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Geometrical Parametrization of Piezoelectric Sensors for Acoustical Monitoring in Hadrontherapy[†]

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Abstract: The hadrontherapy has been in constant evolution by leaps and bounds since the fifties, when the use of heavy particles was proposed as an alternative treatment to radiotherapy with gamma rays or electrons. The main objective of this treatment is to maximize the dose applied to the tumour avoiding damage to the surrounding tissue. One of the keys to the success of the hadrontherapy is to achieve an instantaneous monitoring of this energy deposition in the environment. Since the energy deposition leads to the generation of a thermoacoustic pulse, acoustic technologies have been tested with successful results. However, for this purpose, it is essential to increase the sensitivity of the sensors for the acoustical signal and, therefore, to optimize their geometry as a function of the beam that would be used. We have studied a PTZ material in volumetric and surface volumes through experimental measures and FEM methods. In this text, we start with numerical studies which determine the dependence of the thermoacoustic signal frequency with the energy and duration of the hadron beam.

Keywords: Hadrontherapy; Bragg Peak; Piezoelectric Devices; Optimization of ceramics

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1. Introduction

Piezoelectric sensors have been extensively used due to its basic direct and inverse piezoelectric effect that take part in the relation between electric field and mechanical deformation. A useful piezoelectric geometry is the circular cylindrical shape. It is used in several applications in actuators, sensors for mechanical structures, underwater monitoring and medical research. Nowadays, one of the main aspects in medical applications is the use of piezoelectric materials in the detections of pressure pulse produced by a thermoacoustic effect due to interaction of proton beams in human issues. In fact, one of the fields of medicine is the use of directed beams of ionizing radiation (electrons, X-ray, protons) whereby radiosurgery is an important method of treatment of malignant tumours and isolated metastases. However, the radiation over healthy tissue is a challenge to detect acoustic signal the energy deposition in small tumours or areas where the radiation is not safe because an over irradiation in near areas would bring problems to the patients. Hadrotherapy monitoring consists of the detection of the pressure pulse produced as a result of the behaviour of the Bragg peak created by a pulsed proton beam. In those cases, proton-acoustic signal depends on a variety of parameters such as the beam pulse width, energy, spot size, and measurement noise. There are some studies about the detection limits on proton-acoustic signals in clinical proton therapy scenarios to determine the detection threshold of the proton-acoustic method. The results set the limit on the sensitivity of the proton-acoustic method and should establish a quick reference for assessing whether a given irradiation scenario produces a detectable proton-acoustic signal [1].

In previous studies about piezoelectric geometric optimization, it has been researched the relation between diameter and thickness according to geometry for a unique dimension [2] [3]. Using this information, in this work, an optimization of cylindrical piezoelectric PZT material has been developed to improve the sensibility according to the characteristics of the beam and signal-to-noise ratio for a matrix of 36 different diameters and thickness. The aim is modifying this geometrical shape to determine the better diameter-thickness ratio for each case and, according to the required frequency, to set up the shape that maximize the sensor sensitivity, mainly in low frequencies. For this, several circular PIC255 piezoelectric ceramic with different width and height were studied with analytical and numerical method contrasted with experimental measurements. There are previous works with circular PZT where the authors studied the optimization of shape for 2 fixed shapes modifying the diameter and thickness [2] [3].With these, the optimization is based on obtain the better electromechanical coupling factor related with first, second and third resonance modes. This factor depends on the resonance f_r and antiresonance f_a frequencies of the electrical impedance and its amplitude. The product of each frequency resonance and the length (thickness, t or diameter, d) is associated with the mode of vibration ($f_r \cdot d$ and $f_a \cdot t$) and the piezoelectric coupling factor $k^2 = f_a^2 - f_r^2/f_a^2$ can be obtained. Therewith, the ratio of coupling factor k_1/k_2 in low frequency give a quantified estimation of the energy distribution. Based on these studies, the method proposed in this paper is evaluate with many thickness and diameter the improve of receive sensitivity according to the hadronterapy technique.

