Design of Multilayer Piezoelectric Generators for Fuze Systems

White Paper

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Contents

INTRODUCTION

In military ammunition, a fuze is the part of a device that initiates functioning. Fuze systems are safety mechanisms that protect users from premature or accidental detonation, and they can be designed to initiate with a timer, on impact, by proximity to the target, or a combination of these [Jacob, Gawlick, Mattsson]. Piezoelectric devices are used as generators within fuze systems, converting mechanical energy into electrical energy either at launch or on impact.

Advanced fuze systems require the use of electronics for smart functions, which in turn require small amounts of electrical energy. Batteries have been widely used to power advanced fuze systems, but are limited in terms of performance and storage life, leading to high maintenance costs and low reliability. Piezoelectric generators represent a superior alternative in terms of durability, resistance to vibrations, packaging size, and shelf life.

This white paper provides data on multilayer generators for energy generation at launch, allowing the design of customized generators for advanced fuze applications. Relationships between critical application parameters (acceleration, electrical impedance, voltage, energy) and device design parameters (dimensions, stress, material, internal layer thickness) are provided.

THEORETICAL BACKGROUND

According to the linear piezoelectric model, the dielectric charge output of a thickness mode piezoelectric element in short circuit and under uniaxial stress follows the linear relationship:

$$D_3 = d_{33} \cdot T_3 \text{ (Eq. 1)}$$

- With D_3 the dielectric charge density, electrodes being orthogonal to the poling direction
  d_{33} the piezoelectric charge coefficient for stress and field along the poling direction
  T_3 the mechanical stress along the poling direction

However, it is known from the same reference [Jaffe] that the behavior of the piezoelectric material is highly non-linear. Experiments show that the slope of the charge-stress curve increases in a first place, leading to outputs much higher than estimated by the linear equation. Above a certain stress level, the output saturates. In the process, the piezoelectric element has been progressively stress-depoled, meaning that it has lost its original polarity and therefore does not return to its initial state. This is illustrated in fig. 1.

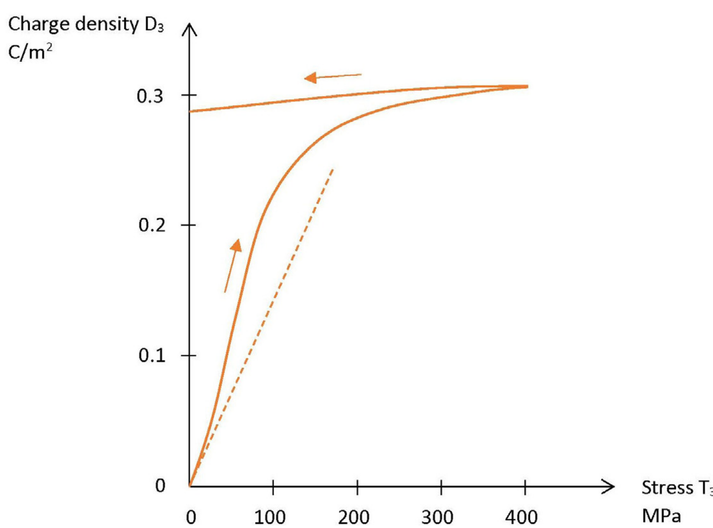

Fig. 1: Charge density versus stress, reproduced from [Zhou]. Solid line: published data. Dashed line: tangent at origin (linear piezoelectric equations).

For proper design of a generator system, it is therefore essential to rely on experimental data under representative stress. Experiments have been performed with our soft-doped PZT compositions NCE51 and NCE56.

Regardless of the non-linearity, intuitively and according to the principle of superposition, it is apparent that the output energy of a generator in given stress conditions is proportional to its volume.

However, as will be discussed later, variations in both electrical (impedance) and mechanical (stress) conditions will cause a deviation from this principle.

EXPERIMENTAL SETUP

The experimental data presented in this white paper was generated through impact tests on multilayer piezoelectric generators. For each test, a new, poled generator was used. The typical dimensions of the tested generators are 5x5x2mm but smaller and larger elements have also been used to assess scalability.

