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Development of an Innovative Ultrasonic Reader for the Authentication and Identification of Copper Canisters for Spent Nuclear Fuel

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***Abstract*—The final disposal of nuclear spent fuel in long-term geological repositories introduces the need to develop new technologies to keep the Continuity of Knowledge of nuclear spent fuel. In the recent past, an innovative approach based on ultrasound has been proposed by authors and several studies have been accomplished to validate the method. This work aims to describe the development of a new ultrasonic reading system which can be considered as an optimized version of previous prototypes. This paper describes the development of a new reader prototype designed to provide a remote control of the scanning and speed up the acquisition time, without losing accuracy. The novel version includes a stepper motor to move the transducer and the Seal Fingerprint Acquisition Device (SFAD), that is used to control the motor, transmit/receive signals to/from the probe through a SPI bus and send data wirelessly to a control station.**

Keywords—ultrasound, identification, authentication, stepper motor, electronic instrument, ultrasound system

I. Introduction

The safe and secure management of nuclear spent fuel is an important issue in the field of the Nuclear Safeguards. Several countries in Europe are planning to store nuclear spent fuel in long-term geological repositories, inserted in copper canisters with iron inserts (Fig. 1). According to the Swedish approach, after the encapsulation of the fuel at the encapsulation plant in Oskarshamn, the copper lid will be welded onto the canister by Friction Stir Welding and then transported to the final repository in Forsmark [1]. During handling, transport and storage of canisters, the Continuity of Knowledge of the fuel must be kept. An option could be providing to each canister a unique identity (identification) which gives evidence of counterfeiting or duplication (authentication) [2].

Fig. 1. Partial section of a copper canister with iron insert hosting a spent fuel assembly.

An external engraving or marking of the canister surface should be avoided since it could trigger a corrosion process which could affect the integrity of the container. Therefore, in addition to traditional tagging techniques [3], innovative methods have been studied. Among them, the ultrasonic pulse-echo method is a promising solution to give a unique identification and authentication fingerprint to each canister [4]. This approach is based on the acquisition of an artificial and a natural fingerprint. On the one hand, the ultrasonic amplitude responses of a configuration of chamfers machined in the inner surface of the canister's lid (identification fingerprint); on the other hand, the ultrasonic amplitude response of the internal gap between lid and canister after welding (authentication fingerprint) [5]. Both concepts have been validated with experimental tests on copper samples and different reader prototypes have been developed for this purpose. This paper describes the latest advancements in the electronic design of an optimized ultrasonic reader. This new version will include the same mechanical structure of previous prototypes with the addition of a new motor and a new data acquisition and transmission system: the Seal Fingerprint Acquisition Device (SFAD).

II. THE SFAD: SEAL FINGERPRINT ACQUISITION DEVICE

The Seal Fingerprint Acquisition Device (SFAD) is an innovative system developed by the University of Florence, in collaboration with the Joint Research Centre of the European Commission. The device has been designed as an upgrade of the original electronic box used to acquire ultrasonic fingerprints from stainless steel seals applied on nuclear casks for underwater or dry storages. When the top of the seal is scanned with a rotating ultrasonic transducer, the core of the seal gives a unique reflective fingerprint [6]. In contrast to the previous acquisition system, the SFAD satisfies the need of having a portable solution able to quickly perform ultrasonic testing and send acquired fingerprints to a remote control unit. The main features of the device are:

- capacity to control a motor for the mechanical rotation of the ultrasonic probe;
- possibility to accomplish ultrasonic tests transmitting/ receiving signals to/from the ultrasonic transducer;
- processing of acquired data to generate fingerprints;
- ability to send fingerprints to a remote control station (Notebook PC or tablet) over a secure network connection.
- low power consumption to achieve a minimum operating time of five hours

The SFAD looks like a compact cube (about 180 mm each side with a total weight of 2.3 kg) with seal connectors for the communication with the motor, the ultrasonic probe and the battery. A PC can be also wirelessly connected to the device for the setting of the main parameters for the ultrasonic test, the processing of acquired data, and the display of fingerprints (Fig. 2). The core of the SFAD is an electronic instrument which consists of different blocks for the management of the power consumption, the control of an asynchronous or synchronous motor, the transmission of signals via wireless connection and the storage of data in an external SD card. The ultrasonic measurements are performed by an US-SPI module (Lecoeur electronique) which is connected to the electronic board. This module hosts a SPI high speed connection for the transmission/reception of data and the delivering of power supply. The probe is excited in a pulse-echo mode and all measurements parameters can be programmed by the user. In particular, the transmitter voltage level and width of generated pulses can be adjusted, as well as the receiver gain (from 0 to 80 dB) and the position of three gates, for the record of the greatest amplitude echo within a certain time window. Received ultrasonic signals are then digitized by a 12 bits AD converter with a sampling frequency of 80MHz. The communication between the US-SPI module and the other components of the SFAD is regulated by two ATMEL processors (ATSAMA5D44A for the software – ATSAM4E16E for the firmware). Moreover, a software interface has been developed to allow the user the setting of main measurements parameters, process acquired signal and display fingerprints.

