New piezocomposite transducers for therapeutic ultrasound

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Abstract

The development of therapeutic applications of ultrasound depends notably on the availability of high-performance transducers. New piezocomposite technologies offer performances that have proved to be particularly well adapted for such applications thanks to high power density generation with high efficiency. Moreover this technology enables a wide variety of shapes and the design of array transducers for electronic focusing, scanning and steering of the beam. This article details these advantages as well as other interests such as a large bandwidth or the MRI compatibility allowing the imaging / therapy association. Furthermore, the feasibility of highly focused transducers and complex array structures will be illustrated through various examples.

Introduction

Ultrasound therapy has been the subject of research for many years [1, 2, 3], but it is only recently that this technique has found effective and widespread medical applications. The potential of this technique is extremely promising, but there remains progress to be made, notably in the area of the generation of ultrasonic waves.
The large range of potential applications creates a wide range of different objectives. The main parameters are the required action on the biological tissue, the volume and location of the treatment zone inside the body, the acoustic access to the target area, the limitations on treatment time, the limitations on the acoustic exposure of surrounding tissues, the associated imaging techniques.
Compared with other medical ultrasonic techniques like those used in medical diagnostic this will lead to specific requirements :

- Generate high power acoustic waves that are precisely localised and precisely controlled in amplitude,
- Provide 3D scanning of the beam with a high degree of flexibility,
- Have a physical compatibility with imaging equipment and associated sensors,
- Guarantee an improved degree of reliability and safety taking into account the use of a larger amount of electrical and acoustical energy

Based on the above application requirements the transducer designer will have to take into account transducer specifications that includes :

- The production of high acoustic power at the surface of the transducer,
- 2D large active radiating apertures with f-number ~1.

Maintaining the treatment time in a reasonable range is often an important objective. Flexibility of operation and easiness of control are also important criteria. On those aspects electronic beam synthesis focusing and steering with transducer arrays opens many routes for solutions.

When MRI imaging technique is to be used the material compatibility with MRI environment of transducer and other parts of the system is required.
When ultrasonic imaging technique is chosen it makes necessary to combine diagnostic requirements and therapeutic ones. Various configurations can be used :

- different transducers in separated housings mechanically positioned one to the other in order to obtain a precisely controlled location of respective beams in the same setting mark. The position of one transducer relative to the other may be adjustable or not.
- different transducers with a fixed position in the same mechanical assembly or in the same housing in order to obtain a very stable and constant positioning of one transducer relatively to the other.
- using the same transducer or the same group of transducer elements having the capability to function in both modes. This will obviously require transducers with a high power capability, at least at the chosen frequency for the therapeutic use, and a wide band capability, at least in the frequency range of imaging for diagnostic use.

State of the art technologies developed for high power ultrasound as well as technologies developed for low power ultrasound like medical diagnostic, non destructive testing, flow and distance measurement, etc... have many limitations with respect to above mentioned requirements.

In order to solve these limitations and develop new transducers for therapeutic ultrasound new high-power technologies using piezocomposite technology have been searched and evaluated [3]. Continuous research and development in this piezocomposite route offers now a broad range of technological solutions.

State of the art in piezoceramic and piezocomposite technology

It is well known that one can use piezoceramic bowls or plates made from low losses PZT materials to produce high power transducers. The piezoelectric layer is then excited on its first or third harmonic. These transducers are generally air-backed and array structures can be obtained by making deep grooves in the ceramic layer. This approach allows the manufacturing of high-intensity transducers with high efficiency but involves the following limitations :

- Lateral vibrations in ceramic layer may create parasitic waves producing spurious hotspots,
- Cross talk between array elements may limit beam control performances,
- Producing large size plates or bowls may be difficult,
- Due to the low resilience of piezoceramic materials and due to the presence of grooves in arrays the transducer structure may be fragile under mechanical shocks or pressure,
- Most of these designs give narrow band transducers.

On the other hand 1-3 and other piezocomposite technologies have received a large interest in low power applications like medical diagnostic [4] and non destructive testing. 1-3 piezocomposite technique is based on the use of materials including a large number of piezoceramic rods embedded into a matrix of polymer material (Fig1).

