Enhanced resolution transducers for thick pieces ultrasonic inspection : the FERMAT transducer concept

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Abstract

Aspherical focusing transducers are designed to focus on a precise point in the material with a given refracted angle, through a flat, cylindrical or toric interface.
This talk will present the main advantages of this specific focusing technique, made possible thanks to the piezocomposite technology and its shaping capabilities.
We will also focus on the mechanical and electroacoustical properties of the piezocomposite technology, that allows to design unequalled high resolution and signal/noise ratio transducers.
Some applications requiring particularly adapted inspection means like billet, forging or pressurised components inspection will be highlighted.
The possibility of combination of this technique with the Phased Array concept will also be presented.

Introduction

Some critical components that have to be inspected with non destructive methods are made of material known as difficult for the ultrasound, due to their attenuation or bad homogeneity, like titanium or austenitic steel. These material require low inspection frequency, high sensitivity and large bandwidth.
In the meantime, the size and the depth of the defects to be detected - and sometime sized – require a high lateral resolution. The combination of high lateral resolution, long sound path and low frequency make necessary the use of large aperture and focused transducer.
In addition, the inspection is often done through an interface that have a defocusing effects.
In order to increase the performances of these difficult inspections, Imasonic has developed the Fermat transducer concept.

Concept of Fermat transducers

<u>Transducer definition</u>

The main characteristic of Fermat transducers is their aspherically focused active surface, that often has large dimensions compared to conventional transducers.
The definition of the transducer is made by a calculation that define a surface from which each point is at the same time of flight to defect. The transducer is dedicated to one particular set-up taking into account :

- The material to inspect (sound velocity)
- The expected refracted angle
- The inspection depth or sound path

- The interface geometry (flat, cylindrical, toric, other..)

The active surface is also calculated to take into account the expected lateral resolution and depth of field. Figure 1 shows an example of shape of Fermat transducer.

Figure 1 : example of shape of a Fermat transducer

Theoretical improvement

The figures 2 and 3 illustrate the improvement obtained thanks to the Fermat concept in a given set-up, with a comparison between a conventional focused transducer, and a Fermat transducer. The nominal setup is the following :

- Operating frequency : 2MHz
- Refracted angle : 65°
- Focusing distance : 55 mm
- Lateral resolution : <5mm
- Interface geometry : cylindrical, concave

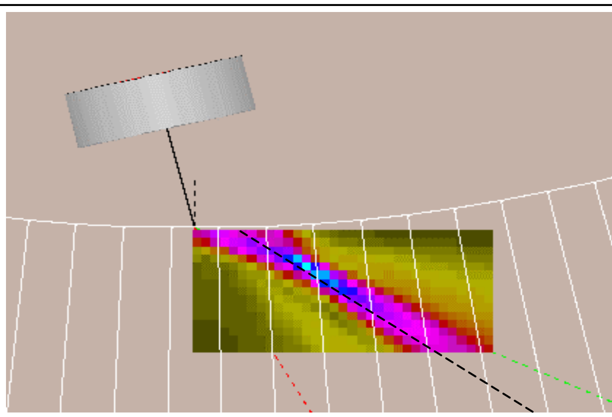


Figure 2 : Beam simulation with conventional focused transducer:
- Refracted angle : 55°
- Focusing distance : 25 mm
- Lateral resolution : 4mm

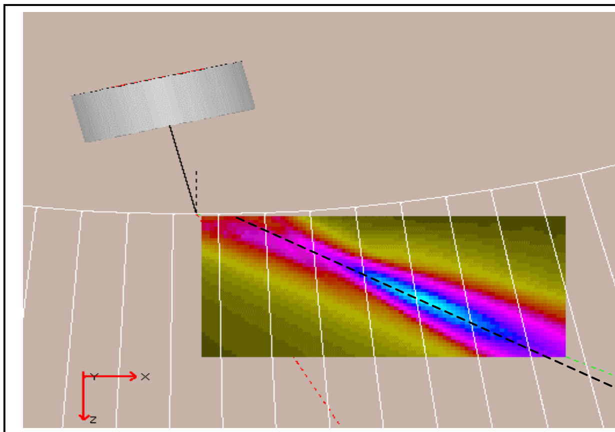


Figure 3 : Beam simulation with Fermat transducer:
- Refracted angle : 62°
- Focusing distance : 55 mm
- Lateral resolution : 4.5 mm

The Fermat concept allows a much more precise focusing with appropriate refracted angle

Technology

The 1-3 Piezocomposite materials

Fermat transducers piezoelectric layer is made of piezocomposite. Imasonic's piezocomposite materials have a structure called 1-3, shown in figure 4. The piezoelectric ceramic rods are embedded in a polymer material.