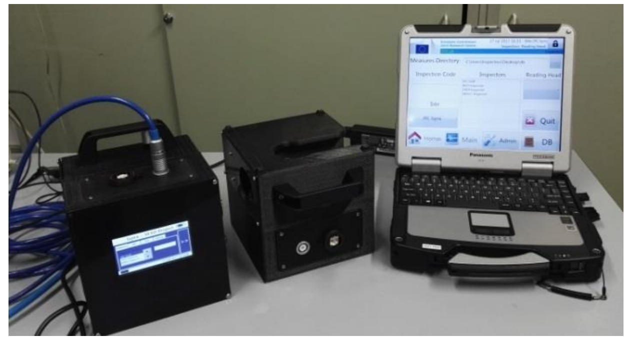

Fig. 2. Picture of two SFAD systems, wirelessly connected to a PC where stored data can be displayed by a software interface.

The SFAD has been tested on seals and acquired signals have been compared with fingerprints recorded by the existing acquisition system. The aim of tests was demonstrating that the SFAD can meet all the functionalities already included in the current seals reader and, in addition, can provide new features to make measurements more automated. In fact, the acquisition of identification fingerprints from seals is usually performed by a nuclear inspector directly at the storage facility. With the introduction of the wireless transmission of data, the presence of the inspector is not mandatory anymore and fingerprints could be verified remotely. As a consequence, the firmware and software of the SFAD can be also adapted for the acquisition of ultrasonic fingerprints from copper canisters. In fact, several features of the device perfectly match the requirements for a new version of ultrasonic reader for copper canisters.

III. THE ULTRASONIC READER FOR COPPER CANISTERS

Following the experimental validation of the ultrasonic method for the identification and authentication of copper canisters, the realization of an optimized version of ultrasonic reader device is an important step forward in the research project. One of the last developed reader prototypes (Fig. 3) was basically composed by three arms to centre the equipment above the canister and a rotating bar hosting a 10MHZ immersion transducer. A control box hosted an electronic board connected to an US-Key module (Lecoeur electronique) for the excitation of the probe, the acquisition of signals, and the regulation of an asynchronous motor. The control box included also a 220V to 24V AC inverter to power the motor. Lastly, received data were transferred via USB to a computer for the processing and displaying of signals.

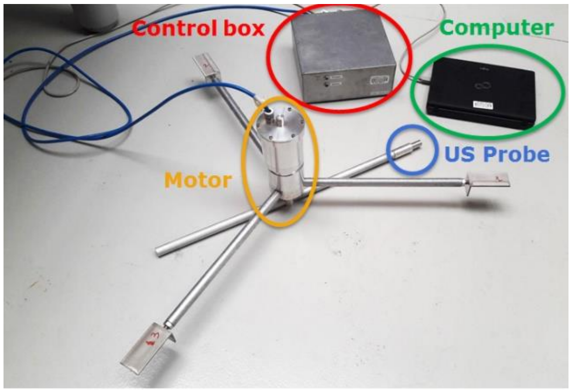

Fig. 3. Old prototype of ultrasonic reader for the identification and authentication of copper canisters for spent nuclear fuel.

According to tests performed with this prototype [7], the authentication fingerprint can be acquired rotating 360° the transducer around the canister circumference in about four minutes. Received signals are then transferred from the US-Key module to the PC via USB.

In order to improve the performance of this device, a new reader prototype has been designed and tested. The mechanical structure of this optimized version is similar to the old one but includes a different mechanism for the regulation of the probe height and, above all, a stepper motor (minimum motor step with gearbox is 0.0112º) for the rotation of the transducer. One of the main advantages of this solution is the possibility to set the motor speed according to the desired sampling frequency. In a first laboratory prototype, the motor has been controlled by an Arduino UNO connected to a motor stepper driver. The experimental test of this prototype has been tested on a full scale copper lid already welded (Fig. 4).

Fig. 4. New version of the ultrasonic reader prototype during test on a real copper lid already welded onto the canister.