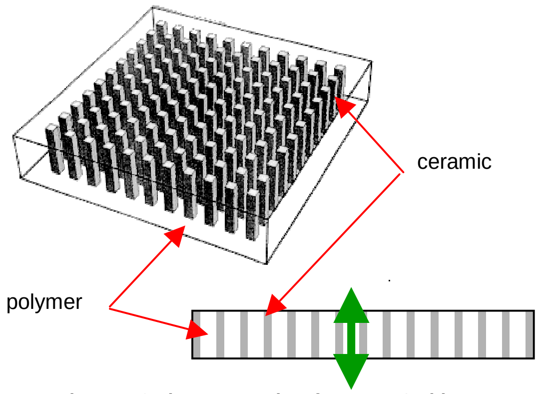

Fig. 1 : 1-3 Piezocomposite after W. A. Smith

The main benefit of a properly designed 1-3 piezocomposite material is an enhanced vibration in thickness mode and a reduction of the influence of lateral modes. The good properties in the thickness mode can be described by the coupling coefficient that is higher than the coupling coefficient of a plate made of the same ceramic material.
The most current design of so called 1-3 piezocomposite transducers based on the use of 1-3 piezocomposite materials implies the following choices:

- Use of low glass transition temperature (Tg) polymer filler : epoxy or polyurethane
- Thermal shaping of the piezocomposite structure in order to create a shell. This shell structure may be used to produce the mechanical focusing characteristics of the transducer.
- Create an array structure by using a pattern of engraved electrodes and making profit of the low lateral cross talk
- Use of solid backing material with relatively low acoustical impedance in order to have a good mechanical resistance and a high efficiency.

The use of 1-3 piezocomposite technology facilitates the reduction of lateral waves in large transducer shells as demonstrated by Cathignol and al [5] and provided that the piezocomposite is properly designed, one can obtain beam patterns with an excellent correlation with predicted beams from theoretical models.

Based on the above reasons the use of piezocomposite technology is attractive for therapeutic applications.
One important point must be remembered at this stage. High power ultrasound cannot be produced without electrical and mechanical losses inside the materials of the transducer and such losses make a part of the electrical and mechanical energy to be converted into thermal energy inside the transducer itself. As for instance it is well known that losses play an important role in the power capability of transducers based on ceramic technology and in that case one must take care to use special low loss piezoceramic materials in order to obtain high power characteristics. In addition one must take care of the losses in the used electrical interconnections, cables and matching networks.

Also it is well known that 1-3 piezocomposite materials have relatively high losses compared to ceramic materials used in power applications. The existence of losses implies that high power generation cannot be envisaged without a special and careful design of the thermal properties of materials and structures. As for instance maximum inside temperature of the currently used piezocomposite materials in low power applications is limited by low thermal glass transition temperature (Tg) usually around 60°C (140 °F). A transducer built with piezocomposite technologies designed for low power applications will rapidly be damaged under high power excitations. Therefore the use of 1-3 piezocomposite technology for therapeutic applications requires specific structural design and adapted materials.

New high-power piezocomposite technologies

Due to above mentioned variety of requirements in therapeutic applications and due to the limitations of state of the art technologies we have been willing to overcome encountered limitations and we have designed several piezocomposite materials and structures for therapeutic applications.
This work was based upon the development and the combination of three key technological aspects :

- The use of new 1-3 piezocomposite materials using high Curie temperature ceramic rods embedded into high glass transition temperature (Tg above 120°C) polymer matrices.
- The use of special shaping processes allowing the making of highly curved shells. These processes are not revealed in this article due to their proprietary aspect.
- The use of newly designed structures combining piezocomposite layer with matching layers and backing. These new structures have been made necessary in order to keep low mechanical stress and thus keep the structure integrity under the inherent variations of the inside temperature that are produced by losses under high power generation.

In our team we have developed two technologies named HI1 and HI2.