The electroacoustical and mechanical performances of these piezocomposite materials are of great interest for the Fermat transducers. (see paper (1) in references below)

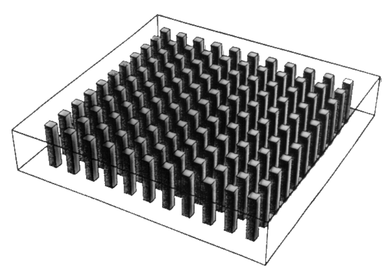


Figure 4 : schematic representation of 1-3 Piezocomposite structure

Electroacoustic performance

One of the characteristics of the 1-3 structure is the percentage of ceramic. It can be adapted by modifying the size of the rods and their spacing. Figure 5 shows the influence of the percentage of ceramic on the performances of the piezocomposite. The vertical red line shows the optimal percentage for a Fermat transducer. It corresponds to a high electric impedance (low dielectric constant E_{33}), low acoustic impedance (Z), and high coupling coefficient (kt).

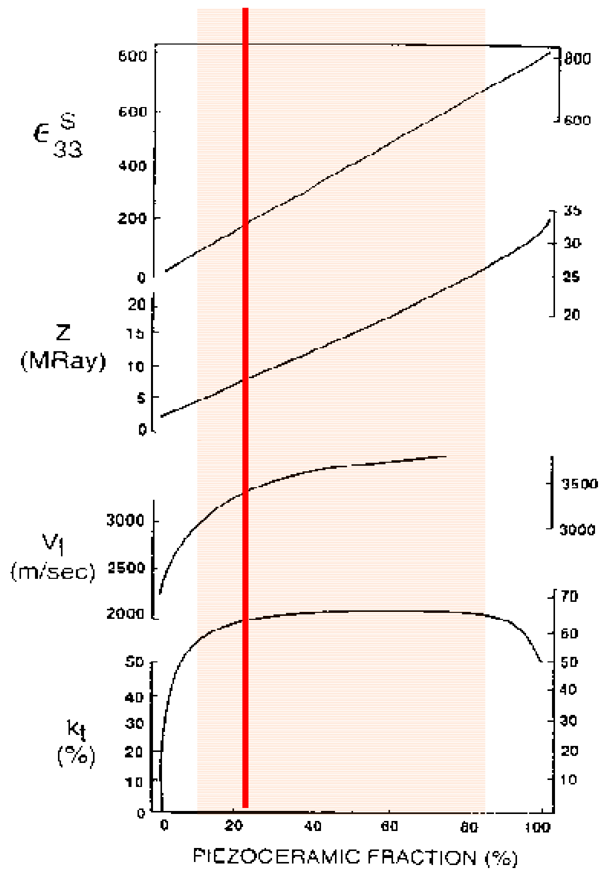


Figure 5 : Variation of the characteristics of a piezocomposite material according to the percentage of ceramic

High electric impedance

The high electric impedance allows a large aperture transducer while keeping an electrical impedance compatible with most of the ultrasonic pulsers/receivers.

Low acoustic impedance

The acoustic impedance is matched to water. This results in a better transfer of energy which, combined with a strong electroacoustic performance, gives a level of sensitivity from 10 to 50dB greater compared with monolithic piezoelectric ceramics

High coupling coefficient

The consequence of the high coupling coefficient is a high level of sensitivity, and a high signal / noise ratio.

In addition, the natural damping of composite materials allows a relative bandwidth of 60% to 90% obtained while keeping a very good level of sensitivity.

