig. 3.

Table 2 Characteristics of the piezo electric crystal used in this study

Properties	Symbol	Magnitude	Units
Diameter	d	15	mm
Thickness (mm)	h	3	mm
Young's modulus	E	111	GPa
Capacitance	C_p	2.08	nF
Load proportionality constant	d_{33}	598	C/N

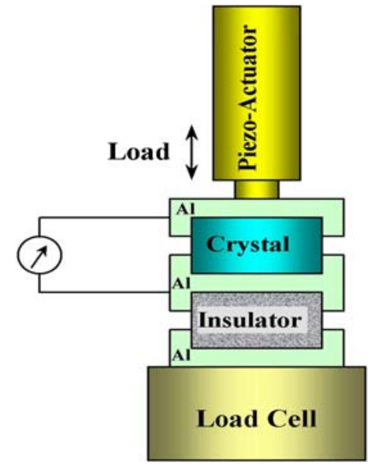

Fig. 3 Schematic of experimental setup for the examination of effect of load range, mean load and frequency on power generation of piezo crystal

3 Results and discussion

3.1 Effects of cyclic loading

The results of mechanical testing of the piezo crystal are summarized in Figs. 4–6. The voltage decreases with increasing mean load (Fig. 4), but the increases with increasing cyclic frequency (Fig. 5). The voltage also increases with increasing resistance, as shown in Fig. 6. The variation of the output voltage with load is presented in Fig. 6. The output voltage increases with the load range in a nearly-linear manner. It clearly shows that the dynamic range of the applied load is directly responsible for the output power.

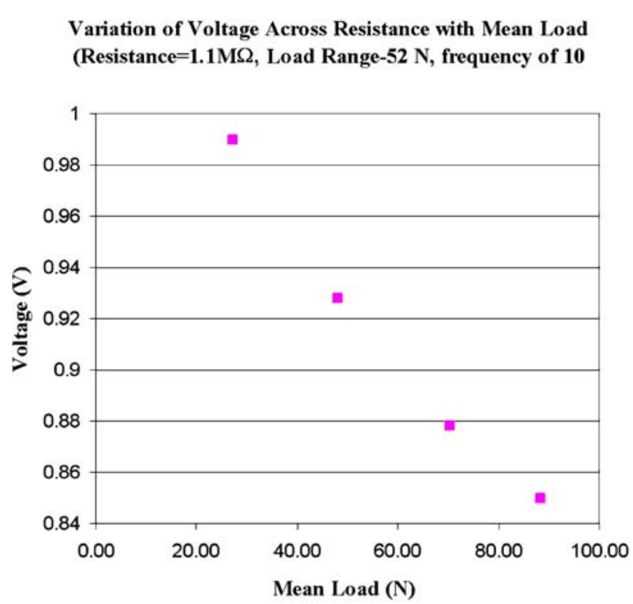

Fig. 4 Effect of mean load on output voltage

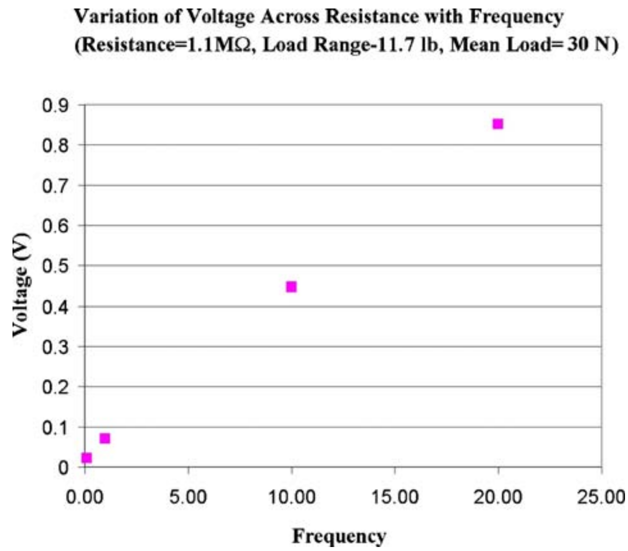

Fig. 5 Effect of frequency on output voltage

The effect of mean load is shown in Fig. 4. The tests were performed at a constant load range to exclude its effect on the output voltage. The frequency was also maintained at 10 Hz. The mean load has only a small effect on the output voltage. The results show an inverse dependence of the output voltage on the mean load. This implies that for a given dynamic load range, the highest output power is achieved at lowest possible mean load. Mean load here may be thought of as isostatic pressure in piezo crystal. Hence, it affects the mobility of electrons in the crystal lattice.

