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Experimental Determination of the Maximum Allowable Stresses for High-Power Piezoelectric Generators

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Abstract

High mechanical loads and/or electric fields or a combination of both tractions may lead to significant changes in the properties and parameters of PZT ceramics owing to the ferro-elastic processes in ceramics, domain wall motion, switching domains and the restructuring of the domain structures. This study uses well-designed tests to investigate the various parameters of high-power multi-element piezoelectric generators made from PZT ceramic under long-term cyclic external mechanical loading and presents maximum allowable working mechanical stresses. It has been shown that a stress of 30 MPa can be considered as a safe-side stress level, while 50 MPa can be regarded as the highest applicable stress; above or near 50 MPa, the PZT properties are substantially reduced, yielding a less effective high-power generator.

Keywords: PZT, power generator, stress, cyclic loads, electrical resistance

I. Introduction

Piezoelectric PZT ceramics are widely used in sonar transducers, as actuators, in piezoelectric motors, ultrasound cleaners, and in other devices that operate at high mechanical and electrical traction levels. Each of these applications requires specific studies to determine changes that might occur in the properties and parameters of piezoelectric ceramics when they are subjected to high mechanical and electric loading. It is known that high mechanical loads and/or electric fields or a combination of both tractions may lead to significant changes in the properties and parameters of the PZT ceramics owing to the ferro-elastic processes in ceramics, domain wall motion, switching domains and the restructuring of the domain structures [1–3]. Under certain conditions, these changes can be partially or completely irreversible.

The effect of high mechanical stresses and high electric fields on PZT piezoceramics has been investigated in a number of studies. These studies, however, were conducted using quasi static-loaded ceramic samples. Changes in the properties of PZT ceramics under dynamic external actions have not been studied so intensively [4–10]. The dynamic parameters of the external loading, mechanical or electric or both, such as frequency, amplitude growth rate and amplitude lowering rate might accelerate the changes in the elastic and electric subsystem ceramics. Ultimately the dynamic external tractions might significantly limit the range of linear properties of the piezoelectric ceramics and lead to reduced operating and device efficiency.

Piezoelectric high-power generators are a recent piezoelectric macro application in which mechanical stresses are applied to generate electricity [11]. They are usually composed of multiple piezoelectric elements and use the direct piezoelectric effect wherein mechanical energy is transformed into electrical energy. Their operation is in the mode of pulsed loading, stemming from variable external forces which might have amplitudes of up to tens of thousands of newtons. The rise time of the loading pulse, Δt, might be in the range of 0.005 – 0.05 seconds [12].

Therefore, the aim of the present study is to perform well-designed tests to investigate the various parameters of these high-power multi-element piezoelectric generators under long-term cyclic external mechanical loading and to determine their maximum allowable working mechanical stresses.

II. Test Set-Up

The basic experimental studies and the accompanied measurements were conducted with a typical three-layer piezoelectric power generator. The outer layers are composed of rigid aluminum plates. The inner layer is composed of twelve piezoelectric discs, each having a diameter of 10 mm and a height of 4 mm. The external mechanical stress is transferred to the piezoelectric elements via the rigid plates. The twelve piezoelectric elements are electrically connected in parallel. The schematic structural layout of the piezoelectric power generator is shown in Fig. 1.

The generators used in this experiment were made using commercially available PZT piezoelectric ceramics, which were produced by three different manufacturers and designated M1, M2 and M3[1)]. Each generator was assembled

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1) The names of the manufacturers were omitted to prevent commercialism.

using piezoelectric elements from a single supplier, either M1 or M2 or M3. The PZT piezoelectric materials are in the broad category of soft-hard ferroelectric piezoelectric ceramics and their basic constants are listed in Table 1.