Three gates are set to acquire the maximum amplitude echo within different time windows for the acquisition of the interface water-copper echo (at 26 µs), the internal gap echo (at 49 µs), and the external wall echo (at 70 µs) (Fig. 5). An example of ultrasonic amplitude response, successfully recorded, can be seen in Fig. 6. The possibility to adjust the speed of the stepper motor is extremely advantageous since allows performing measurements faster or less depending on the type of fingerprints to be recorded. In fact, whereas the identification code realized by chamfers could be reconstructed with around 600 samples, the authentication fingerprint involves the acquisition of a sample each 0.3° (about 1200 samples/360°).

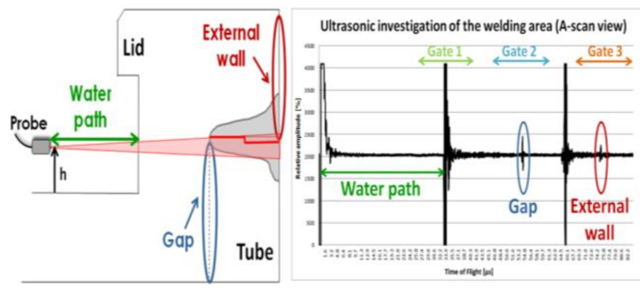

Fig. 5. Position of the ultrasonic probe for the investigation of the welding area (on the left) and correspondent A-scan acquisition (on the right). Three gates are set to acquire the amplitude and time of flight of echoes from the interface water/copper (gate 1: 20 µs - 35 µs), the gap (gate 2: 35 µs - 50 µs), and the external wall (gate 3: 60 µs - 75 µs).

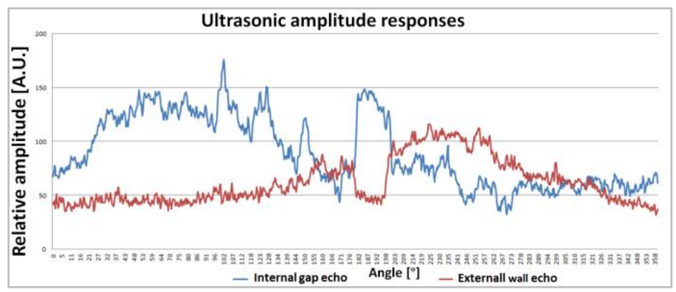

Fig. 6. Ultrasonic amplitude responses acquired by a 360° rotation of the transducer around the welded lid. In blue, the amplitude echo of the internal gap and, in red, the amplitude echo of the external wall. About 1200 samples have been acquired with a sampling frequency of 5 samples/s.

The innovative idea for latest version of ultrasonic reader is combining the functionalities provided by the SFAD with the stepper motor and the probe already included in the previous prototype. The old control box is then replaced with the SFAD to improve performances of the device. The presence of a SPI bus for the transmission of data allows speeding up the acquisition time without losing in resolution (each sample can be acquired each 0.3°). In particular, with the use of the SFAD, a complete rotation of the probe could be accomplished in only one minute. Moreover, the presence of a $LiFePO_4$ battery pack (12V, 3.5Ah) removes the need of a fixed socket for the power supply. In the end, received data can be locally stored or sent remotely to a control station avoiding the need of an operator to perform the test. Ultrasonic fingerprints could be acquired and recorded after the welding process of the canister at the encapsulation plant. The idea is to implement completely autonomous measurements leaning the reader against the canister thanks to a crane. The acquisition of fingerprints could be regulated a priori and after a complete rotation of the probe, data could be directly sent to a remote unit. In case of CoK losses, in addition to traditional verification techniques, the ultrasonic fingerprints of canisters could be acquired again at the final repository, and the identity and authenticity of each container could be verified by correlating old and new measures.

IV. Conclusions

The acquisition of copper canisters' identification and authentication fingerprints has been accomplished using several ultrasonic reader prototypes. With the aim to improve the reader performances, a new solution has been studied combining the mechanical structure of the old prototype, stepper motor included, with the electronics onboard of the SFAD. The firmware and software of the device have been developed for the verification of stainless steel seals for underwater and dry storages. However, the SFAD design has been achieved to control also the ultrasonic acquisition of the identification and authentication fingerprints of copper canisters. The use of a SPI bus and a stepper motor contributes to speed up the acquisition time up to four times. Moreover, the presence of a battery makes the reader a portable device and the secure/encrypted wireless connection to a control station allows performing a remote acquisition. As a result, the involvement of the operator on site is limited to the handling of the instrument for measurements but the evaluation of acquired fingerprints can be realized remotely thanks to the wireless connection of the device to a remote control unit.

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