The output voltage increases with increasing cyclic frequency, as shown in Fig. 5. This can be understood in terms of the increased mechanical work that is performed when the piezo crystal is loaded at a higher frequency. In fact, the mechanical work that is performed on the piezo crystal is proportional to the area under the load-displacement curve. However, this area does not significantly change with the strain rate for this crystal (e.g. same amount of work is performed at a higher strain rate). Hence, more cycles will mean more energy input into the crystal in a given period of time. This higher energy input is seen to have yielded a higher energy output (manifested by a higher output voltage). Hence, doubling the frequency to 20 Hz translates into a near doubling in the output voltage, as shown in Fig. 5.

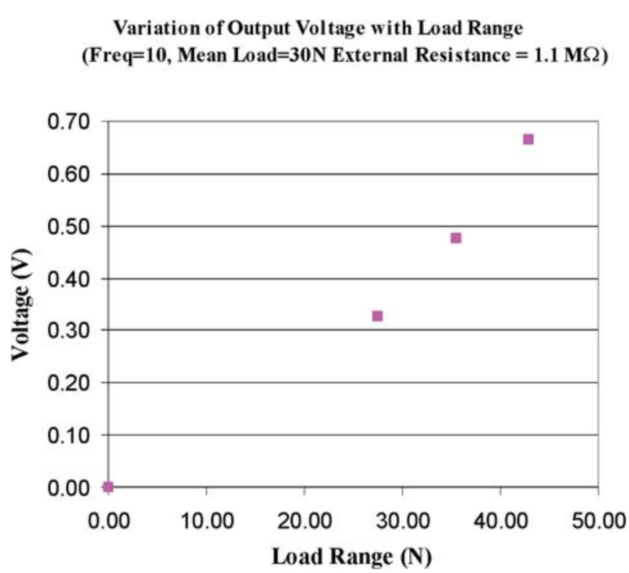

Fig. 6 Voltage vs load range

All these tests were performed with a resistor attached to the crystal. This resistor was chosen to be 1.1 MΩ. In this manner, the output voltage was representative of the power output of the crystal through the relationship: $P = V^2/R$. The dependence of the power output on frequency and dynamic load will then be through this power law, meaning, doubling the frequency will quadruple the output power. An interesting outcome of this experiment is that the power output increases with square of the values for frequency and dynamic load range. This means that the efficiency of the crystal is a function of the frequency and load range, increasing with both of these factors.

Two important conclusions can be made based on the outcome of these experiments. The first one points to the application of piezoelectric crystals in higher frequency applications where higher efficiencies are achieved. The second one points to the higher dynamic load range applications, where the efficiency reaches a maximum. In both of these applications the mean load should be minimized in order for the efficiency to be optimum.

Increasing the dynamic load range at constant mean load and a frequency of 10 Hz increases the output voltage of the piezo crystal. The increase in the output voltage with the load range is summarized in Fig. 2. There is a significant change in the output voltage with an increase in the dynamic load range. The effect is seen to be much greater at higher load ranges. The magnified effect of load range will greatly boost the efficiency at higher load ranges.

3.2 Voltage output and power consumed

The output voltage of the crystal varied almost linearly with the value of the resistor used across the two leads of the multimeter. This is shown in Fig. 7. Since power is a square function of voltage, and increase in the resistance will greatly increase the power extracted from the piezo crystal.