2. Numerical Analysis

The optimization of the piezoelectric volume is based on a free bounded circular ceramic. Figure 2 shows the geometrical scheme of a piezoelectric ceramic. The ceramic is polarized through the z axis and the xy surfaces conform the electrodes. The vibration characterisitcs are obtained from the constitutive equations for piezoelectric materials [4] [5]. Of the three different modes of vibration of piezoelectric disck (radial, extensional, tangential and transverse), a theorical and experimental analysis [6] have demostred that only radial vibration mode can be measured in an impedance analysis. For that reason, just an analyse of vibrational characteristics of extensional mode had been carried out. According to some studies [3], the analytical model has been contrasted with simulation data. In these studies, the results have been validated in radial vibration on piezoelectric disks in different diameter-thickness ratio. The impedance curves to study the behaviour of piezoelectric material were implemented in COMSOL Multiphysics in Acoustic-Piezoelectric Interaction module. In this software, the size of tetrahedral meshing elements were taken into account that the smaller wavelength and it was discretized in almost ten parts. A mechanical free boundary condition was set in all the contours of the transducer and uniformly electrical open-circuit voltages were set to the electrodes. The voltage applied on the electrodes was set up in $500\ mV$ and the polarized direction corresponding with the thickness of the shape (z axis). The geometry of the shapes simulated depend on the frequency who is produced by the set-up parameters in the hadrontherapy applications. In these cases, frequencies between 50 and $350\ kHz$ has been studied. For this reason, it was proposed diameters and thickness from 5 to $40\ mm$ every $1\ mm$. In total, 1296 simulations were completed to get results in optimization.

2.2. Optimization Method.

In previous studies, the optimization of the volume in a piezoelectric ceramic has been applied to 1 diameter and 1 thickness [2]. In that case, the number of numerical results were taken from the relationship between diameter and thickness for radial and thickness vibration. However, in this paper, has only been borne in mind the radial mode because of the frequencies studied in hadrontherapy applications are reproduced in low frequency mode. A scheme of optimization method is shown in Figure 1 where is described the input and the output in function of the requires. This optimization method has been split into 4 stages, which sum up the relation between the piezoelectric device parameters and the hadrontherapy parameters, and how it has been related according to the frequency. As for the first step form the piezoelectric device, a radius and thickness contribute to the radial vibrational mode, whereby a relationship between the geometry of the ceramic and the frequency could be written as [7] $N_p = f_r/d$ and $N_t = f_r/th$, where N_p and N_t represent the frequency constant which for PZT PIC255 material is 2000. The N_p expression gives the analytical resonance frequency in radial and thickness vibrational modes. According to different studies, these frequencies vary between $60kHz$ to $380kHz$ in accord with input parameters typical in hadrontherapy simulations. Using the expression for N_p and N_t, the diameter and thickness range will set up between $4[mm]$ and $40[mm]$. These lengths cover the bandwidth and also will be the input parameters in the model. Once the input parameters have been defined, in step 2, the impedance modulus will be export from the numerical model for each frequency which the minimum value in impedance will represent the resonance frequency and the maximum value of the impedance the anti-resonance frequency in the first and second radial mode respectively. As it will see later, for each pair of resonance and anti-resonance frequencies in the first and second mode, the electromechanical coupling coefficient could be got.