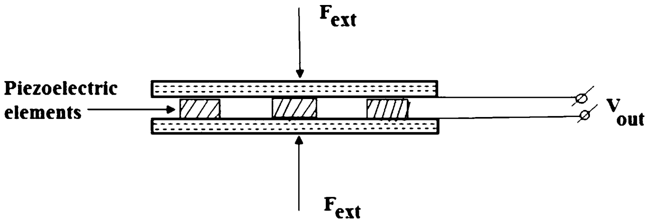

Fig. 1 : Schematic showing the structural layout generator.

Table 1: Values of the basic piezoelectric constants used in the experimental series.

Piezoelectric coefficient d_{33} [pC/N]	Relative permittivity $\varepsilon_{33}T/\varepsilon_0$	Electromechanical coupling coefficient k_{33}
450-500	2200-2400	~ 0.7

The axial external loading was applied to the generators with a hydraulic MTS 250 kN test rig and Test-Star IIs software (MTS Systems Corporation, Eden Prairie MN, US). The applied external loadings were: 23.5 KN, 47.1 KN, 70.6 KN and 94.2 KN. These loads corresponded to stresses of 25 MPa, 50 MPa, 75 MPa, and 100 MPa, respectively. The number of loading cycles was 2 000 and the applied frequency was 5 Hz.

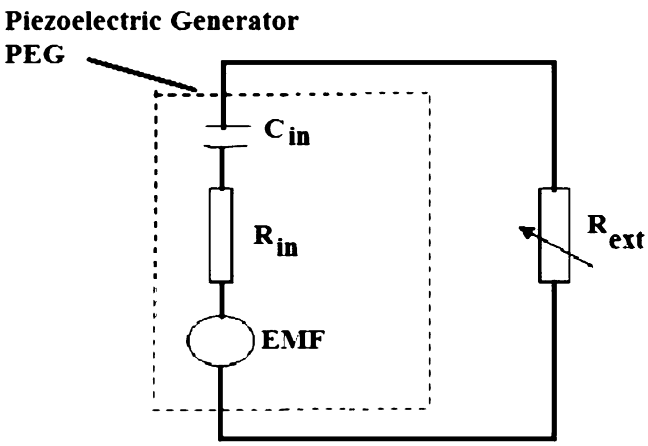

Fig. 2 : The equivalent electrical circuit of the PEG and the external resistor.

During the test series, the maximum output power of the tested generators, P_{output}, for each mechanical stress level was determined by varying an external active resistance using a variable resistor and measuring the power developed on it. The electric measurement scheme is shown in Fig. 2. The piezoelectric power generator is shown in the dashed-line box. It is accepted in the literature that a piezoelectric generator, transforming mechanical energy into electrical energy, can be represented as a source of electromotive (EMF) potential having internal resistance R_{in} and an internal capacity C_{in}.

The generator power output, P_{out}, as measured on the external resistor is defined as:

$$P_{out}=\frac{V_{ext}^2}{R_{ext}} \quad (1)$$

where V_{ext} is the voltage on the external resistance, the value of which can be determined with the following equation:

$$V_{ext}=V_{out}\frac{R_{ext}}{|Z|} \quad (2)$$

where V_{out} is the EMF of the generator (in volts) and $|Z|$ = the total electrical impedance of the circuit that can be defined as :

$$|Z|=\sqrt{(R_{in}+R_{ext})^2+X_c^2} \quad \text{and } X_c=\frac{1}{2\pi fC} \quad (3)$$

C is the capacitance of the PEG and f is its frequency.

It should be noted that changes in the internal impedance of the generator are due to changes in the conductivity of piezoelectric ceramics. It should also be noted that according to the present test results, the changes in the conductivity can be attributed to the changes in the internal resistance (the internal active resistance), R_{in}. Conductivity was shown to be frequency-dependent [9], and can generally increase or decrease with frequency. The present measurements show that in the low frequency range the conductivity of the PZT ceramics would increase with increasing frequency. It was also found that the electrical conductivity also increases with increasing external mechanical force, F_{ext}.

