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Design and testing of an ultrasonic projector for operation in liquid sodium

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***Abstract*— PRUNA ultrasonic transducer (French acronym standing for "PRojecteur Ultrasonore en Na") is designed for operation under liquid sodium. Under sodium tests results obtained show that this type of transducer has very high sensitivity and sufficiently good acoustic properties to perform basic NDT of a structure immersed under liquid sodium at approx. 200°C using conventional immersion ultrasonic technics. Artificial defects made in a stainless steel block could clearly be detected.**

***Keywords*— PRUNA, transducer, ultrasound, NDT, NDE, sodium, nuclear reactor, ISI&R, SFR, FBR, high temperature.**

I. INTRODUCTION

Sodium Fast Reactors (SFR) offer great potential for a sustainable nuclear energy [1], with advantages such as increased uranium utilization, breeding of fissile material, reduction of radioactive waste, utilization of fission products, etc. Regardless of these advantages, SFRs raise specific problems For instance, looking at the available feedback of SFRs operation, In-Service Inspection and Repair (ISI&R) is a significant issue to deal with and plays an important role in the safety approach of the plant for complying with up to date safety standards [2]. Non-Destructive Testing (NDT) of the components immersed in liquid sodium is particularly challenging because of the harshness of the environment: high temperature, chemical aggression and irradiation. The opacity of the medium is also a specificity, which makes ultrasonic testing a well-adapted candidate for performing NDT inside the primary circuit of these reactors. Prior work on the demonstration of the feasibility of NDT under liquid sodium was reported in [3] using TUCSS transducers.

This paper presents the design and performance of a new type of transducer for operation in harsh environment: the ultrasonic projector. This concept was first presented in [4] for underwater operation. It consists in redirecting the ultrasonic beams generated on both sides of a piezoelectric plate by a set of acoustic mirrors, as shown in Fig. 2. Here, we report on an ultrasonic projector operating in immersion under liquid sodium at 200°C without external cooling.

The concept of an ultrasonic projector is first recalled, then the design and fabrication of the PRUNA is described. Subsequently, the methodology and experimental setup are described before showing experimental results of NDT under liquid sodium.

II. ULTRASONIC PROJECTOR CONCEPT

Conventional ultrasonic transducers are generally made with a piezoelectric plate (or disc) vibrating on its thickness mode. This vibration induces two ultrasonic waves, as shown in Fig.1. One wave travels forward (useful acoustic energy), which will be used for making the ultrasonic beam and collect echoes for the inspected medium. Another one travels backward, which needs to be completely attenuated so that no unwanted echoes come back from this side.

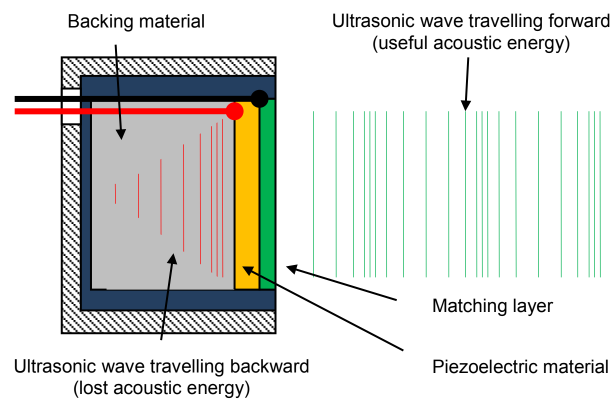

Fig. 1. Conventional ultrasonic transducer principle.

The concept of an ultrasonic projector also relies on the vibration of a piezoelectric plate to produce two ultrasonic waves. However, in this concept, both waves are used to generate the effective ultrasonic beam by means of a set of acoustic mirrors (with an angle of 45°) redirecting the two waves towards the same direction, as shown in Fig 2.