Mechanical properties

The polymer's mechanical properties are used to enable the piezocomposite materials to be shaped for focused transducers. Figure 6 shows a wide-aperture Fermat transducer, which active area is convex in order to focus through the cylindrical interface of a bore.
The 1-3 structure gives also to composites better resistance to mechanical shocks and vibrations.
The expansion coefficients of the polymer being close to those of the other components of the transducer (front face, backing, etc), results in the sensor having an improved performance in terms of temperature and thermal shock.

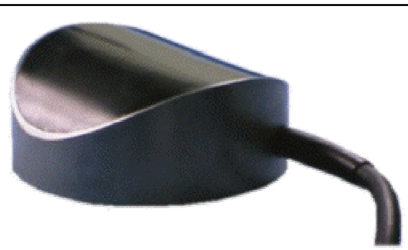


Figure 6 : Example of a wide aperture probe (100mm) with shaping of the active area

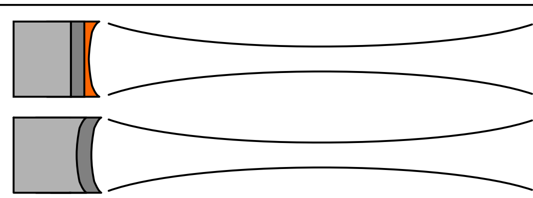


Figure 7 : Comparison between focusing with a lens and focusing with shaping of the active area

Design

Active surface calculation

Imasonic has developed a specific software (see figure 8), with 2 main objectives

- Quick simulation of lateral resolution for a given frequency and active dimensions, or quick calculation of the active dimensions for a given frequency and lateral resolution
- Calculation of the shape of the active surface for the manufacturing of the transducer

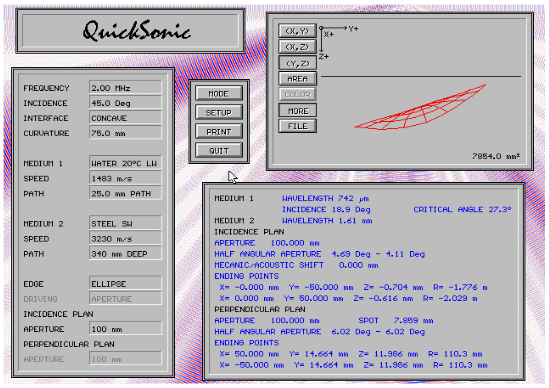


Figure 8 : Quick Sonic software, developed by Imasonic for Fermat transducer calculation

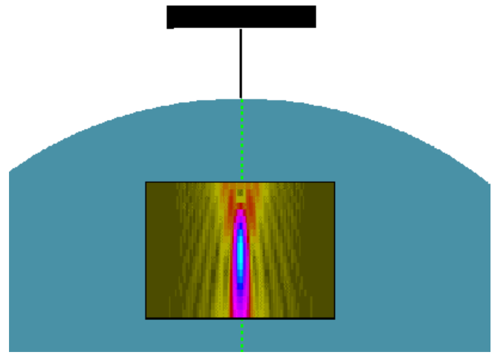


Figure 9 : CIVA simulation software, developed by the CEA, used for Fermat transducer design

Beam simulation

The precise design of the transducer is done with CIVA software (see figure 9), developed by the CEA, allowing in this case two types of simulation :

- Beam simulation through the interface, taking into account the Fermat active surface
- Simulation of the interaction between the above calculated beam and the defects that can be described in the software

Optional features

Fermat transducers are typically single element immersion transducers. However, they can be featured to match different using conditions or to be combined with phased array technology (see papers (2) in references below).