Fig. 2: Impact Test System

In the impact test, the high acceleration normally caused by the launch is simulated by the impact of a falling mass. The force profile is measured using a load cell. The profile of the impact can be tuned to precisely mimic actual launch conditions by adding damping material and springs. However, experience shows that the peak stress is by far the most important parameter for the output, the shape and duration of the impact being of lesser importance. The generator's charge output is recorded using charge amplifier (Kistler). Figures 2 and 3 illustrate the impact tester and sample impact curves.

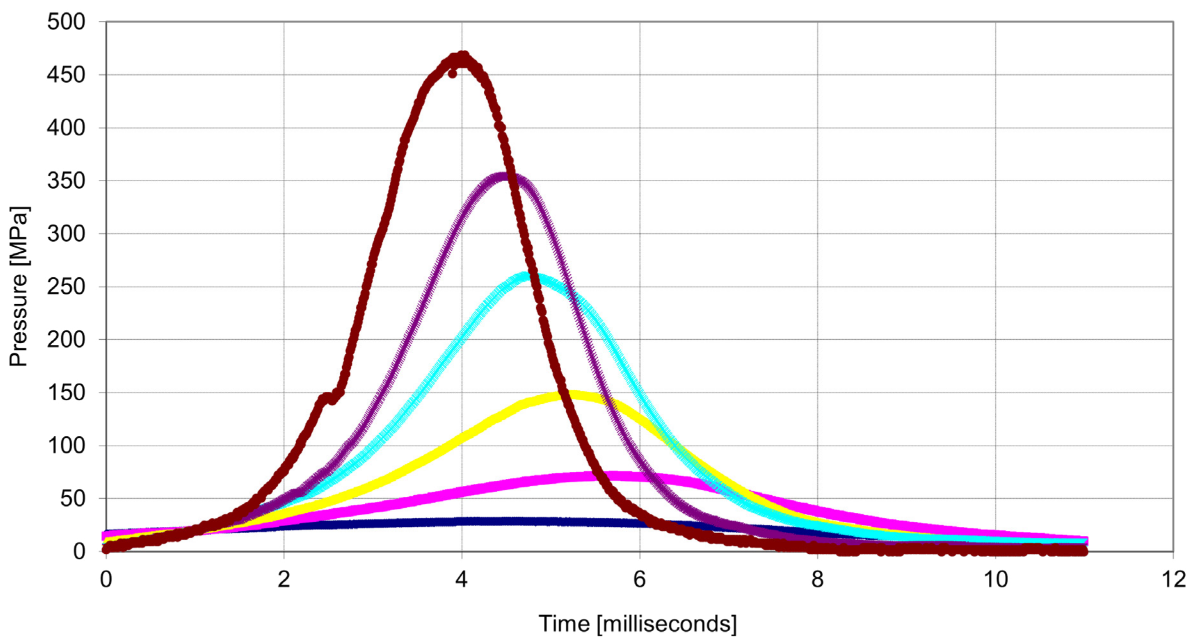

Fig. 3: Sample Impact Curves

ELECTRICAL BOUNDARY CONDITIONS

In a typical fuze application, the piezoelectric generator powers electronics through an energy storage and regulation unit. The simplest layout for energy storage is to combine diode D1 and storage capacitor Cp as depicted on the next figure.

In the rest of this paper, the energy levels are expressed in terms of electrical energy at the storage capacitor. This energy can be expressed:

$$E_P = ½ . C_P . V_P^2 \text{ (Eq. 2)}$$

- With E_P the electrical energy at the storage capacitor
  C_P the capacitance of the storage capacitor
  V_P the voltage across the storage capacitor

Consequently, the dielectric charge at the storage capacitor can be expressed:

$$Q_P = C_P . V_P \text{ (Eq. 3)}$$

- With Q_P the dielectric charge at the storage capacitor

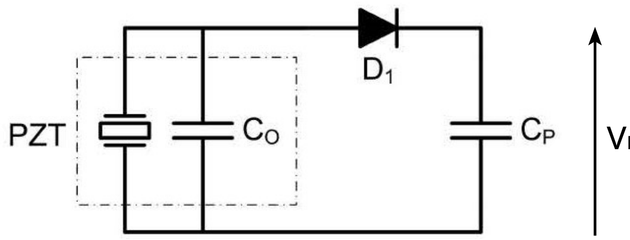

Fig. 4: Simple energy storage circuitry

More advanced layouts have been proposed in order to maximize the generated energy levels. However, the simple layout provides a good reference for comparison of the results. This layout was selected for the experimental assessment of the energy output.