HI1 technology has been designed and the first prototypes have been manufactured on the very beginning of 1991. Following a demand from the French “Institut National de la Santé et de la Recherche Médicale – Inserm ” and in the framework of a feasibility study made in collaboration with Inserm our objective was to demonstrate the feasibility of transducers for the thermal ablation of tissues. Considering the limitations of existing technologies we decided in our team to experiment the use of technological results including materials structures and processes from previous research and development works dedicated to high temperature transducers for NDT applications. Other results were also available at that time in our lab for the shaping of relatively large transducers with F-number close to 1. First prototypes were characterised by Inserm and high power performances were shown demonstrating the capability to produce high power ultrasound at levels adapted for the thermal ablation of tissues. Previously demonstrated shaping processes were then used to produce the first piezocomposite HIFU transducers.

Considering the date of initial works it may appear that these works are no more really new. However one must consider that therapeutic ultrasound development is a long term process and that the qualification of materials, processes and methods is quite long due to the overall complexity of the objectives including the definition of the treatment itself, the design and realisation of devices, the process of laboratory and clinical experiments.

More recently HI2 technology has been developed with the objective to have more power capability in some applications. A solid backing that is not described in this paper gives better thermal cooling while keeping a good bandwidth. In addition this HI2 technology allows the design of transducers which are extremely resistant to mechanical and thermal shocks.

Both developed technologies have been shown suitable to produce high power ultrasound for therapeutic applications. Other characteristics are as follows :

Characteristics of Imasonic HI1 and HI2 technologies	
Common features	- Flexibility in shapes, sizes and array patterns, - Mechanically robust
Imasonic HI-1	
Transducer efficiency	60% to 70%
Working frequency range	200 kHz to 10 MHz
Maximum acoustical power	5 to 10 W / cm²
Backing	Air
Imasonic HI-2	
Transducer efficiency	40% to 60%
Working frequency range	200 kHz to 5 MHz
Maximum acoustical power	up to 30 W / cm²
Backing	Solid

TABLE 1 **: Characteristics of Imasonic HI-1 and HI-2 technologies**

HI1 and HI2 performances through some examples

Access to array technique :

the structure of the piezocomposite material allows a significant reduction of spurious modes of vibrations and privileges the thickness mode. This property makes possible the design of array transducers as the elements can be made acoustically independent. It is also beneficial for avoiding the generation of parasitic radiation. Both HI1 and HI2 technologies can be used to make arrays and this is illustrated in various following examples.

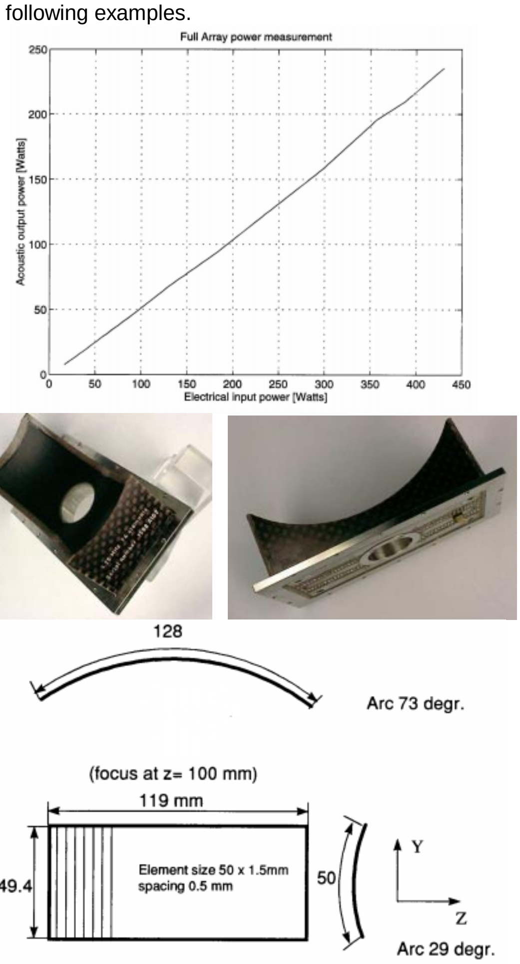

Fig. 2: HI1 linear concave array - 64 elements with measurements of total acoustic output power as a function of electrical input power

Acoustical power and efficiency:

Thanks to a high coupling coefficient, superior to that of the ceramic material, and a lower acoustic impedance (8 to 12 Mrayl) that facilitates the transfer of energy to water, and due to their specific thermal and mechanical design, transducers based on HI1 and HI2 piezocomposite technologies can generate acoustical power that can be as high as 30 Watts / cm² with a high efficiency. In order to meet therapeutic applications, Ultrasonic transducers have to withstand the applied electrical power in a continuous manner for several seconds, or even several minutes. Under such conditions, the internal heating due to electrical or mechanical losses constitutes a first source of limitations. The efficiency of the HI1 and HI2 piezocomposite transducers, typically around 50 - 60%, remains stable at high level of power over a long time.

The following example illustrates the stability of efficiency in the case of HI2 transducers :

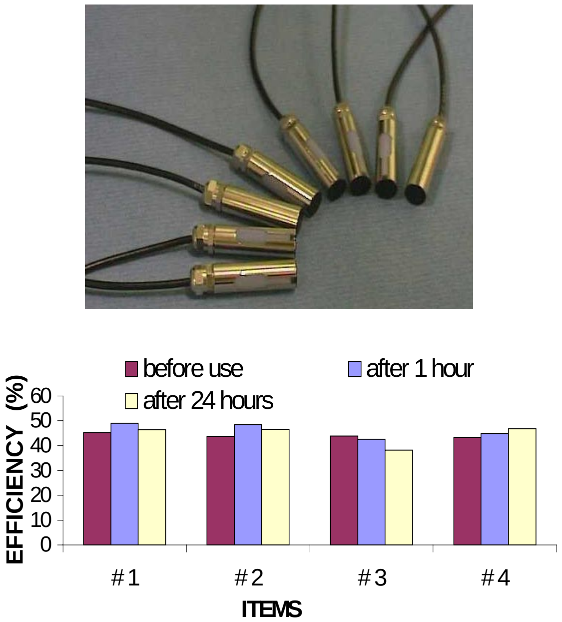

Fig. 3: **Single element transducers – Evolution of the efficiency after 1 hour and 24 hours (Emitted acoustical power : 10 W/cm² - Duty cycle : 10 sec. ON – 60 sec. OFF)**

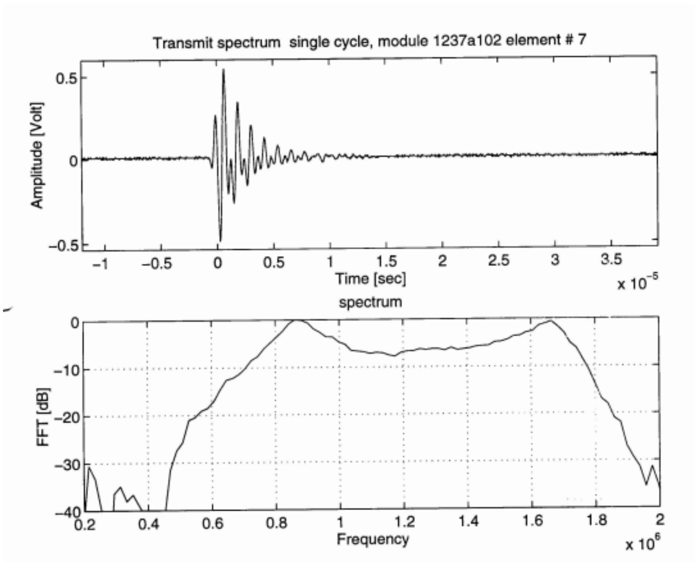

Fig. 4 **: Temporal response and frequential analysis of a high-power HI1 transducer**

Bandwidth, Beam Quality and Imaging / Therapy association:

The structure of the piezocomposite material privileges the thickness mode of vibration of the active element. Typically, the thickness mode coupling coefficient k_T is on the order of 0.60. Beyond the interest for energy conversion, it facilitates also the widening of the bandwidth. This feature has an interest in many cases. First it facilitates the tuning with the electrical circuit. This means that the transducer can operate in a relatively wide frequency range around the nominal value with an efficiency that remains high. In some applications this allows to sweep the frequency in order to obtain specific effect like the reduction of grating lobes [6]. Moreover this allows to adjust the frequency according to some parameters of the treatment like the depth of tissue, the nature of tissue, etc.

