Energetic optimization of a piezo-based touch-operated button for man–machine interfaces

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Abstract

This paper discusses the optimization of a touch-operated button for man–machine interfaces based on piezoelectric energy harvesting techniques. In the mechanical button, a common piezoelectric diaphragm, is assembled to harvest the ambient energy from the source, i.e. the operator's touch. Under touch force load, the integrated diaphragm will have a bending deformation. Then, its mechanical strain is converted into the required electrical energy by means of the piezoelectric effect presented to the diaphragm. Structural design (i) makes the piezoceramic work under static compressive stress instead of static or dynamic tensile stress, (ii) achieves a satisfactory stress level and (iii) provides the diaphragm and the button with a fatigue lifetime in excess of millions of touch operations. To improve the button's function, the effect of some key properties consisting of dimension, boundary condition and load condition on electrical behavior of the piezoelectric diaphragm are evaluated by electromechanical coupling analysis in ANSYS. The finite element analysis (FEA) results indicate that the modification of these properties could enhance the diaphragm significantly. Based on the key properties' different contributions to the improvement of the diaphragm's electrical energy output, they are incorporated into the piezoelectric diaphragm's redesign or the structural design of the piezo-based button. The comparison of the original structure and the optimal result shows that electrical energy stored in the diaphragm and the voltage output are increased by 1576% and 120%, respectively, and the volume of the piezoceramic is reduced to 33.6%. These results will be adopted to update the design of the self-powered button, thus enabling a large decrease of energy consumption and lifetime cost of the MMI.

(Some figures may appear in colour only in the online journal)

1. Introduction

A man–machine interface (MMI) is a console where interaction between humans and machines occurs. In a MMI, the operator normally presses a mechanical button to access the system and make operational decisions. Present-day MMI is a market that is of significant size already, having a growth rate about 25% a year. MMI is rapidly becoming more common and important in daily life, such as the remote controller of sound equipment, the TV and for car keys. MMI design follows conventional technology trends, but also faces extra challenges, such as lifetime cost, haptic feedback and especially the power source which normally is a traditional battery. Although batteries have been employed as energy sources in MMI products for many years, they are increasingly unable to meet the needs of these products due to their intrinsic drawbacks, like considerable space requirement, short lifetime and expensive replacement.

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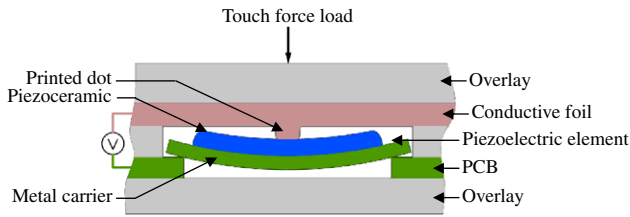
Figure 1. Cross section of piezo-based touch-operated button.

Moreover, discarded batteries cause serious environmental damage. The number of batteries used in the world still rises yearly. These predicaments influence people to look for clean alternative energy sources. They try to invent some micropower generating equipment to substitute for the traditional battery or charge it automatically. Recently, more and more investment and attention is attracted by these new equipment.

In practical applications, power sources in ambient environment provide possible energy generation strategies, including the exploitation of the piezoelectric effect, electromagnetic and static electricity, and then the systemic design of the power generating equipment. In suitable kinds of equipment, such as in MMIs, piezoelectric devices may have a simple configuration, no additional electromagnetic pollution and are easier for microminiaturization and integration. Therefore, they receive more attention than others, and may be considered as a substitute for the traditional battery in the MMI. Some of them have been tested in RFID transmitters [1], vibration monitoring and control [2], air tanks [3] and so on.

To supply professional and consumer MMIs with operational manipulation functionality, the human input is usually accomplished by pressing buttons. The movement of the button under finger touch operation represents a typical kind of ambient energy that could be available surrounding the MMI. It is obviously possible for the button to convert the mechanical energy into usable electrical energy.

This paper therefore presents a new touch-operated button based on the piezoelectric energy harvesting technique. This new energy source using a piezoelectric diaphragm is developed to replace traditional batteries in the MMI and contributes to lower cost, performance improvement and size reduction of the touch-operated MMI. Electromechanical coupling analysis is carried out to investigate how the key properties including dimension, boundary condition and load condition in the piezo-based button affects its electrical and mechanical performance. After that, optimization tools are used to optimize the systemic design of the piezo-based button in order to obtain maximum electrical energy.

2. Structural design and working principle

2.1. Systemic structure

Figure 1 is the cross section of a piezo-based touch-operated button.