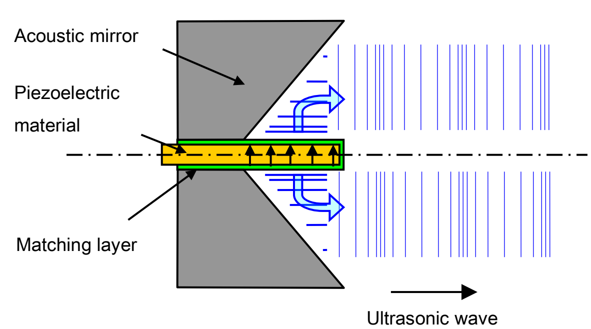

Fig. 2. Ultrasonic projector principle.

This concept presents several basic advantages compared to a conventional transducer configuration [4]. For instance, the totality of the acoustic energy is useful in this concept, whereas in the conventional configuration the backing drains approximately half of the generated acoustic energy. Even though there is no backing, it was shown in [4] that it is possible to achieve a damped ultrasonic pulse in immersion under water by using piezocomposite material and an appropriate set of matching layers.

III. Ultrasonic Projector for Under Sodium Operation

The ultrasonic projector in this study is designed for operation under liquid sodium at about 200°C without external cooling. This harsh environment presents several technical challenges such as temperature resistance, chemical resistance, acoustic wettability and acoustic performances compatible with NDT requirements.

A photograph of the PRUNA projector (French acronym for "PRojecteur Ultrasonore en Na", i.e. "under-sodium ultrasonic projector") is shown in Fig. 3 and a schematic representation is shown in Fig. 4.

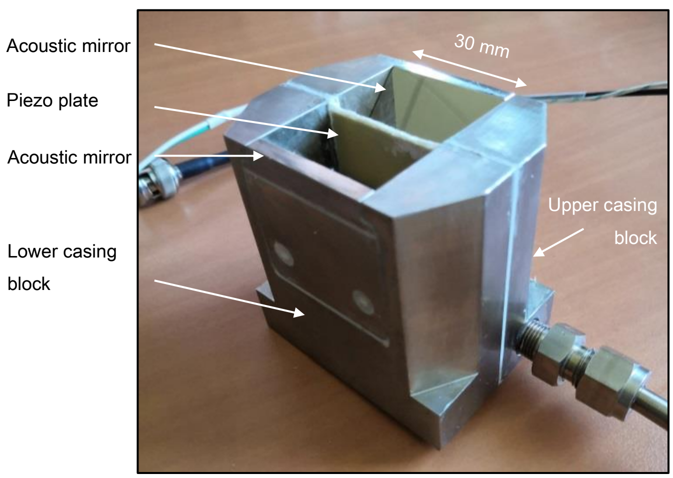

Fig. 3. Photograph of a PRUNA projector.

It can be seen that a plate made from piezoelectric material is sandwiched between two Casing Blocks. These blocks include removable acoustic mirror plates. These acoustic mirrors are polished (optical quality surface) in order to achieve homogeneous surface tension with liquid sodium over the whole surface.

Electrical connections with the electrodes of the piezoelectric plate are made inside the casing blocks, by a set of spring loaded electrical contacts. The piezoelectric plate has electrode patterns that overlap only underneath the acoustic mirrors over a 15x30 mm² surface (see poling arrows on Fig. 4). Thus, electroacoustic energy is only converted over this active area. The developed acoustic aperture of this projector is approximately 30x30 mm² and its operation frequency is 1MHz. The piezoelectric plate has a matching layer on both sides and a wetting layer which was deposited over the whole active area. The wetting layer is necessary to transmit acoustic energy through the active surface as sodium (liquid metal) difficultly wets materials at this temperature.

Note that there is no bond between the piezoelectric plate and the casing blocks, there is simply a seal on the periphery. This allows for the piezoelectric plate structure to expand freely and hence to make a robust solution for high temperature applications. Indeed, conventional transducers have more material expanding at different rates, especially between the voluminous "soft" backing material and the relatively stiff piezoelectric material. This difference in thermal expansion coefficients is often the origin of bonding failures. Another source of failure in high temperature transducers is coming from soldering / electrodes interface failures. The present projector has spring loaded electrical contacts which makes it a more robust solution compared to conventional designs.