More recently came an increasing interest in making transducers allowing a combined use in therapeutic mode and imaging mode. As for instance the wide band characteristic of HI1 combined with innovative signal processing was used by Ebbini and al [10] in order to produce images from a linear array transducer initially developed for therapeutic purpose. This opens new paths for the combination of Therapeutic ultrasound with Imaging ultrasound. The following figure shows the transmit temporal and frequential characteristics of a HI1 linear array transducer.

In the same goal of making therapeutic transducers compatible with imaging techniques HI-1 and HI2 based transducers have been developed using MRI compatible materials in order to use them under MRI imaging and hence to associate ultrasonic treatment with MRI monitoring.

Fig.5 : **104 elements high power MRI compatible transducers**

Picture in Fig 5 shows HI1 2D arrays for Focused Ultrasound Surgery under MRI imaging and Fig 6 shows an MRI image with the transducer in the bottom part of the image.

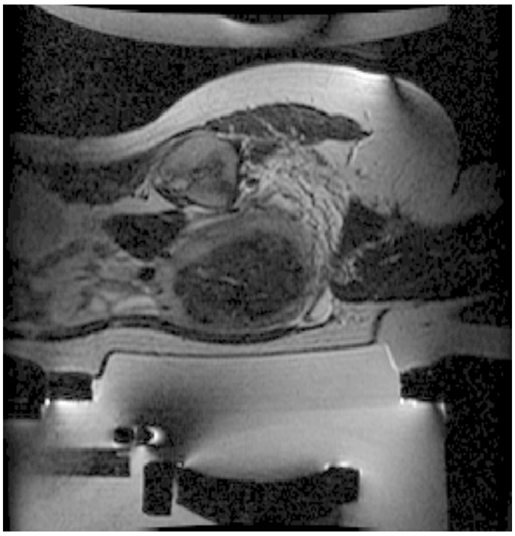

Fig. 6 **: MRI imaging with therapeutic transducer**

An other important requirement in most therapeutic applications is the high level of control of beam quality. This is particularly important in HIFU techniques were a precise volume of tissue is being ablated. This is also important in methods including the synthesis of beams with special spatial distribution in order to treat a larger volume of tissue and to reduce the time of the treatment. Fig 7 shows an example of beam distribution from a 2D array made in HI 1 technology.

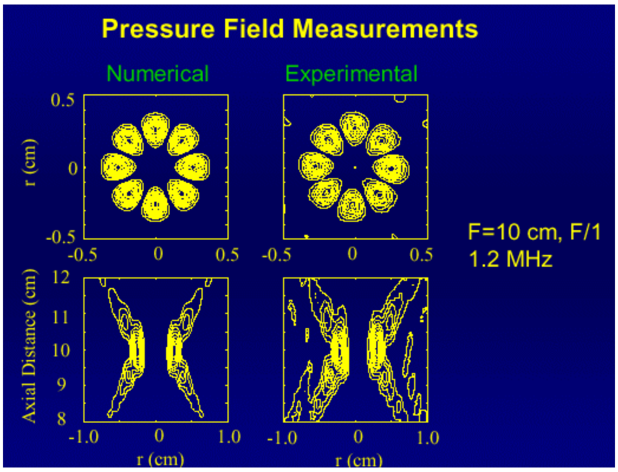

Fig. 7: Pressure field measurements of a 104 elements 2D array. Note that the results obtained are very close to the simulations (after JL. Raymond, R. King , K. Hynynen)

Conclusion

The evolution of ultrasonic therapy and the variety of applications and combinations with imaging techniques make increasingly necessary to take into account the specific nature of each application. Imasonic HI-1 and HI-2 technologies have been developed to bring adapted technological solutions in a wide range of cases including array techniques. Theses technologies make feasible efficient transducers with a high degree of confidence in beam predictability. Solutions are also designed to be electrically and mechanically safe and compatible with other constraints like MRI imaging. Moreover, routes are being opened to obtain echographic images with the same transducers.

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