This button stackup includes four layers: overlays (top and bottom), conductive foil, the piezoelectric element and the PCB. As the core unit in the button, the preferred piezoelectric element is a diaphragm that is cheap enough for the button, easy to purchase and mass-produced. The piezoelectric diaphragm is placed in a pit with precise tolerance. Its bottom surface, the metal carrier layer, connects with the PCB as an electrode. Its top surface, the piezoelectric material layer, connects with conductive foil as the other electrode. The two overlays cover the whole structure to avoid vandalism and water damage [4].

The piezo-based button needs to meet some main requirements to work properly. The first requirement is a stable electrical connection between the diaphragm and the external circuit. For this purpose, a dot is printed on the conductive foil above the piezoelectric element. This extra thickness pushes against the piezoelectric diaphragm, resulting in a small bending deformation of the diaphragm during assembly. The reaction force between the dot and the piezoelectric diaphragm presses the top conductive foil, the middle piezoelectric diaphragm and the bottom PCB together. This process achieves a good electrical connection between them. The circular dot size is equal to the diameter of the force load's touch area. A second requirement is that, underneath the piezoelectric diaphragm, there must be a clearance for the piezoelectric element that is large enough to let it bend freely to convert enough electrical energy, but never fracture. The required clearance can be calculated by electromechanical coupling analysis or determined by testing of the piezoelectric diaphragm.

2.2. Working mode

The piezo-based touch-operated button exploits the direct piezoelectric effect. When a touch force is applied to the button, the overlay transfers the force load to the conductive foil. The pre-pressured piezoelectric diaphragm will move with the touch press and bend. In this deformation, part of the input mechanical energy will be converted into electrical energy by the piezoelectric material in the diaphragm. Then the induced charge stored on the diaphragm surfaces could be extracted by a harvesting circuit to supply the external electrical load with power and achieve the function of the button.

It is well known that the most widely utilized material in piezoelectric energy harvesting is piezoceramic. For the selected diaphragm, the piezoelectric ceramic is PZT-5A, one of the very common types of piezoceramic. This piezoceramic, like other ceramics, is brittle and hard, strong in compression, weak in tension and shear. Its compressive strength is significantly much larger than its tensile strength. The Morgan Crucible Company reports the compressive strength of PZT-5A to be more than 517 MPa and yet both the static and dynamic tensile strengths of PZT-5A are hardly comparable with its own compressive strength or other typical engineering materials [5]. The reported static and dynamic tensile strength values of PZT-5A are 75.8 MPa and 27.6 MPa, respectively. With regard to vibration or shock
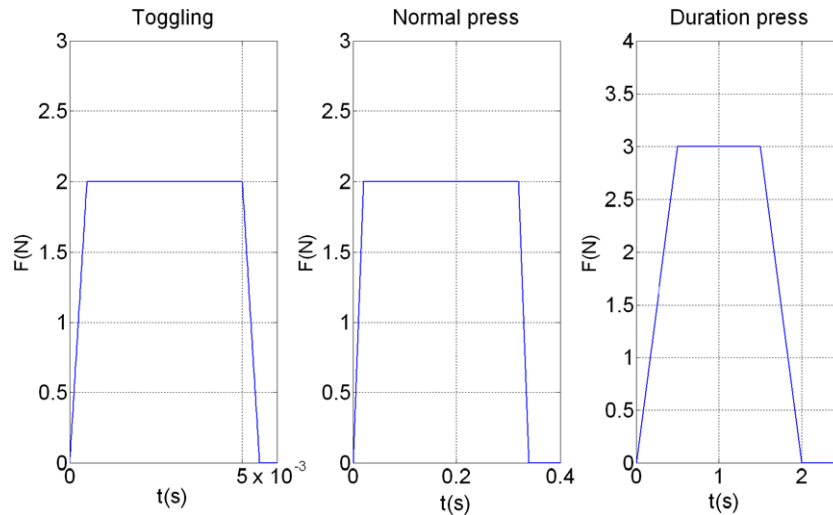
Figure 2. Time history of touch force loads. (Note the differences in the timescales.)
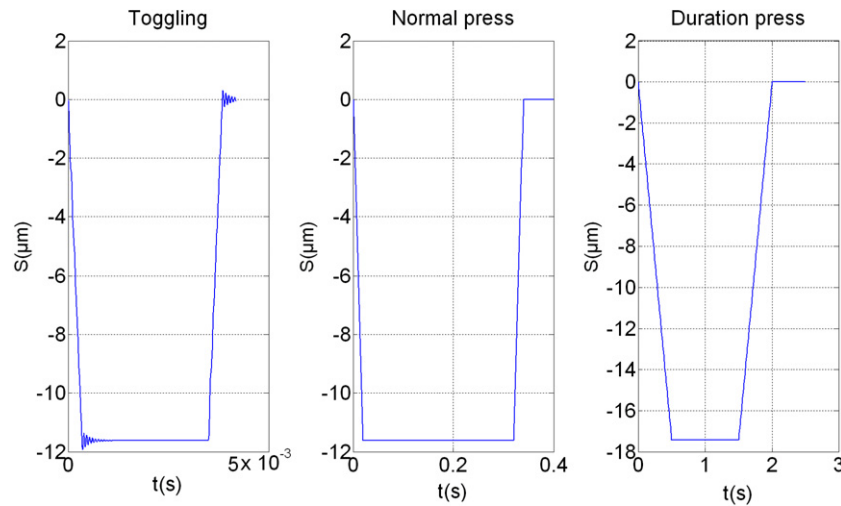