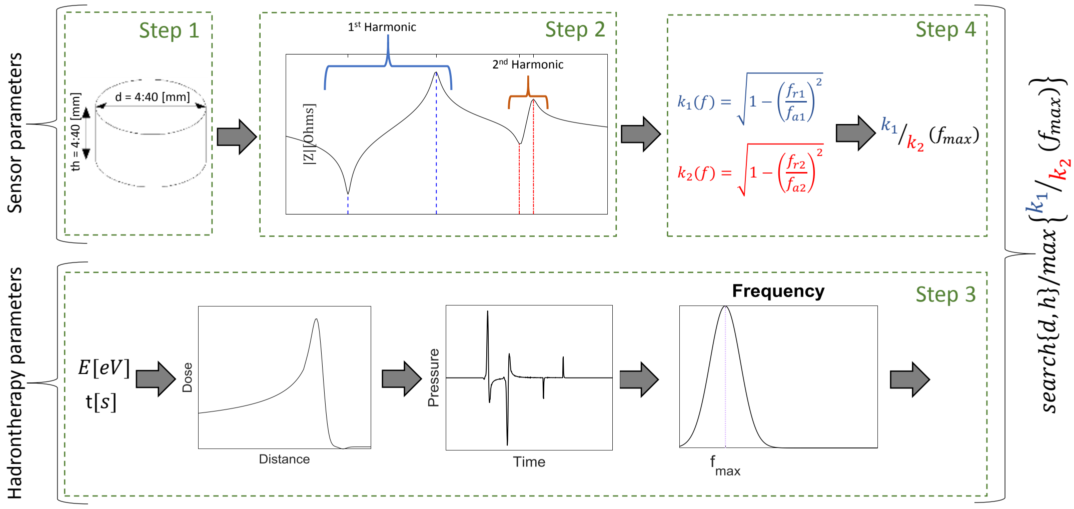


Figure 1. Input parameters for different diameters and thickness that produce output parameters.

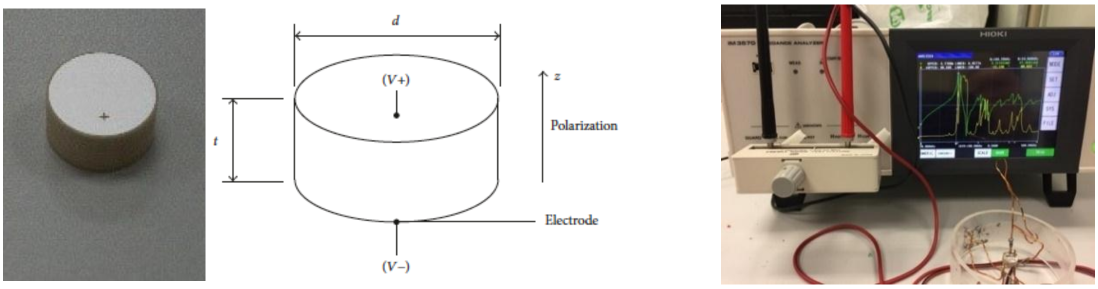
The thermoacoustic parameters can be evaluated carefully in different experimental and analytical studies [1] [8] [9] [10] [11]. To sum up, the energy of the beam and the temporal profile are the input parameters in the Bragg peak [12] and thermoacoustic model [11]. As a result, in the step 3, the proton interactions with the tissue and the characteristic Bragg peak behaviour of them, produce a pressure in the PTZ sensor whose amplitude is related to the number of protons per pulse [1] and the frequency with the temporal profile of the source.

Due to the frequency results in the thermoacoustic model, it is possible to relate the hadronterapy parameters with the piezoelectric device characteristics. In step 4, the electromechanical coupling coefficient is calculated for the first two modes and a relation of those is shown as k_1/k_2. On the one hand, once a respective frequency has been obtained from the thermoacoustic model, the region where this fit with resonance and anti-resonance frequencies with the maximum in the electromechanical coupling coefficient will be the best match to the diameter-thickness ratio. Considering that there are some values in the region of the k_1/k_2 that could fit the solution, in this paper has been evaluated the maximum of k_1/k_2 as of the frequency in the thermoacoustic model.

3. Experimental Setup

To compare the numerical solution a measured of electrical impedance was made. For this case, the method described in [2] was used in piezoelectric disc. The bandwidth frequency impedance response was measured of PIC255 piezoceramics with diameters $D = 10$ mm and thickness $t = 5$ mm. The measurements were done through the resonance method using Wayner Kerr Electronics

6500PLF impedance analyser. The electrodes were located in each surface on the ceramic in air. Figure 2 shows the ceramic and the experimental set up.