Contact Fermat transducers

When immersion technique is not possible for environmental or industrial reasons, a wedge can be used with Fermat transducers as a replacement for the water path. Imasonic implements in this case a soft material wedge, having acoustical properties close to water. The wedge can be matched to the interface geometry. The coupling is done with a water film, and the probe can integrate the water irrigation system (see figure 10).
The advantages of this type of wedge are :

- The soft front face can slightly fit to irregularities on the interface
- The acoustic impedance close to water reduces the problems due to thickness variation of the water film

Figure 10 : Contact Fermat transducer with soft material wedge and water coupling system

Phased array Fermat transducers

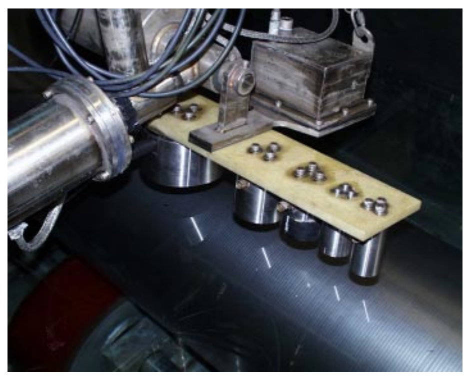
The Fermat concept can also be combined with phased array technique. In this case, beyond to the mechanical focusing, the beam can be electronically controlled to increase the inspected area. Different solutions have been developed, that will be shown more in detail in the examples of applications below.

Examples of applications

Inspection of titanium billets

Different sets of Fermat transducers have been designed and manufactured for the multizone inspection of titanium billets from 6” to 13” diameter, according to GE standards. Some of these transducers for 6” billets are shown in figure 11a.
The inspection is carried out in immersion with L0° transducers, each transducer is dedicated to a depth range of about 1”. FBH #2 (0.8mm) have to be detected in this range with homogeneity better than 3dB between holes at beginning and end of zone, and the minimum requirement for signal to noise ration is 16dB.

All type of transducers designed at this date were successfully tested and implemented in the industrial inspection system (shown in figure 11b).



Figures 11a & 11b : Set of single-element Fermat transducers for the inspection of titanium billets

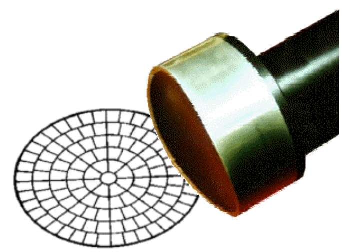


Figure 12 : Matrix Fermat transducer for titanium billet inspection with time reversal mirror technique

Inspection of Titanium Billets with Phased Array Technology

Some special matrix phased array Fermat transducers have been developed for SNECMA for titanium billet inspection. These transducers have been used with Time reversal Mirror technique developed by M.FINK (ESPCI- France) (see paper (3) in references below). This technique allows a 3D beam steering and a compensation of the effect of inhomogeneity of the titanium; An example of such matrix Fermat transducer is shown in figure 12.

The results obtained were very promising, and FBH #1 (0.4mm) were detected at 140mm depth with unequalled signal to noise ratio

Inspection of rotor blade grooves from the internal bores

Three Fermat transducers have been developed in collaboration with Tecnatom for the inspection of turbine blade grooves from the internal bore (see paper (2) in the references below). One of these transducer which active surface is divided into 16 rings to electronically change the focussing distance is shown in figure 6 above, and the three transducers are shown on their probe holder in figure 13.

One of the main difficulties of the inspection was the combination of different parameters :

- A very long UT path of about 400mm
- Only access from the internal bore of 150mm diameter
- Defects to be detected in a complex geometry area, with critical size of 1.5mm

The inspection was successfully tested with calibration blocks were all defects were detected, and further inspections have been carried out in thermal power plants, demonstrating the industrial applicability of this technique.
In the meantime, a destructive testing method was replaced by a non destructive method, and inspection times and costs have been reduced.

High temperature nuclear vessel inspection

Special Fermat transducers were developed with CEA CEREM (Commissariat à l’énergie Atomique – France), for high temperature inspection of nuclear vessel (see figure 14). The inspection was done in immersion at 180°C.

The design of the probe had to combine the large aperture of the transducer and the thermal constraints. Mechanical properties of piezocomposite material allowed to withstand the temperature variation, while keeping the shape and performances of the active area.