Figure 3. Deformation responses under different touch force loads.

energy harvesting, a piezoelectric element works under tensile stress and compressive stress circularly. The upper limit of the working stress of the piezoelectric diaphragm must therefore be less than 27.6 MPa. Piezoceramic brittleness causes a serious limit in working stress to make it safely convert mechanical energy without being damaged. It is better to make a piezoceramic work under static stress but not dynamic stress, meanwhile ensuring compression stress but not tension stress. This important decision has a large influence upon the structural design and mechanical analysis.

2.3. Response analysis

The input touch force load decides the mechanical and electrical response of the piezoelectric diaphragm. Figure 2 plots some typical time histories of touch force loads.

Generally, the time history of the finger touch may be very short, but its frequency cannot be higher than 10 Hz, and hence is much less than the natural frequency of the piezoelectric diaphragm, which is of the order of thousands of Hz. Therefore, it is impossible for the touch operation load to excite the diaphragm to be resonant. The intermedia transferring the force load are the finger, the overlay and the conductive foil which are all soft damping materials. This structural design and material combination utilized in the button seriously weaken the impact of the pulse force load. Accordingly, the force load cannot reach a peak from zero or be zero from the peak immediately. It shows a clear rise/fall edge in the force load time history and these edges are much longer than the vibration period. As demonstrated in figure 3, the deformation responses of the diaphragm are almost completely linear with the time histories shown in figure 2. The vibration decay occurs after the first toggling load and reduces to zero very fast. The effect of the vibration response of the diaphragm on its electrical and mechanical behavior can therefore be neglected in the analysis hereafter.

Consequently, piezoelectric energy conversion in the button is considered as a static energy harvesting rather than a vibration or a shock energy harvesting. It means that the stress state of the piezoelectric diaphragm, consisting of
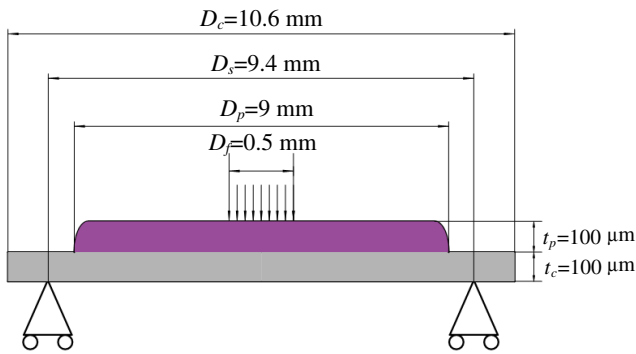
Figure 4. Dimensions of Stelco GmbH SS11-JDQ-000.

Table 1. Material parameters.

Parameters	SUS-304	PZT-5A
Elastic constant (GPa)	193	—
Density (kg m^{-3})	7800	7700
Poisson's ratio	0.3	0.33

Figure 5. Finite element model of Stelco GmbH SS11-JDQ-000.

Table 2. Result comparison.

Parameters			Test	FEA	Error (%)
Force	F	(N)	1	1	—
Energy conversion efficiency	η	(%)	14.24	14.43	1.30
Electrical energy	E	(μJ)	0.79	0.87	10.32
Voltage	U	(V)	13.33	14.20	6.50
Capacitance	C	(nF)	8.9	8.66	2.74
Deformation	S	(μm)	11.11	12.10	8.91

a metal layer and the piezoceramic layer, will always be positive or negative during the response. Since the metal layer and the piezoceramic layer are located on two sides of the neutral plane, if the metal layer has a tensile stress state the piezoceramic layer will have a compressive state, and vice versa. Combined with the strength data discussed in section 2.2, the side facing load is suitable for piezoceramic applications. Undergoing bending deformation, the stress state of the piezoceramic layer will be purely compressive and does not contain tensile strain. The metal layer is subjected to tensile stress, for which it is well suited. Thus, this working mode appears to be best suited for both layers.