It can be shown that to maximize the power measured on the external resistor (see Fig. 2) it is necessary to vary the external resistor until it reaches the internal resistance, R_{in}, of the PEG. For that value, the EMF of the PEG due to an external mechanical load can then be back-calculated. It should be noted that this is true only when there is no external capacitance electrically connected to the PEG, as in our case. When general impedance is electrically connected to a PEG, to maximize its power, the external impedance (X_{ext}) should be matched to the internal impedance (X_{in}) of the PEG.

For an off-resonance condition [13–14], as in our case, the magnitude of the transduction is governed by the properties of the piezoelectric material, namely the effective piezoelectric strain constant, d_{33eff}, and the effective piezoelectric voltage constant, g_{33eff}. Using linear constitutive piezoelectric equations, a relatively simple relation can be derived between the energy density of the piezoelectric material and the transduction coefficient $(d \cdot g)_{33_{eff}}$ under an applied mechanical stress, T.

The need to introduce effective values for the piezoelectric modulus and the dielectric constant is due to the fact that with the high level of external actions the elastic, piezoelectric and dielectric constants of piezoelectric ceramics undergo significant changes and their values do not match the standard (table) values measured at the low levels of external influence.

The open circuit EMF (V_{out}) voltage being generated on the electrodes of a piezoelectric structure with a thickness t and area A, due to an applied force ($= \sigma \cdot A$) is given by the following expression:

$$V_{out}=E_{33}\cdot t=-g_{33_{eff}}\cdot\sigma\cdot t=-g_{33_{eff}}\frac{F}{A}t \quad (4)$$

where E_{33} is the electric field developed due to the mechanical traction in the piezoelectric material. The piezoelectric material behaves mainly (far from resonance) as a capacitor, having a capacitance C. Hence the electric energy would be written as:

$$W=\frac{1}{2}C\cdot\frac{g_{33_{eff}}^2\cdot F^2\cdot t^2}{A^2} \quad (5)$$

Taking into account the following relationships:

$$C=\frac{\varepsilon_{33_{eff}}\cdot A}{t};\ g_{33_{eff}}=\frac{d_{33_{eff}}}{\varepsilon_{33_{eff}}};\ Volume=A\cdot t \quad (6)$$

where ε is the permittivity of the piezoelectric material. Substituting the relationships from (6) into Eq. (5) yields:

$$W=\frac{1}{2}(d\cdot g)_{33_{eff}}\left(\frac{F}{A}\right)^2\cdot Volume = =\frac{1}{2}(d\cdot g)_{33_{eff}}\sigma^2\cdot Volume \quad (7)$$

From Eq. (7) it can be concluded that the harvested energy is a linear function of the product $(d\cdot g)_{33_{eff}}$ and the piezoelectric volume, and is dependent on the square of the applied stress.

From Eq. (7), the expression for the generated power, P, can be obtained:

$$P=\frac{energy}{time}=W\cdot f=\frac{1}{2}(d\cdot g)_{33_{eff}}\sigma^2\cdot f\cdot Volume \quad (8)$$

Eq. (8) can be presented in a form excluding effective piezoelectric voltage constant, g_{33eff}, yielding

$$P=\frac{1}{2}\left(\frac{d_{33}^2}{\varepsilon_{33}^T}\right)_{eff}\cdot\sigma^2\cdot f\cdot Volume \quad (9)$$

The electrical power output ratio between two loading cases can then be written as follows:

$$\left(\frac{P_1}{P_2}\right)_{output}=\left(\frac{\sigma_1}{\sigma_2}\right)^2=\left(\frac{F_1}{F_2}\right)^2 \quad (10)$$

The ratio presented in Eq. (10) can be used as a basis to compare the maximum generator output for different external loads, and to determine the stress level at which the piezoelectric properties of the PZT ceramics cease to be linear. That stress level would then be considered as the recommended working stress for the PEG.