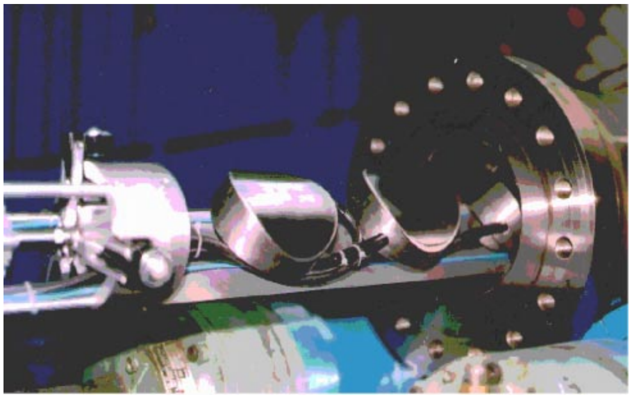


Figure 13 : three Fermat transducers on the probe holder

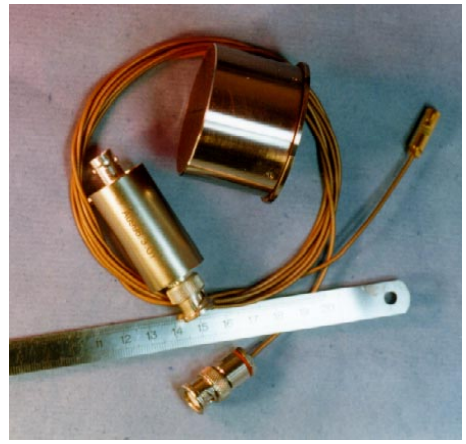


Figure 14 : High temperature Fermat transducer

Inspection of thermal barrier of primary pumps

The main requirements of the inspection of thermal barrier of primary pump were the following (see fig. 15)

- Inspection through a 200mm sound path in austenitic steel
- Inspection through a toric interface with 50mm smallest radius
- Capability to detect defects of 5mm, and size their circumferential extension with resolution of 5mm
- Refracted angles of 0°LW

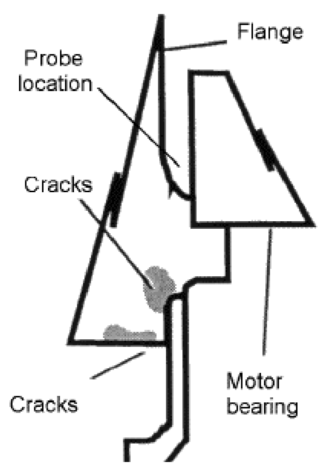


Figure 15 : schematic representation of the inspection configuration of thermal barrier

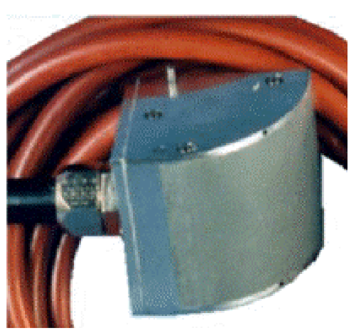


Figure 16 : Contact Fermat linear phased array probe

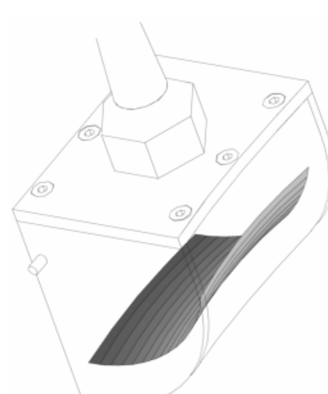


Figure 17 : view of the active area of the probe shown in figure 16

In order to meet these requirements, Imasonic has designed and manufactured a curved linear phased array probe with Fermat surface. The probe is shown in figure 16, and the Fermat active surface divided in 16 elements is illustrated in figure 17.

- The linear array was used to steer the beam and size the extension of the defects
- The Fermat surface was designed to focus through the toric interface
- A soft material wedge was implemented to make the coupling with a water film.

The beam dimension in the focusing zone was about 12x13mm, which was very coherent with the simulations. The feasibility of this inspection with this technique was successfully demonstrated.

Conclusion

The examples illustrated in this paper clearly put into evidence the capability and performances of the Fermat transducers.
Several inspections can benefit of performance improvement on the following parameters :

- Sensitivity and signal to noise ratio
- Lateral resolution
- Beam prediction and control

In the meantime, new inspection techniques can be developed, with solutions for the following problems :

- Complex interface geometries
- Long sound path
- Hard to inspect materials

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