VOLTAGE AND IMPEDANCE MATCHING

The principle of impedance matching is to adapt the characteristics of the generator to the characteristics of the connected electrical load. In theory for the considered circuitry, the generator and the storage capacitor should have a similar capacitance value. For a given generator, a small storage capacitor would mean high voltage generation with low current. A large storage capacitor would result in low voltage generation with high current. From an energy point of view, the transfer would be ideal for a matched impedance.

In practice, due to the non-linear response of the piezoelectric material, the apparent impedance changes during the acceleration phase (or impact test). Experiments show that the optimum energy transfer and therefore impedance matching is achieved with a storage capacitor about 5% smaller than the static capacitance of the generator (fig. 5, results are similar for NCE56). The curve describes a plateau, which makes impedance matching relatively easy to achieve.

In some cases, it can be beneficial to operate with an un-matched load. Typically, the storage capacitor is designed bigger than the optimum in order to obtain the energy at a more workable voltage, at the expense of energy efficiency.

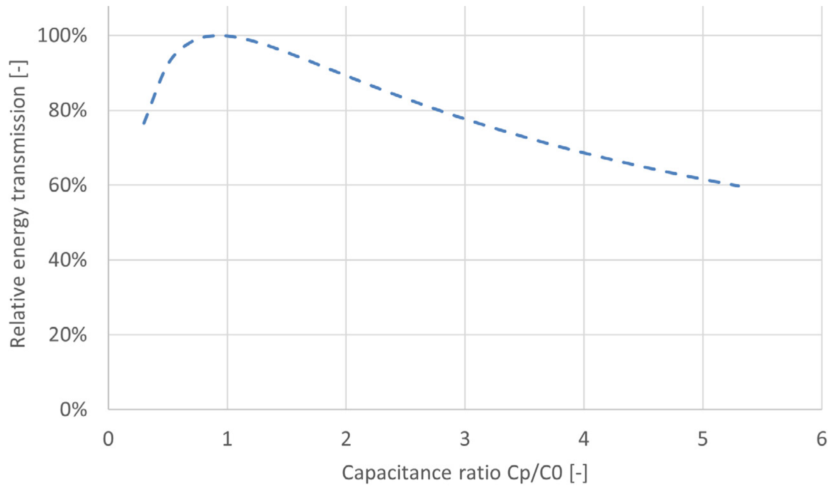

Fig. 5: Illustration of impedance matching, NCE51 material.

STRESS AND ENERGY DENSITY

As discussed above, in the linear piezoelectric behavior model, generated dielectric charge is proportional to stress. Output energy therefore has a quadratic trend. However, due to the mechanical de-poling of the piezoelectric material, the actual response is non-linear. At high stress levels, the material is completely de-poled and saturation occurs. This is visible in Fig. 6, which is based on experimental data for the two considered materials. The vertical axis represents energy density, i.e. the electrical energy at the storage capacitor (Eq. 2) divided by the volume of the piezoelectric component.

Above 400MPa, the risk of mechanical failure in this test setup is significant. Typically, unevenness in the mounting of the ceramic component causes stress concentrations, particularly in the corners of the generator. Even in the event of a mechanical failure, it is still possible to extract high levels of energy from the generator. However, since fracture will occur differently on different samples, the electrical output will vary. In addition, energy output starts to saturate above 400MPa, making higher pressures less beneficial for the application.

Comparing the two materials, despite having a higher d_{33} coefficient (table 1), NCE56 provides lower energy levels at high stress. This is due to the non-linear response of the material, which is more susceptible to mechanical depoling. Nevertheless, NCE56 constitutes a good alternative, as the high relative permittivity implies a higher capacitance, and therefore that the energy is available at lower voltage. This is a clear advantage for impedance matching to common electronics, removing the need for inefficient and bulky power converters.

Material	NCE51	NCE56
Relative permittivity [-]	1900	2900
Piezoelectric coefficient d_{33} [pC/N]	443	580

Table 1: Selected catalog properties for NCE51 and NCE56 materials [CTS].