3. Electromechanical coupling analysis in ANSYS and experimental test

As a starting point for optimization, a design of a piezo-based button is available that originates from applications wherein energy harvesting has not been a goal. The piezoelectric diaphragm in this original design is Stelco GmbH SS11-JDQ-000, shown in figure 4. The material of the piezoceramic layer and the carrier layer are piezoceramic PZT-5A and stainless steel SUS-304. Table 1 lists the material properties.

During the initial stages of modeling, factors such as bonding layer and silver electrode layer that are associated with energy harvesting have been studied. The results proved that, compared with the piezoceramic layer or the carrier layer, the bonding layer and silver electrode layer are thin enough to be neglected in the following analysis. After meshing, the carrier is constructed using 580 solid95 elements and the piezoceramic is modeled by 420 solid226 elements. Figure 5 shows the meshed model of the diaphragm. The modeling and meshing will be upgraded later, according to results found during different parameter optimizations.

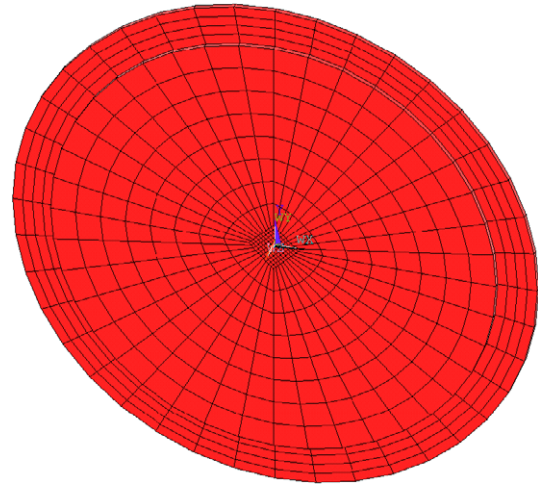The carrier's bottom surface is hinged supported circularly in accordance with the assembly in the piezo-based button. The nodes in the outer surfaces of the piezoceramic and the carrier are defined as two sets of coupled nodes that represent the top and bottom electrodes of the voltage source, respectively. Finally, coupling analysis is separated into two parts. One is inverse piezoelectric effect analysis. In this part, a 1 V DC voltage source is coupled with the two electrodes. Then, on the top surface of the piezoceramic, there will be some induced electric charge, the amount of which is determined by the value of the diaphragm's capacitance C. The other part is direct piezoelectric effect analysis. The area load force is fixed at $F = 3$ N and is applied at the center of the piezoelectric diaphragm. In the postprocessor, we get the output voltage amplitude U by checking the electric potential difference between the two electrodes. With U and C, the converted electrical energy E can be calculated as $U^2C/2$.

Moreover, an experiment is accomplished to test the electrical and mechanical behavior of the diaphragm under step force load. The test result and FEA result are shown in table 2. The energy conversion efficiency by touch operation is equal to the converted electrical energy divided by the input mechanical energy.

It is known that electrical parameters of the piezoelectric diaphragm may have a 10%–25% deviation. The biggest error between the test and FEA is about 10%. Hence we conclude that the FE model used in the study is reliable and accurate enough. It provides a good basis to conduct further parametric property study and design optimization.

Table 3. The significant dimensions for parametric investigation.

Dimensions	Meaning
t_p	Thickness of the piezoceramic layer
t_c	Thickness of the carrier layer
D_p	Diameter of the piezoceramic layer
D_c	Diameter of the carrier layer
D_s	Diameter of the hinged support
D_f	Diameter of the force load area

4. Property study based on FEA

In the overall characterization of the piezo-based button, the electrical energy output is the most critical one. It must be higher than the smallest amount of energy needed in normal operation of the electrical load.

Knowing how the structural and material properties affect the element's electrical characteristics allows a piezo-based button to be designed and improved for a touch-operated interface. Gains in this area are a necessity for successful application of piezoelectric elements in power harvesting devices. Anton and Sodano [6] explain that the power harvesting device's configuration can be changed through the modification of the piezoelectric material, altering the electrode pattern, changing the poling and stress direction, layering material to maximize the active volume, adding pre-stress to maximize coupling and applied strain of the material, and tuning the resonant frequency of the device. However, some of these measures modify the piezoelectric diaphragm in ways that it becomes inconvenient in production and in conflict with given cost constraints. The configuration modification should be done on the premise that the improved element maintains its original advantages.