(**a**) (**c**)

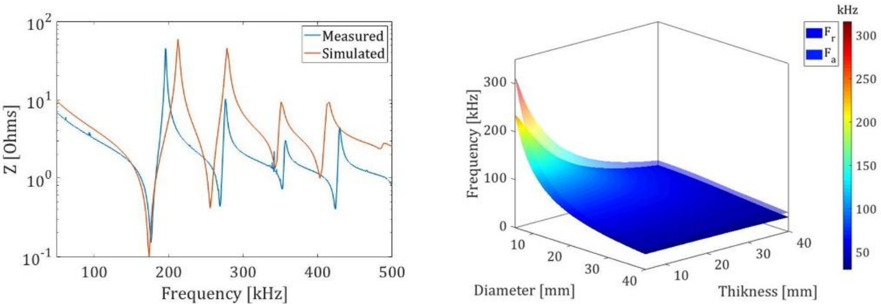
Figure 2. (**a**) Piezoelectric disc with $10\,mm$ diameter and $5\,mm$ thickness with longitudinal polarization; (**b**) Experimental set up to measure the electrical impedance in piezoelectric elements.

When the ceramic is excited in a resonance frequency of radial vibration, the value of the impedance reaches a minimum. As a result, the modulus of the impedance provides information about the resonance and anti-resonance frequencies for each vibration mode.

3. Results

3.1. Resonance and Anti-Resonance Behaviour.

Acording to the theorical electrical impedance modulus, Figure 3 shows the typical behaviour in a piezoelectric ceramic disc in radial mode vibration. The local minumun and maxima appearing in the impedance curve correspond to resonance and anti-resnance frequency respectly. Figure 3a shows numerical and measured results in the transducers studied ($d = 10\,mm$ and $t = 5\,mm$). The frequeny start in numerical simulation and experimental measurement were $100\,Hz$ to $500\,kHz$ with an increse step of $100\,Hz$ measured in a Wayne Kerr impedance analayzer. Figure 3b also shows the relationship between the resonance f_r anti-resonance f_a frequencies, diameter and thickness of the transducer for the first mode for the numerical simulation.



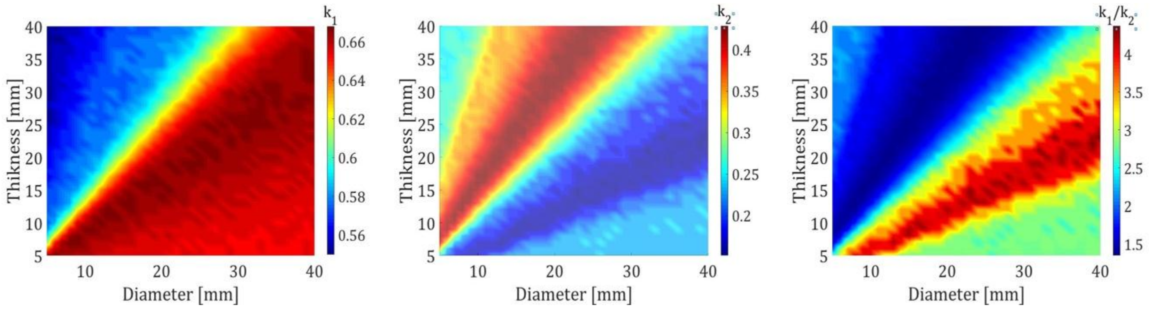
(**a**) (**b**)

Figure 3. (**a**) Comparation in impedance modulus form FEM simulations and measurement; (**b**) Resonance and anti-resonance results of simulations to different diameter and thickness.

In low frequency the analytical and numerical fits give positive results in the bandwidht studied for applications in hadrontherapy [1]. The resonance frequency increase with decreasing diameter in a nonlinear relationship as show in Figure 3.