The effect of cyclic loading on the output voltage can be compared to the results of Engel et al. [1]. The output voltage was obtained from:

$$V_{\text{piezo}} = \frac{d_{33}\,F}{C_{\text{piezo}}} \tag{1}$$

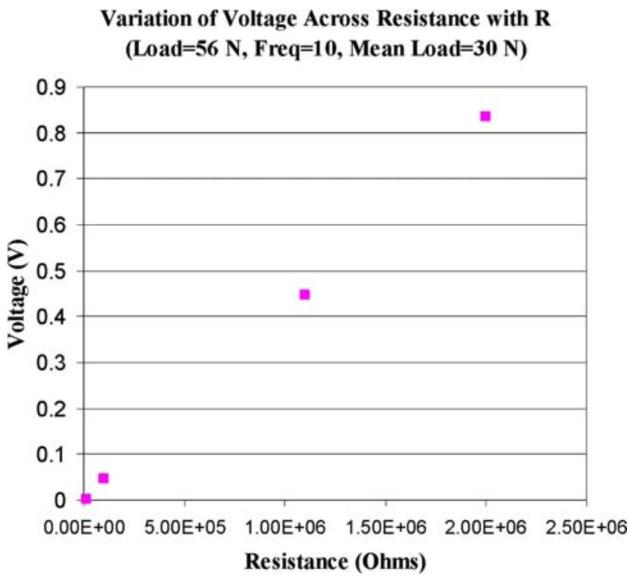

Fig. 7 Variation of voltage with resistance

where V_{piezo} is the voltage across the piezo crystal, d_{33} is the force sensitivity of the crystal, C_{piezo} is the capacitance of the crystal F is the applied force. Equation (1) predicts a voltage of about 10 V at a load level of 50 N. Without the external resistor, the cyclic voltage, measured in this study was bi-directional with a total range (minimum to maximum) was ~5 V.

The power output of the piezo crystal, as determined by the voltage across a resistor that was inserted parallel to the piezo, varies with the resistance. This is shown in Fig. 8. This log-log plot clearly shows an increase in the consumable power extracted from the piezo crystal, as the value of the external resistance increases. It is also important to note that

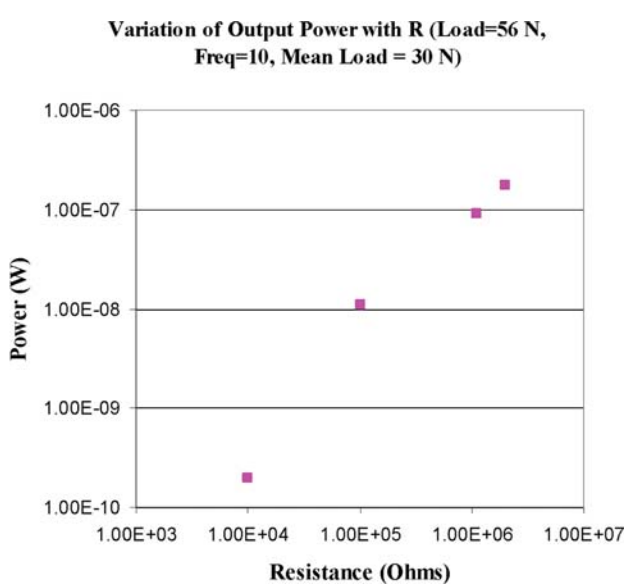

Fig. 8 Variation of output power with resistance

the power consumed in the external resistance is inversely proportional to the resistance value. This gives:

$$P_{\text{consumed}} = \frac{V_{\text{measured}}^2}{R_{\text{external}}} \tag{2}$$

However, the output voltage increases with increasing resistance. Since the effect of voltage on the power is greater than the effect of resistance, the net effect of increasing resistance on the amount of extracted power is positive.