For the shape or the topology modification, the piezoceramic is too brittle to be patterned into structures randomly. Possible modifications are the dimensions rather than the shape or the topology. The interesting dimensions here are the diameter and thickness of the piezoelectric material and of the metal carrier listed in table 3.

In addition, boundary condition and load condition are set as points of study too. The boundary condition of the circular piezoelectric diaphragm is a circular fixed support or hinged support. Taking account of structural design and cost, the latter is simpler to be built. What we could do with the circular hinged support is to change its diameter, which is at least 0.6 mm less than the diameter of the metal carrier. For the load condition, the touch force is set as an average area force applied at the diaphragm's center, of which the value is the maximal amplitude 3 N plotted in figure 2. The circular force load area's diameter is the design variable related to the load condition.

4.1. Thickness

For a piezoelectric diaphragm with a thin piezoceramic layer and carrier layer, the low mechanical stiffness leads to a large deformation, and therewith to a high electrical energy output. To numerically check its effect on the diaphragm's electrical
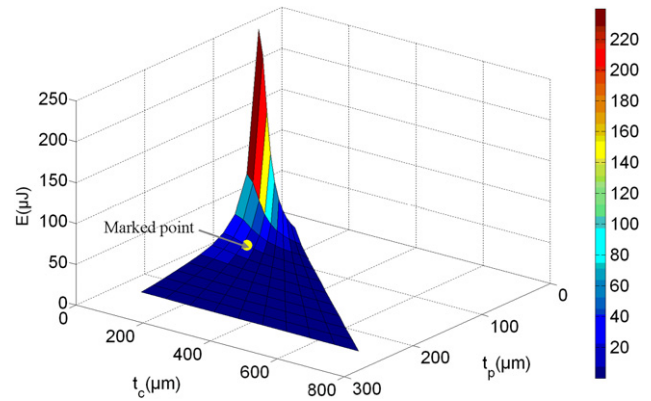
Figure 6. Electrical energy for different thicknesses.

and mechanical performance, the piezoceramic's thickness t_p is varied from 40 to 240 μm. Meanwhile, the carrier's thickness t_c is tuned by a ratio to the piezoceramic's thickness. This ratio is defined as t_c/t_p and varies between 0.3 and 3. Other parameters are kept equal to the original design values and the results of this analysis are shown in figure 6 by 3D space curves of the two variables t_c and t_p. Note that the marked point corresponds to the original structure's result.

Figure 6 shows that the converted electrical energy E has a nonlinear variation trend; it increases exponentially with the decrease of both thicknesses t_p and t_c.

4.2. Diameter of the piezoceramic and the support

In this section, the optimization variable is the diameter of the piezoceramic layer D_p, varying from 2 to 10 mm. The support's value D_s is tuned from D_p to $2D_p$. In order to maintain reliability in touch operation, there must be a minimal tolerance between the size of the support and that of the carrier. For now, the carrier's diameter D_c is always set as 0.6 mm more than D_s, to ensure that the diaphragm contraction in the radial direction under the action of the press load is still larger than the support. Other parameters are kept equal to the original design values.

With the planar size increment of the piezoceramic and the support, the piezoelectric diaphragm becomes soft. This results in more mechanical energy input, as shown in figure 8, so more energy is converted to electrical energy. E increases almost linearly with D_s, and its complex nonlinear relation with D_p is affected by the value of D_s.

Some illustrative results are shown in table 4. σ is the maximal von Mises stress of the piezoceramic layer. The data shows that, to get enough electrical energy output, the ratio of the support's diameter D_s to the piezoceramic's diameter D_p must be enlarged in the first step. Second, there are two choices. One is reducing the piezoceramic size D_p to get a higher conversion efficiency η, as shown in model 2. The differences between model 2 and the original structure indicate that this dimension and boundary condition modification improve the diaphragm comprehensively. Not only is E increased by 6.33%, U by 55.9% and η by 16.0%, but at the same time σ is decreased by 0.7%. The other
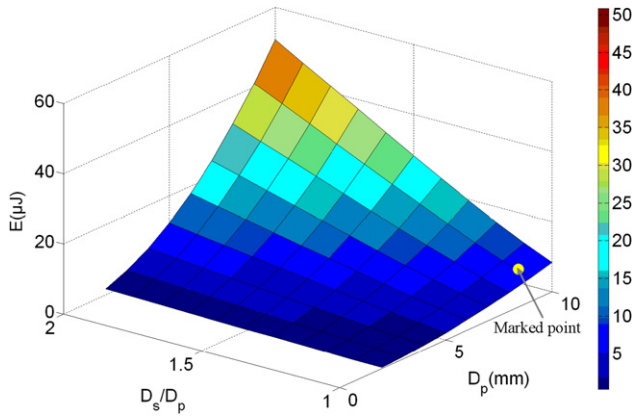
Figure 7. Electrical energy for different diameters of supports and piezoceramic.