3.2. Electromechanical Coupling Coefficient.

The electromechanical coupling coefficient is a measure of the effectiveness with which electrical energy in converted into mechanical energy and vice versa. It was propoused by Manson and it's obtained by the measuring the resonace and anti-resonance frequency through the expresion $k = \sqrt{1-(f_r/f_a)^2}$. This coeffient is an reference to the design of piezoelectric ceramics and it is expresed in values between 0 to 1. Figure 4 shows the value for the electromechanical coupling coefficient for the first and second low frequency mode in function of diameter and thickness.



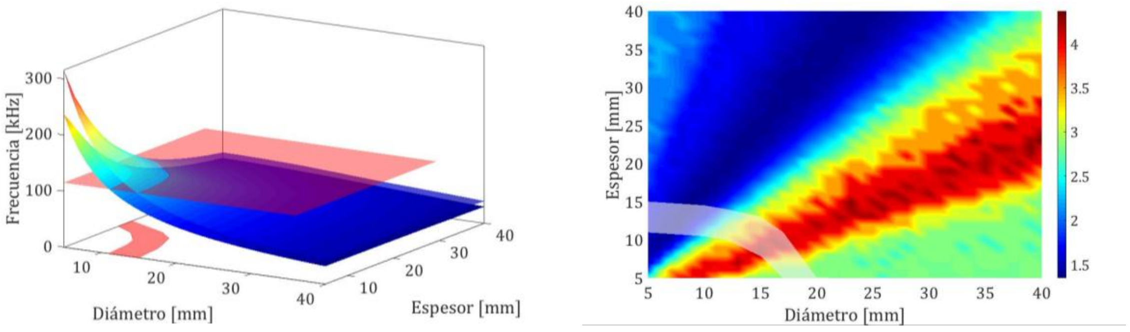
(**a**) (**b**) (c)

Figure 4. Ratio between the electromechanical coupling coefficient k of the first and second lowers modes as a function of diameters and thickness edges. (**a**) electromechanical coupling coefficient in the firs lower mode $(k_{1st.mode})$ in 2D; (**b**) electromechanical coupling coefficient in the second lower mode $(k_{2nd.mode})$ in 2D view; (**c**) k_1/k_2 ratio electromechanical coupling coefficient in 2D.

In general, the best efficiency energy fit for lowest radial mode take place when the diameter is larger than thickness. With this graphic is possible to predict the behaviour in the frequency of a disc ceramic in function of the resonance frequency to improve. Figure 4c shows the ratio between the electromechanical coupling factor of the first mode $(k_{1st.mode})$ and that of the second mode $(k_{2nd.mode})$. A high variation on the ratio between the electromechanical coupling coefficient k happen due to the different nature of the modes observing values of k_1/k_2 up to 4.0. In lower resonance frequencies corresponding with the radial mode and a relatively low coefficient k_1/k_2 (about 1.2) thanks to a great interaction between modes, resulting in a more homogeneous response in this frequency. According to the simulations, there are some geometries that live up the frequency requires of a small volume, low frequency and reduced k_1/k_2 depending on the applications.

3. Discussion and Conclusions

In order to have a first approximation to this optimization problem, the studies were developed to have a optimize tool of piezoelectric sensor design for hadrotherapy applications where was compared the behaviour of a piezoelectric ceramic that was measured in laboratory and simulated according with the method planned before. These studies are the continuation in research of radial extensional modes in piezoelectric disc with mechanical free bounary evaluated with numerical simulations and experimental measurements [2]. To validate the effects of this paper, some research has been analysed in theorical detection of the proton acoustic signal [1] [10] [9] [8] to improve the Received Voltage Response (RVR). The low-pressure amplitudes in hadrontherapy applications is a challenge in the use of ultrasound sensors to adapting protoacoustic measurements for in protoacoustc verification. It's caused by tissue heterogencity in acoustic reflection, absortion, refration, and changes in the medium velocity, all of which distort the pressure wave shape and increase the error in signal detection. For a beam energy of $100\ MeV$, a pulse with of $5\ \mu s$, a spot size of $10\ mm$ and $5.0 \cdot 10^6$ proton per pulse, the central frequency is $128\ kHz$ [1]. Therefore, in this case, the pressure in the sensor at 20 mm from the Bragg peak is 0.2 Pa. If we take a plane where it cut the resonance frequency and anti-resonance frequency, is possible choose a best geometric fit. Figure 5a shows an evaluated plane in a frequency of $128\ kHz$.