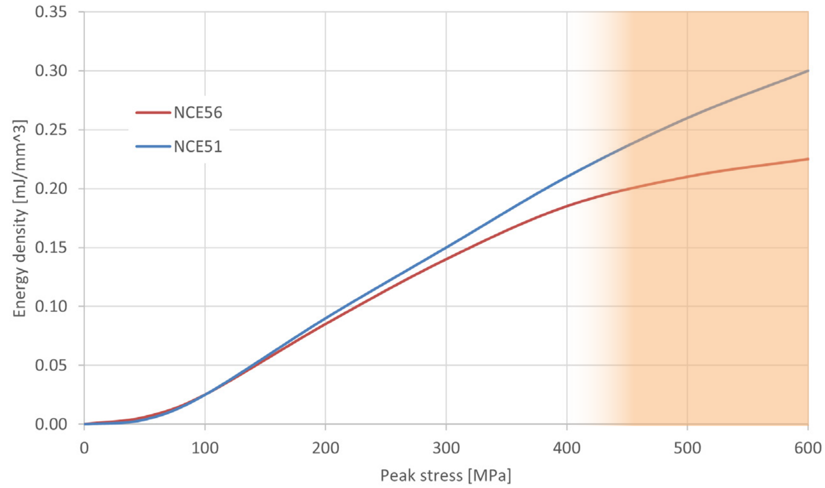

Fig. 6: Energy density as a function of peak impact stress for NCE51 and NCE56 materials.

CAPACITANCE

The capacitance of the generator is an important parameter when it comes to estimating the voltage at which the generated energy will be outputted. In the multilayer design, the active volume can be divided almost freely into thin layers. For a given volume, i.e. a given energy output, the output voltage can therefore be adapted within a range.

The two graphs in Fig. 7 illustrate the capacitance levels that are achievable for a given component volume, depending on the thickness of the internal layers. The estimates include some assumptions and can differ from actual specifications; however, they provide a good starting point for a design.

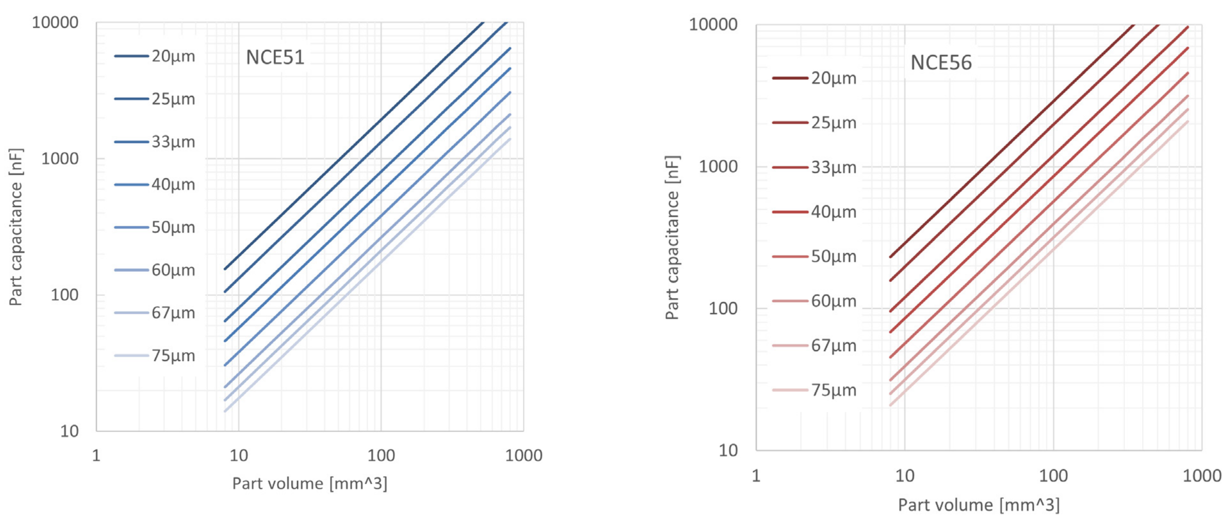

Fig. 7: Capacitance according to volume for standard layer thicknesses. NCE51 and NCE56 materials.

For a given design, NCE56 provides almost 50% higher capacitance compared to NCE51. This allows for an improved impedance matching.

DEVICE DESIGN

The illustration below shows the relationships between the design parameters for a multilayer generator application. This white paper provides the relationships between all the parameters, allowing the designer to conduct the design process in an iterative manner.