Table 4. FEA result comparison.

Model	D_p (mm)	D_s (mm)	D_s/D_p	σ (MPa)	U (V)	η (%)	E (μJ)
1	10	20	2	192.2	98.1	11.8	50.8
2	6	8.4	1.4	146.6	66.4	16.7	8.4
Original	9	9.4	1.04	147.6	42.6	14.4	7.9

choice is to expand the support D_s to reduce the mechanical stiffness, as shown in model 1. In this way, σ has a 30.2% increase, but E and U are greatly increased by 543% and 130%, respectively. It is quite obvious that modification by increasing the support's diameter improves the diaphragm more than the first method.

4.3. Diameter of the carrier and the support

Given the results of section 4.2 and the constraint of the carrier's diameter in relation to the support's diameter, we define the following relative size parameter:

$$\delta = \frac{D_s - D_p}{(D_c - 0.6) - D_p} \qquad (1)$$

where δ varies from 0 to 1. $\delta = 0$ means the support's diameter D_s is equal to the minimal value, being the piezoceramic's diameter D_p. $\delta = 1$ means that the support has to be as large as possible, just 0.6 mm less than the carrier. D_c is set as 10.6–19.6 mm. Other parameters are kept equal to the original design values. As shown in figure 9, E increases linearly with δ, and so also has D_s, which is also linear with δ. This is the same as the result plotted in figure 7. With the increment of D_c, the diaphragm stiffness will increase slightly, thus resulting in a nonlinear decrease of the electrical energy as shown in figure 10.

In table 5, model 3 with the biggest carrier and support diameters is listed, which achieves the maximal electrical energy and voltage output because of its large deformation. U and E are 140% and 470% larger respectively than the original structure. This kind of dimension modification is as useful as the one discussed in section 4.2.
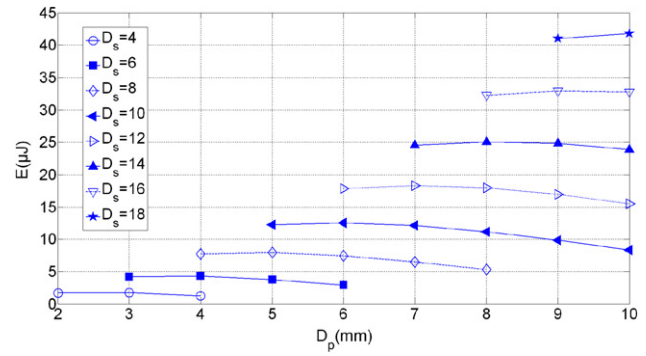

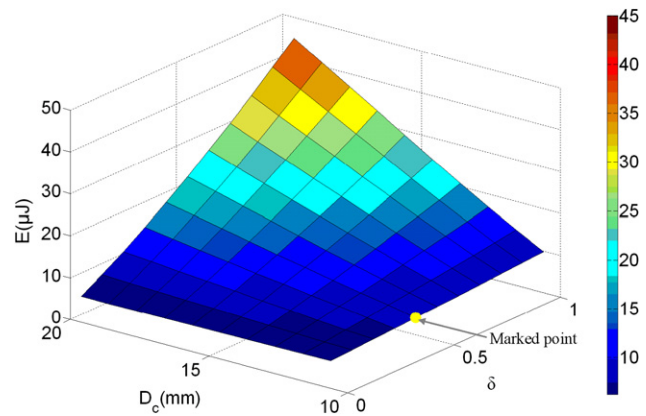**Figure 8.** Electrical energy for different piezoceramic disc diameters.