III. Results and Discussion

Figs. 3 – 5 show the experimental and calculated variation of the maximum normalized output power P_{output} as a function of the applied mechanical stresses, T, for the three piezoelectric energy generators having piezoelectric elements manufactured by M1, M2 and M3, respectively. The maximum power output was normalized by the power at T = 25 MPa, while the calculated values were obtained using Eq. 10. Fig. 6 shows the variation of the internal resistance, R_{in}, as a function of the applied mechanical stresses, T, for the above generators with piezoelectric elements being manufactured by M1, M2 and M3, respectively. The internal resistance of the generators is a function of the external applied mechanical load, and it is visible from the graph (Fig. 6) and for the given range of stresses experienced in the present test series, it has a visible minimum of 3 MΩ for all the specimens tested. The direct measurement of the internal resistance of a piezoelectric driven generator is difficult, therefore it was demonstrated from the present test series that $R_{internal}$ can be estimated to be a given fraction of the internal capacitance impedance, X_c. The relationship can be written as:

$$R_{internal}=\alpha X_c \quad \text{where } \alpha=0.6-0.8 \quad (11)$$

The value of α increases with an increase in the external mechanical loading.

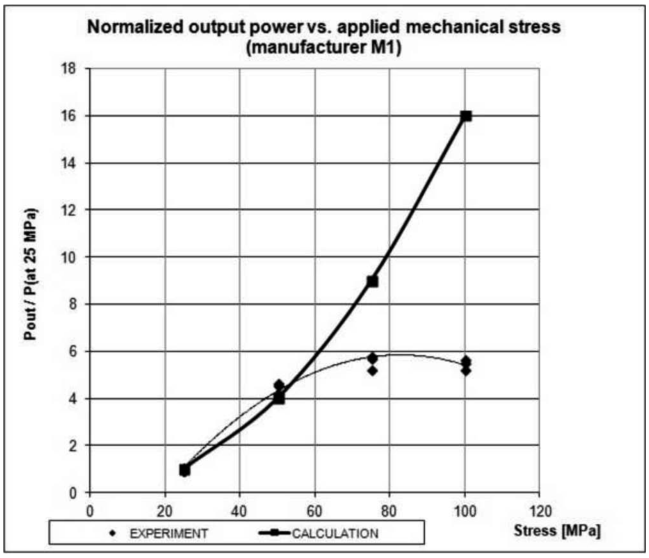

Fig. 3 : Maximum normalized output power vs. applied mechanical stresses – manufacturer M1.

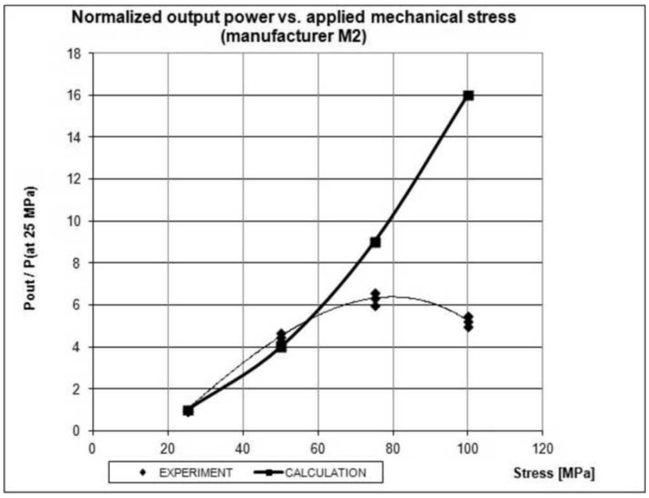

Fig. 4 : Maximum normalized output power vs. applied mechanical stresses –manufacturer M2.