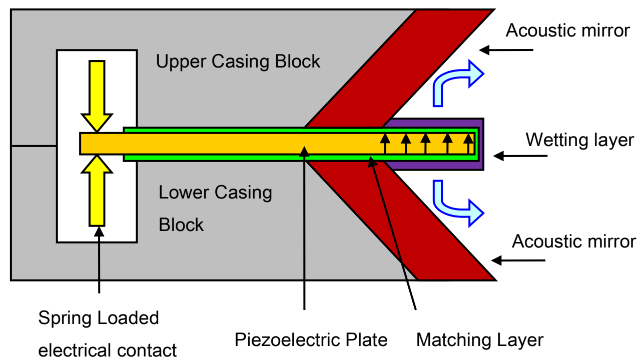

Fig. 4. Schematic representation of a PRUNA projector.

IV. Experimental Setup

Under-sodium tests were conducted in a glove box of CEA-DEN (Cadarache, France) sodium facility (with inert argon gas coverture). The projector was tested in immersion in front of a block made of 316L stainless steel which included several geometry changes and 2 notches R1 and R2 (0.2mm opening width, 20mm deep) made by spark machining (see Fig. 5). The height of this block was 100mm.

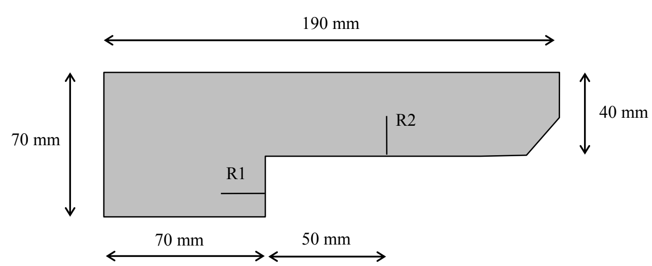

Fig. 5. Schematic representation of the test block.

The tests were conducted in a thermally regulated cylindrical vessel (∅320 x 200 mm) containing 10L of liquid sodium (pure sodium fusion temperature is ~98°C). A characterization device, called DEFO, was specifically designed and fabricated in order to accurately move the transducer in front of the test block inside this sodium filled vessel. This apparatus was the same that was used for testing the TUCSS transducer presented in [3]. Photographs of DEFO placed in the sodium vessel can be seen in Fig. 6.

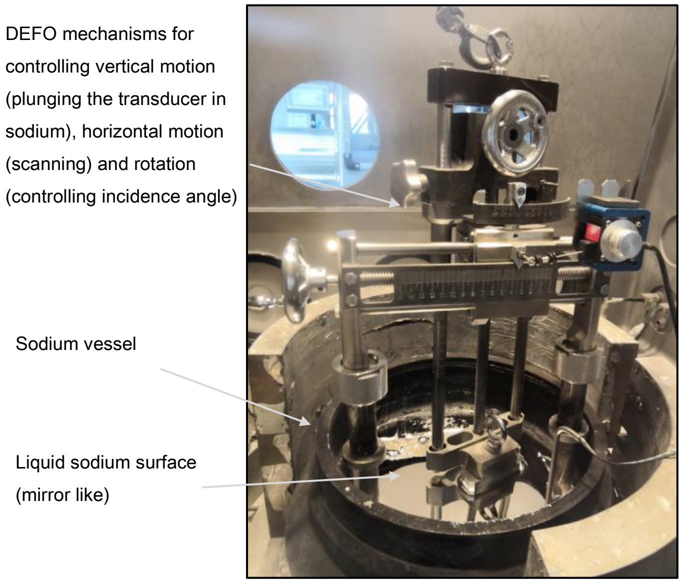

Fig. 6. Photograph of DEFO mechanism placed in the sodium vessel, inside the MONARQUE glove box of the PAPIRUS Plateform of CEA.

Acquisitions are made using a TabletUT ultrasonic NDT system (Mistras Eurosonic, Vitrolles, France).

V. Results

The projector was immersed in the sodium bath at 200°C and exhibited a very good sensitivity; the test block entrance echo could be received with no gain for a 50V excitation as shown on the A-scan in Fig. 7 (test block entrance echo = A; test block backwall echo = B).