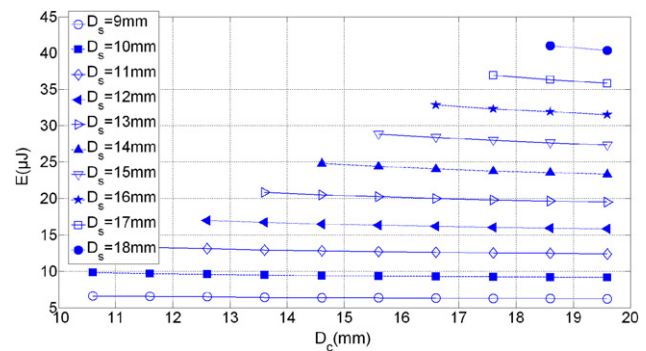**Figure 9.** Electrical energy for different diameters of carrier and support.

Figure 10. Electrical energy for different diameters of carrier.

Table 5. FEA result comparison.

Model	D_c (mm)	D_s (mm)	δ	σ (MPa)	U (V)	η (%)	E (μJ)
3	19.6	19	1	190.9	102.6	10.8	45.0
Original	10.6	9.4	0.4	147.6	42.6	14.4	7.9

4.4. Load condition

In the FE analysis, the force load amplitude was fixed at the value of 3 N during its entire period of application. The force is transferred to the piezoelectric diaphragm uniformly by the dot printed under the conductive foil. The dot's diameter
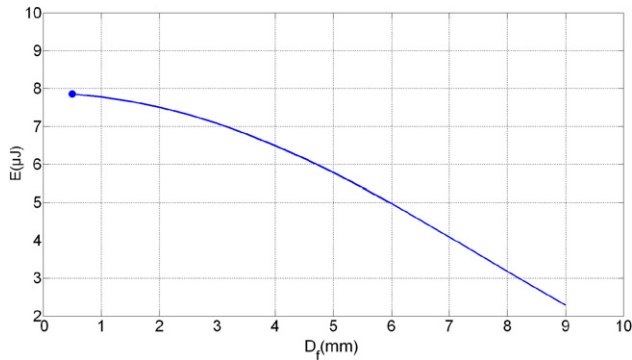
Figure 11. Electrical energy for different force load areas.

is equal to the diameter of the force load area D_f, and we now analyze the effects when it increases from the original value of 0.5 mm to the maximum value 9 mm, which is the piezoceramic disc diameter. Other parameters are kept equal to the original design values. The FEA result is shown in figure 11.

When the force load area expands to the edge of the piezoelectric diaphragm's top surface, a larger part of the force is exerted close to the support. The deformation and input mechanical energy will therefore decrease. This leads to a reduction of the converted electrical energy. A positive effect is that stress level σ will be greatly reduced; it decreases by 80% for the largest force load area.

4.5. Result analysis

The FEA results indicate that changing some dimensions, boundary conditions and load conditions could improve the piezoelectric diaphragm's electrical and mechanical characteristics greatly. The relations between the performance and the three types of properties are different in nature; most are nonlinear and just a few are linear. Moreover, these relations interact with each other.

For the four dimensions of the piezoelectric diaphragm, the carrier's thickness t_c and the piezoceramic's thickness t_p make the most significant contribution to the maximization of the electrical energy generation E of the diaphragm, because of the increment of the stress level. The increment of the piezoceramic's diameter D_p means that there will be more piezoelectric material involved in the energy conversion from mechanical to electrical. However, under different support conditions, obviously, it has a different optimal value to achieve a maximum E. It is the second largest contributor to the improvement of the piezoelectric diaphragm. For the carrier's diameter D_c, we would like to emphasize that it is the easiest one to be changed in the four dimensions. And it should not be tuned in isolation, but rather must be combined with the support dimension, resulting in significant design improvement.

The support's diameter D_s, which represents the circular hinged boundary condition, increases the electrical energy output linearly. It should be as large as possible. In contrast, the load condition, determined by the diameter of the printed

dot on the conductive foil, should be as little as possible to get more energy.

Among these properties, the first four, t_c, t_p, D_c and D_p, are related to the design of the piezoelectric diaphragm. The last two, D_s and D_f, belong to the structural design of the piezo-based button. Generally, if a piezoelectric diaphragm has been selected from the list of available products, what we can do is to tune the boundary condition D_s and the load condition D_f to obtain enough electrical energy output. Otherwise, if the piezoelectric diaphragm could be redesigned, its metal carrier diameter should be considered first in structural design, and then there are D_p, t_c and t_p. Of course, the boundary condition and the load condition could be taken into account at the same time.