Figs. 3 – 5 indicate that at mechanical stresses higher than 50 MPa, the dependence of the power output on the applied mechanical stress ceases to be squared, leading to the conclusion that the piezoelectric properties of the soft-hard piezoelectric PZT ceramics used in the generators from all three manufacturers become non-linear. The same threshold value of the stress, T = 50 MPa which was shown to be critical to maintain the linearity of PZT ceramics properties agrees well with values previously determined [8–10] for both soft and hard materials. Our present studies exclude any influence of the way the generator was designed and therefore it reflects only the dependence of the output power on changes in the piezoelectric ceramic properties. Our present results and similar results from the literature suggest that a stress of T = 50 MPa can be considered as the upper limit for maintaining the linear piezoelectric properties behavior of PZT ceramics. Furthermore, it may be considered to be a fundamental characteristic of this type of ceramics.

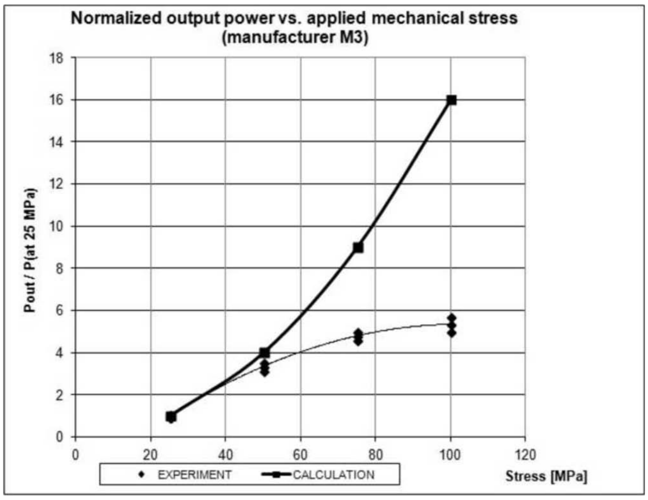

Fig. 5 : Maximum normalized output power vs. applied mechanical stresses – manufacturer M3.

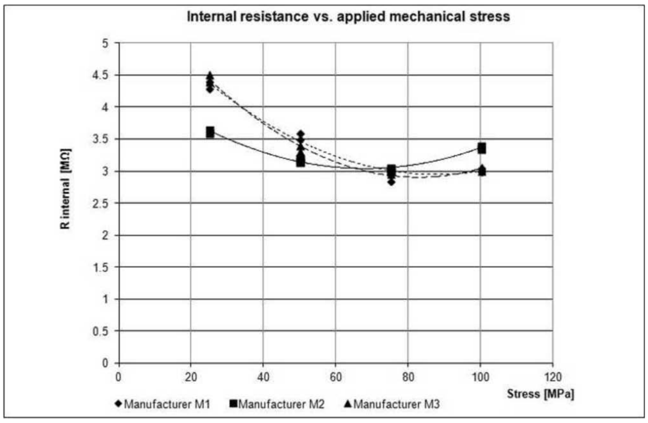

Fig. 6 : Internal resistance vs. applied mechanical stresses – manufacturers M1, M2 and M3.

Note that the determination of the stress level T = 50 MPa as the limit for the linear and nonlinear piezoelectric properties of PZT ceramics should only be considered as an indicative value owing to relative large intervals between the applied stresses encountered in the experiments. Irreversible changes in the electrical properties of PZT ceramics may have begun to form at values lower than 50 MPa. In real applications the reliable performance of piezoelectric devices is highly dependent on the reproducibility of the output parameters in the full range of operation. Parallel to this, knowledge of the maximum permissible stress level is crucial during the design of piezoelectric energy generators operating at high mechanical stresses. This value will determine the number of active piezoelectric elements and the respective area required to maximize the effective action of the external load and to maximize the efficiency of the piezoelectric generator.

To more accurately determine the maximum operating stress levels for multi-element piezoelectric power generators, additional tests were conducted using stress values of 10, 20, 30, 40, 50 and 60 MPa. Measurements were performed according to the scheme presented in Fig. 2.

Fig. 7 shows the normalized output power of a multi-element power generator constructed with a single layer of 24 piezoelectric active elements each having a diameter of 7 mm and a height of 4 mm located between rigid upper and lower plates manufactured by M2. The load frequency was 5 Hz. For reference, the calculated values of the output are also presented on the graph.