3.3 Efficiency of piezo crystal

For piezo electric crystal deformed under cyclic loading with a capacitor of 2.8 nF, the stored energy per cycle time τ_{cycle} can be calculated as:

$$P_{\text{piezo}} = \frac{C_{\text{piezo}} V_{\text{measured}}^2}{2\tau_{cycle}} \tag{3}$$

With no external resistance, the output power of the piezo will be ~3.75×10^{-7} W. As expected, this value is greater than the energy consumed by the external 2 MΩ resistance (e.g. 1.75×10^{-7} W). To calculate the efficiency of the crystal, under different loading conditions, we need to determine the amount of mechanical work performed on the crystal.

$$P_{\text{mechanical}} = \frac{h_{\text{piezo}} F^2}{2\ Y\ A_{\text{piezo}}} \tag{4}$$

Here force (F), applied on the crystal, is measured directly by the load cell in the load train. It will include forces originating from the acceleration of the piezo mass, damping of the piezo crystal and the elastic response of the crystal. Since the sum of all forces is measured instantaneously, there is no need to calculate various force components separately. Using parameters presented in Table 2 for the piezo crystal used in this study, the efficiency, η is determined as the ratio of the electrical power output of the crystal to the mechanical power provided to the crystal. This is given by:

$$\eta = \frac{P_{\text{piezo}}}{P_{\text{mechanical}}} \times 100 \tag{5}$$

where P_{piezo} is the output power generated and $P_{\text{mechanical}}$ is the input power.

The variation of the efficiency with cyclic load range is presented in Fig. 9. As expected, the efficiency of the piezo crystal increases with increasing load range. For all data points, the mean load has been maintained constant at 30 N. The increase in the efficiency is nearly linear. A similar trend is observed in the variation of efficiency with frequency (Fig. 10). The application of increasing mechanical work to

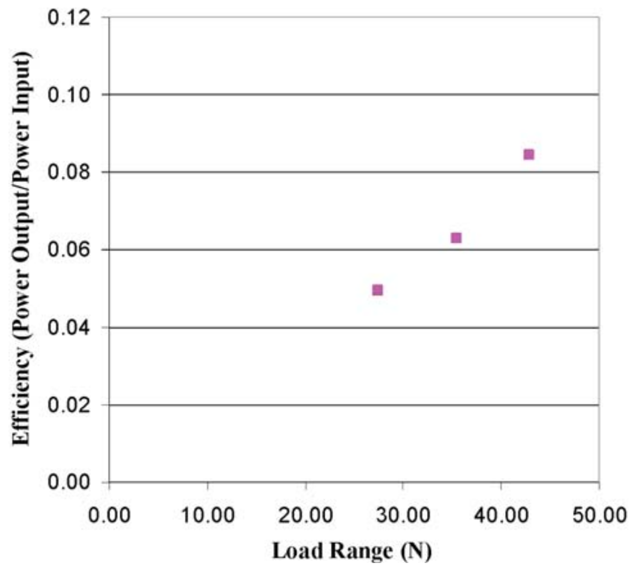

Fig. 9 Variation of efficiency with load range

the crystal generates more electrical power. Also, the cyclic frequencies that were used in this study are small enough to allow for full relaxation of the crystal between loading cycles. This leads to an additive effect of sequential cycles that impose mechanical work on the crystal.

The most intriguing result of this study is illustrated in Fig. 11. The efficiency of the piezo crystal drastically decreases with increasing mean load. There are two contributions to this effect. The smaller contribution comes from the hydrostatic pressure that is applied to the crystal at higher mean loads. This reduces the output voltage, possibly by affecting the mobility of the electrons in the crystal lattice of the piezo material. The more important factor in the loss of