(*a*) (*b*)

Figure 5. Optimization method. (**a**) Resonance and anti-resonance results, in this case, a $128\,kHz$ show the area where the planes are cut (**b**) k_1/k_2 electromechanical coupling coefficient ratio to which is being cut by the frequencies area.

Once the intersection points where the plane match with a resonance frequency and anti-resonance frequency are defined, it is possible to determine the values of diameter and thickness which are the best fit with this frequency. In the electromechanical coupling coefficient ratio, it is possible to search the maximum value which these sizes match with the best frequency fit. As a result of the analysis, the RVR is got in the specific case. Table 1 in Figure 6 shows the values of diameter and thickness in these intersection points for the resonance and anti resonance frequency. According to the electromechanical coupling coefficient ratio, the best fit to optimize the sensibility in 128 kHz is in a diameter $(D = 15\,mm)$ and a thickness $(t = 9\,mm)$ where the relationship between k_1/k_2 is maximum. Figure 6 shows a new geometry to improve the sensitivity. The experimental (red line) and simulated (black line) RVR for a ceramic studied is shown where the RVR corresponding with $-185\,dB$ in frequency studied. In addition, the new geometrical fix match with a diameter $(D = 15\,mm)$ and thickness $(t = 9\,mm)$ present a substantial improvement at the same frequency with a value of $-171 dB$.

Table 1. Diameter and thickness intersection points for resonance and anti resonance frequency.

Resonance Frequency	Diameter [mm]	5–13
	Thickness [mm]	5–20
Anti-Resonance Frequency	Diameter [mm]	5–17
	Thickness [mm]	5–24

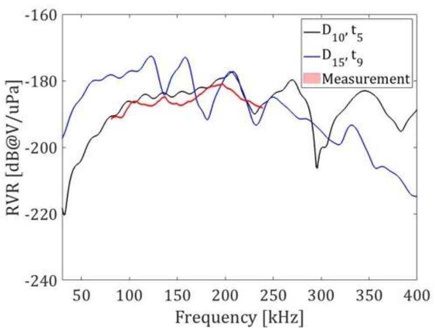


Figure 6. Left, range of geometries where a 110 kHz frequency could improve the sensibility in PZT material. Right, Received Voltage Response for simulations ceramics.

Taking into account that: elecomechanical coupling k indicates a different interation between first and second modes for different radius and thickness values, the studies and results presented here are specially relevant for low frequencies near first and second resonance modes. Little changes in the size of the material produced maximums and minimums in the RVR what is more significant when the resonance frequency in diameter and thickness shapes concide with each other. In consequence, when first and second resonance modes are closer there is a maximum in the relation k_1/k_2 for the frequency evaluated, which entails an increase in the sensibility in that frequency. In this region, the maximum values form the k_1/k_2 ratio are near 4.5. These results in a significant contrast in the efficiency between the first two modes of the ceramic. On the plus side Figure 5 shown also a noticeable increase in the sensitivity in the bandwidth below 200kHz. The way forward is will find the best fit to have a better relationship in the bandwidth in low frequency where in based on the maximum frequency of hadrontherapy applications, existed the possibility of increase sensibility below of that maximum frequency. To sum up, it is possible establish a method to improve the receibed votage response (RVR) according to the frequency requirements in hadrontherapy applications. It would be usefull to optimize the vulume in piezoelectric sensors considering the compromise between low k_1/k_2.

Conflicts of Interest: The authors declare no conflict of interest.

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