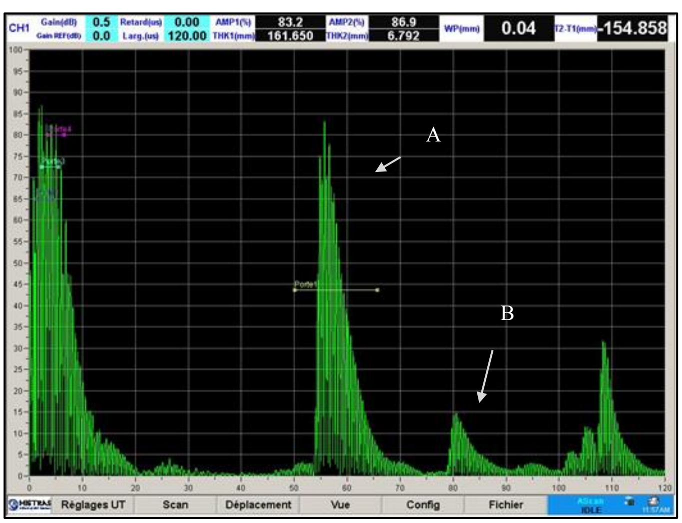

Fig. 7. A-scan made at 0° incidence angle and scanning position = 30mm, in 200°C sodium

Several B-scans were recorded at different incidence angles. Fig. 8 shows a B-scan when the projector is oriented with an incidence angle of 0°, i.e. PRUNA axis perpendicular to the surface of the test block. This scan can be interpreted as follows:

- The traces from 0 to 30µs are the saturated dead zone of the transducer.
- The linear trace at 55µs is the echo coming from the front surface of the block. It is present at all scan positions from 0mm to 145mm. It is marked "A" on the sketch.
- The linear trace at 80µs [10mm:50mm] is the echo coming from the back surface of the block marked "B" on the sketch.
- The linear trace at 77µs [50mm:70mm] is the echo coming from the notch R1.
- The linear trace at 70µs [70mm:145mm] is the echo coming from the back surface of the block marked "C" on the sketch. The linear trace at 80µs [70mm:145mm] is the repletion of this echo inside the test block.

All the normal indications inside the block were successfully detected and resolved during this 0° incidence scan.

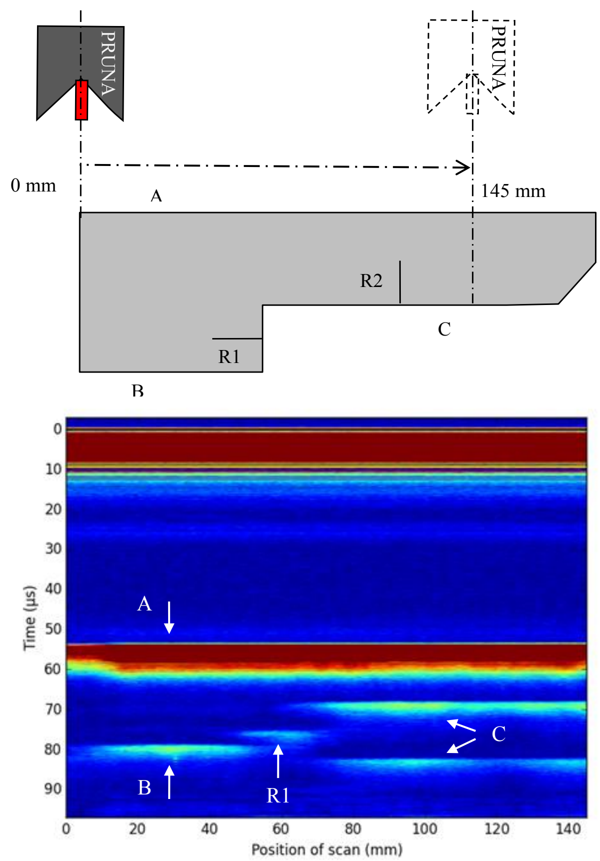

Fig. 8. B-scan made at 0° incidence angle, in sodium at 200°C

The notch R2 and the 45° chamfer could also be detected using a non-normal incidence angle. The best result was obtained when using 30° incidence angle, (corresponding to the angular limit of the DEFO mechanism) which produced shear 38° waves in the block. Fig. 9 shows the results of this 30° incidence angle B-scan.