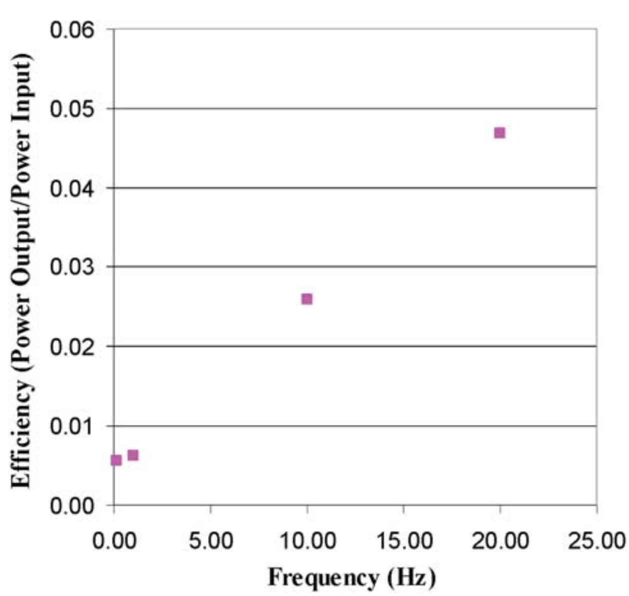

Fig. 10 Variation of efficiency with frequency

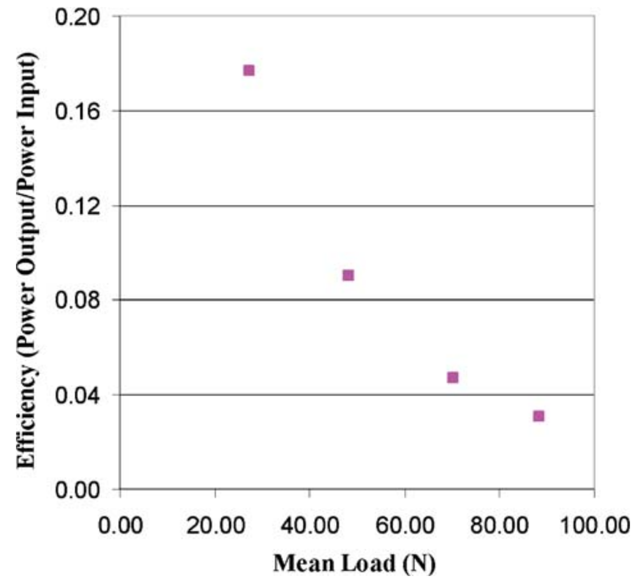

Fig. 11 Variation of efficiency with mean load

efficiency, since the mean load comes from the significant increase in the mechanical work expended in the actuation of the piezo crystal. Higher mean load dramatically increases the mechanical work. In conjunction with a constant load range, this leads to a significant drop in efficiency.

3.4 Implications

The results of this study shed light on a number of important parameters that affect the efficiency of piezo electric crystals. With the current renewed interest in alternative sources of energy (as a result of higher oil and gas prices), optimization of processes that produce electric energy from natural forces such as wind and waves becomes important. However, the power outputs of piezoelectric power generation are currently insufficiently insufficient to meet the requirements of most large-scale applications.

In contrast, the power outputs of the piezoelectric generator examined in this study are in a range that can meet the applications requirements for implantable bioMEMS and microelectronics systems [8, 9]. As discussed earlier, one of the potential sources of mechanical energy (for use in piezoelectric power generation) is the energy associated with occlusal activity in the oral cavity. In a recent study completed by Morneburg [12], chewing was associated with mean loads of ∼220 N, and maximum loads as high as 450 N. Loading occurs at a cyclic frequency of 64 cycles per minute with bilateral chewing, and 102 cycles per minute with fast chewing. These correspond to cyclic frequencies of ∼1–2 Hz. The forces associated with unilateral and bilateral clenching are ∼450 and 570 N, respectively. Also bruxism has been shown to occur ∼166 times per night (∼21 times per hour) with an average net duration of ∼8.5 sec per episode, with similar forces to clenching [12].

The above ranges of occlusal loading conditions are clearly in a range where significant piezoelectric power can be generated for potential applications in implantable small structures. However, significant challenges must be overcome before such devices can be fully considered for potential applications such as the ones illustrated in Figs. 1 and 2. First, the biocompatibility of PZT-based piezoelectrics is of some concern. In particular, the use of lead in PZT poses a significant challenge for implantation into the human body. This suggests a need for alternative piezoelectric chemistries and/or coatings. Secondly, the electrical isolation of the generators (from the surrounding structures) must be considered carefully along with electrical methods of connecting the piezoelectric generators to bioMEMS structures and electrical systems. These are clearly challenges for future work.