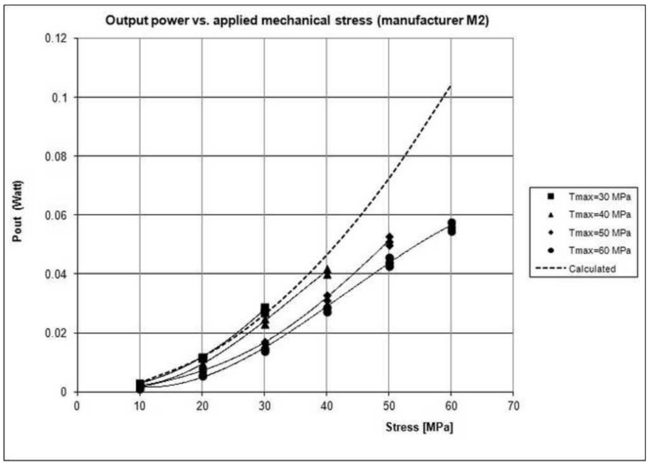

Fig. 7 : Output power of the multi-element piezoelectric power generator (one layer 24 of piezoelectric elements with dimensions d = 7 mm, h = 4 mm), measured after application of a maximum stress: 30 MPa, 40 MPa, 50 MPa and 60 MPa, respectively.

First the piezoelectric generator was "stabilized" and the output power was measured after 5 000 loading cycles at 30 MPa mechanical stress. The "stabilization" process is aimed at providing a stable power output for an increasing number of load cycles. Then the generator was loaded at a lower stress, 20 MPa, for another 2 000 loading cycles and then the procedure was repeated at a stress of 10 MPa for 2 000 cycles. The mechanical stress was removed and a second test was initiated. The stress was increased to 40 MPa, 5 000 cycles were applied and the output power was monitored. Then the applied stress was reduced to 30 MPa, 20 MPa, and 10 MPa and the output power was measured after 2 000 cycles at each stress level. A third test was then performed with a maximum stress of 50 MPa, while the last test had a maximum stress level of 60 MPa. The same sequential reduction of stress and number of cycles was applied at each stress level.

As can be seen from Fig. 7, applying a low number of cycles at each loading stress up to 60 MPa can only be reproduced for the two lower stresses, 30 and 40 MPa, however, compared to the theoretical (calculated) values, there is a distinct stress level (approx. 50 MPa) at which the experimental measured power stops following the predicted levels. From that level of stress the experimental power is lower than the predicted one, and the difference grows with the increase in the applied mechanical stress.

Owing to the fact that the results presented previously are based on a relatively low number of stress cycles, it is important to check the stability of the properties of piezoelectric material (and thus, the potential stability of the generator) by applying a large number of loading cycles, as expected for the overall lifetime of operation of a piezoelectric generator.

To study this, an additional experiment was performed. A piezoelectric power generator obtained from Innowattech Ltd. (Haifa, Israel) which contains PZT disks measuring 10 mm in diameter and 4 mm in height was loaded at a stress T = 30 MPa for 1 million cycles (see Table 1 for the nominal properties), at a frequency of 5 Hz. The testing circuit used is shown in Fig. 2. Fig. 8 shows the results of the power output as a function of the loading cycles. It should be noted that this experiment has been performed with continuous loading over time, with only short interruptions to collect the data.