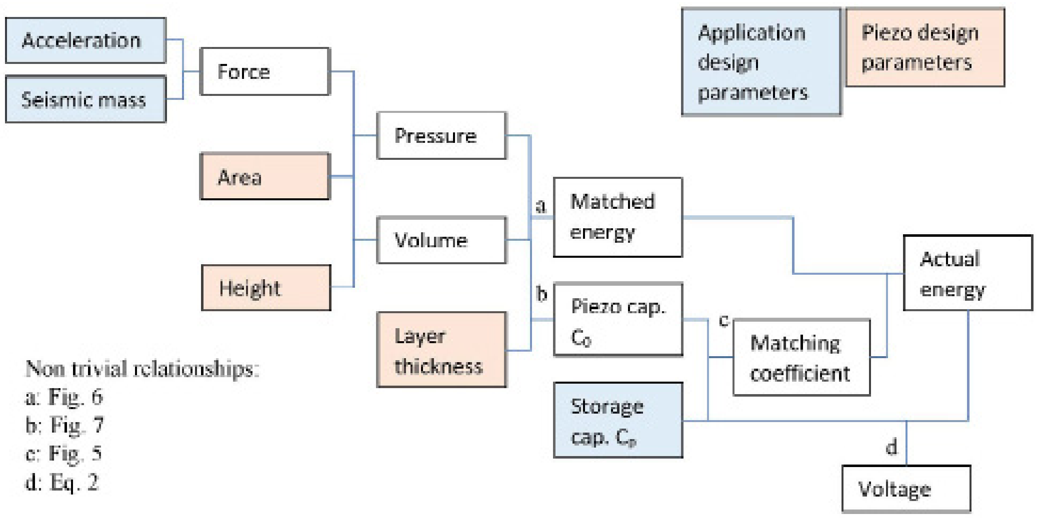

Fig. 8. Relationships between design parameters and outputs.

Designing a multilayer generator requires the consideration of several parameters:

- Material. NCE51 material provides the highest energy outputs. However, NCE56 can be a good alternative for impedance matching reasons.

- Shape. Plate generators are a more cost-effective solution. Rings offer an improved stress repartition and a better use of the available volume in the ammunition.

- Volume. Volume drives the maximum energy level, assuming that stress and impedance matching are constant.

- Area. Considering the non-linear relationship between energy density and pressure, it is important to adjust the area to reach optimal stress levels. For a given impact force, a smaller piezo is submitted to higher stress and typically generates higher energy.

- Thickness. For manufacturing reasons, a thickness of 2mm is preferred. Thinner, thicker or stacked solutions are also possible.

- Layer thickness. Layer thickness has only a secondary impact on energy levels, through impedance matching. It has a more significant impact on output voltage, in conjunction with the storage capacitor. Thinner layers are often preferred for low output voltage adapted to electronics.

- External electrodes. While standard electrodes are located on opposite side faces, custom and wrap-around electrodes provide alternative placement to facilitate integration and electrical contacting.

- Electrode material. Silver and silver-palladium electrodes are adapted to soldering, while gold electrodes are preferred for mechanical contact.

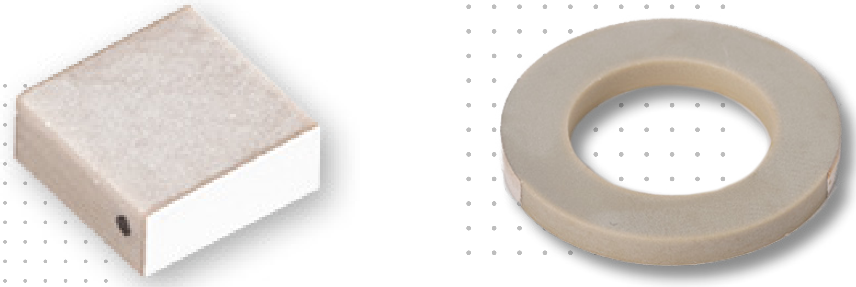

Fig. 9. Multilayer ceramic generator plate and ring.

CONCLUSIONS

Multilayer generators enable advanced functions for fuze systems, providing high reliability and low maintenance compared to batteries. This white paper provides the designer with the necessary data for a first estimation of the output energy levels depending on the main design parameters: dimensions, material, layer thickness, mechanical stress and electrical load.

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