4 Summary and conclusions

This paper presents the results of an experimental study of the effects of cyclic loading parameters on piezoelectric power generation from potential occlusal contacts. Based on the results obtained from cyclic loading experiments performed on a piezo crystal the following conclusions can be made:

(1) The output voltage of a piezo crystal across a resistor is an indicator of the power output of the crystal. The magnitude of this output voltage increases with dynamic load range, frequency and decreases with increasing mean load.
(2) The power output of the crystal, as expressed by V^2/R, greatly increases with the dynamic load range and with frequency. The optimum power generation is associated with the highest frequency, the highest dynamic load range and the lowest mean load.
(3) The efficiency of a power generation through a resistor increases with cyclic actuation frequency and with cyclic load range. However, the efficiency of the piezo system decreases drastically with increasing mean load.
(4) Due to high load ranges associated with chewing, clenching and bruxism due to occlusal contact stated in this report, it is feasible to envisage the potential for piezoelectric power generation from the mechanical energy between contacts.

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References

1. T. G. ENGEL, C. KEAWBOONCHUAY and W. C. NUNNALLY, "Energy conversion and high power pulse production using miniature piezoelectric compressors", *IEEE Trans. Plasma Sci.* **28**(5) (2000) 1338–1341.
2. T. G. ENGEL, W. C. NUNNALLY, J. BECKER, R. RAHMAN and C. KEAWBOONCHUAY, "Research progress on compact kinetic-to-electrical energy converters", Presented in *Proceedings of the 12th International Pulsed Power Conference*, 1999, edited by C. K. Stallings, H., Monterey, CA, USA, IEEE, Vol. **1282** (1999) pp. 1287–1290.
3. T. G. ENGEL, W. C. NUNNALLY and N. B. VANKIRK, "Compact kinetic-to-electrical energy conversion", Presented in *Digest of Technical Papers 11th IEEE International Pulsed Power Conference*, (1997), edited by G.V. Cooperstein, I., Baltimore, MA, USA, IEEE, Vol. **1502** 1503–1507.
4. C. KEAWBOONCHUAY and T. G. ENGEL, "Maximum power generation in a piezoelectric pulse generator", *IEEE Trans. Plasma Sci.* **31**(1) (2003) 123–128.
5. C. KEAWBOONCHUAY and T. G. ENGEL, "Electrical power generation characteristics of piezoelectric generator under quasi-static and dynamic stress conditions", *IEEE Trans. on Ultrason., Ferroelect. Frequ. Contr.* **50**(10) (2003) 1377–1382.
6. C. KEAWBOONCHUAY and T. G. ENGEL, "Design, modeling, and implementation of a 30-kW piezoelectric pulse generator", *IEEE Trans. Plasma Sci.* **30**(2) (2002) 679–686.
7. C. N. XU, M. AKIYAMA, K. NONAKA and T. WATANABE, "Electrical power generation characteristics of PZT piezoelectric ceramics", *IEEE Trans. Ultrason., Ferroelectr. Frequ. Contr.* **45**(4) (1998) 1065–1070.
8. M. J. MADOU, "Fundamentals of Microfabrication: The Science of Miniaturization",, 2nd edn (CRC Press, 2004).
9. T. A. KOVACS, "Micromachined Transducers" (McGraw-Hill, New York, 1998).
10. M. COLLINSON, "Analysis of the Response Characteristics of Piezoelectric Cells in Cyclic Loading" (Princeton University, 2005).
11. D. M. BRUNETTE, P.TENGVALL, M. TEXTOR and P. THOMSEN, "Titanium in Medicine" (Springer-Verlag, New York, 2001).
12. T. R. MORNEBURG and P. A. PROSCHEL, "Measurement of masticatory forces and implant loads: A methodologic clinical study", *Int. J. Prosthodontics* (Jan–Feb 2002).
13. S. M. ALLAMEH and W. O. SOBOYEJO, Microstructure and surface topography evolution of Ti and Ni thin structure. *Mater. Manufact. Proc.* **19**(5) (2004) 883–897.