5. Structural design optimization by FEA

According to the energy requirement for use of the original structure shown in [4], the piezoelectric diaphragm must output 131.6 μJ electric energy at least, while keeping the maximal von Mises stress level of the piezoceramic layer under 258.5 MPa. The results demonstrated above show that none of the models can meet the requirement of the electrical energy and the stress level simultaneously. Use of optimization tools to find the qualified models is needed. We could use a basic general directional search optimization algorithm to look for a qualified model or utilize the optimization tool in ANSYS software to calculate the optimal configurations. Here, the latter is chosen to accomplish all of the optimal parameters at once. The ANSYS program offers two optimization methods to accommodate a wide range of optimization problems. The subproblem approximation method is an advanced zero-order method that can be efficiently applied to most engineering problems. The first-order method is based on design sensitivities and is more suitable for problems that require high accuracy. In this study, the subproblem is used firstly to work out the interesting intervals of single or multiple design variables, and then the first-order method is used to search the optimal values in these intervals with higher accuracy again.

In the optimization, the objective function is the volume of the piezoceramic V which should be as little as possible to lower the cost of the piezoelectric diaphragm. The design variables include the diameter of the support and the piezoceramic layer D_s and D_p, and the thickness of the piezoceramic and the carrier t_p and t_c. The force load area at the center of the piezoelectric diaphragm might be the stress concentration point. So, the force load's diameter D_f is set as another variable to achieve a better balance between the stress level and electrical energy output. On account of the data showing that the electrical energy output E is increasing with the support D_s, D_c is directly set as 0.6 mm more than D_s. As the two requirements mentioned above, the state variables are defined as electrical energy output E, which must be more than 131.6 μJ, and the maximum von Mises stress of the piezoceramic layer σ, which must be less than 258.5 MPa. The force load is always 3 N. Considering all these features, the final optimization problem can be stated as:

Table 6. Structure comparisons.

Parameters		Original	Optimal	Increased (%)
t_p	(μm)	100	39.85	−61.15
t_c	(μm)	100	84.18	−15.82
D_p	(mm)	9	8.26	−8.22
D_c	(mm)	10.6	23.78	124.34
D_s	(mm)	9.4	23.18	146.60
D_f	(mm)	0.5	1.84	268
V	(mm^3)	6.36	2.14	−66.36
E	(μJ)	7.86	131.75	1576.64
σ	(MPa)	147.62	237.80	61.08
U	(V)	42.60	93.83	120.26
C	(nF)	8.65	29.93	245.77
S	(μm)	33.33	927.02	2681.34

- Objective function

  Min (V), $V = 0.25\pi D_p^2 t_p$, the volume of the piezoceramic layer V.

- Design variables

  D_p, D_s, D_f, t_p, t_c.

- State variable

  E, $131.6\ \mu J \leq E$

  σ, $258.5\ MPa \geq \sigma$.

Here is the optimal result.

Compared with the FEA results of the original structure in table 6, both thicknesses of the piezoceramic and the metal carrier of the optimal model, t_p and t_c, are reduced to make it less stiff and increase the mechanical stress. Meanwhile, the diameter of the support and of the carrier, D_p and D_c, are enlarged to make the diaphragm softer too. The force load area represented by D_f is increased to weaken the stress concentration around the diaphragm's center. As a result, the optimal model's deformation S is about 27 times that of the original one, while the electrical energy output E is improved about 16 times, with an increment of the stress level σ of about 61%. Furthermore, the objective function V is reduced to one-third of that of the original structure, in which most of the contribution is made by the reduction of the piezoceramic's thickness.

6. Conclusions

The starting point of this research has been an available original design of a piezo-based touch-operated MMI button. This design consists of a diaphragm, i.e. a piezoceramic disc on a metal carrier, embedded in a mechanical structure, and has the following characteristic properties and critical design parameters. The thickness dimensions of the piezoceramic layer and the metal carrier are most suited for the increase of electrical energy output. The decrease of the thicknesses can improve the energy exponentially. The diameters of the piezoceramic and the carrier have a complex nonlinear relation with energy output that won't change too much with variation of the diameter. The boundary condition, represented as the diameter of the hinged circular support, is linear with the energy output. It must be coordinated with the diameters of the piezoceramic layer and the carrier to generate the maximum energy output. The force load should be focused on the center of the diaphragm to improve the converted electrical energy. Based on these conclusions, an optimal model is given to show that the optimization design achieves a 15 times increment of electrical energy output with a 66% reduction of the piezoceramic volume.

In future work, the energy conversion efficiency will be the research point. Besides, more properties such as the material of the piezoceramic disc and the carrier will be considered to study their influences on the electrical and mechanical behavior of the piezoelectric diaphragm.

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