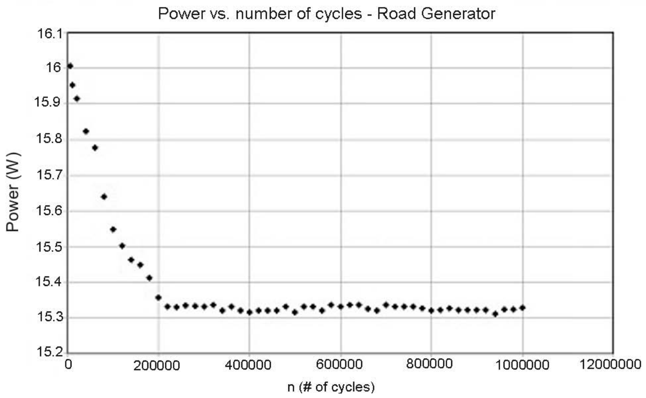

Fig. 8 : The energy output of a piezoelectric power generator loaded at 30 MPa and frequency 5 Hz.

From Fig. 8, it is clear that at this level of mechanical stress, 30 MPa, and for the piezoelectric material used in the generator, the output power is stable with time, implying that this level of stress is safe for applications and the piezoelectric properties are not influenced by the mechanical stress. This value of mechanical stress can therefore be considered on the safe side and suitable for achieving maximum and stable energy output from a PZT piezoelectric power generator.

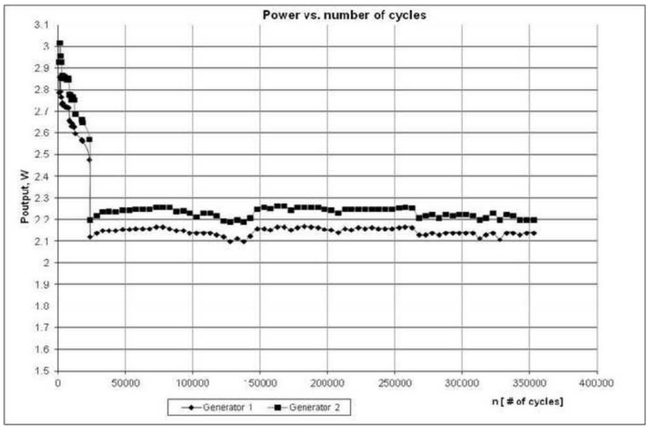

Fig. 9 : The power output of two piezoelectric power generators as a function of the loading cycles at 10 Hz.

To further enhance the reliability of the data presented in Fig. 8, another test series was performed, and its results, the power vs. number of loading cycles at two stress levels, 48 MPa and 38 MPa, are presented in Fig. 9.

Two generators were built from four layers, one on top of the other, each containing 46 rods having a radius of 6.3 mm and a height of 8 mm. The two generators were initially loaded at a stress of 48 MPa, and after 23 700 cycles the stress was reduced to 38 MPa. The first stress was applied for 500 cycles, than the stress was removed for a typical time of 10 minutes, and then it was reloaded for another 500 cycles. The second stress, 38 MPa, was applied for 5 000 cycles, then the stress was removed and the specimens left unloaded for 10 minutes, before being loaded again. This type of loading was performed to simulate a real loading case where there is an interval between two consecutive vehicles, leading to a relaxation time for the generators. It is clear from Fig. 9 that the stress applied at the beginning of the tests, 48 MPa, is too high, and a clear drop in the output power can be observed. Reducing the stresses to only 38 MPa, after both generators experienced 23 700 cycles at the high stress, shows almost no further reduction in the output electrical power. The relative small fluctuations in the output are in the measurement error range and can be attributed to the special loading spectrum applied in the tests. The differences between the two specimens are also relatively small, within the measurement error. The data presented in Fig. 9 confirms the previous results shown in Fig. 8, namely that at a stress in the vicinity of 30 MPa, the piezoelectric materials tested in the present test series will show stable electrical power output for a large number of loading cycles (10^6 cycles).

IV. Conclusions

The operation of multi-element piezoelectric high power generators under high external mechanical loading was investigated both experimentally and numerically.

The safe-side value of the mechanical stress for piezoelectric high power generators was empirically determined to be T = 30 MPa.

The stress value T = 50 MPa was confirmed as the highest applicable stress, above or near its value, the PZT properties are substantially reduced, yielding a less effective high-power generator.

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