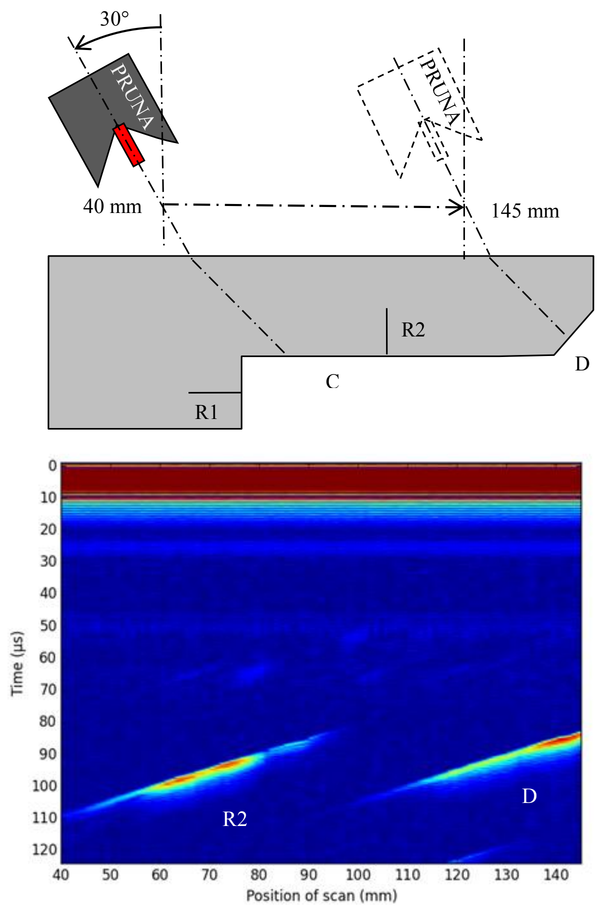

Fig. 9. B-scan made at 30° incidence angle, producing SW38° wave, in sodium at 200°C.

This scan can be interpreted as follows:

- The traces from 0 to 30µs are the saturated dead zone of the transducer.
- The linear oblique trace at [100µs:90µs] [60mm:80mm] is the echo coming back from the notch R2.
- The linear oblique trace at [120µs:145µs] [100mm:85mm] is the echo coming back from the 45° chamfer marked "D".

VI. Discussion and Further Work

The damping of the ultrasonic pulse should still be improved to compare with regular air/water NDT transducer performances. Nevertheless, its performance is already good enough to perform visualization under liquid sodium or some basic NDT under liquid sodium at 200°C. The long pulse can principally be attributed to the wetting layer that has an acoustic impedance Z_{WL}=0.59 MRayl at 200°C. This creates an acoustic barrier to the evacuation of ultrasound in sodium, which has an acoustic impedance of 2.23MRayl.

The stability of performance should also be improved. It was noticed that the PRUNA's sensitivity was degrading in time probably due to a loss of acoustic wetting.

The use of curved mirrors should also be studied in order to produce a focused ultrasonic beam and to increase the projector's resolution. This could be interesting to increase Signal to Noise Ratio when looking for smaller reflectors/defects and for performing imaging with high resolution.

VII. Conclusions

The concept of ultrasonic projector was tested for applications at 200°C in immersion under liquid sodium without external cooling. This concept was found to be well suited to high temperature operation due to the reduction of rigid bonds and solderless electrical contacts, allowing the internal structures to thermally expand freely. This concept should also be a promising technology to perform reliable inspections with focused ultrasound technology.

The damping of the ultrasonic pulse should still be improved to compare with regular air/water NDT transducer performances. Nevertheless its performance is already good enough to perform visualization under liquid sodium or some basic NDT under liquid sodium at 200°C.

Acknowledgment

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The projector concept is covered by the patent [6].

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