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Development of the specular echoes estimator to predict relevant modes for Total Focusing Method imaging

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ABSTRACT

Total Focusing Method imaging is an ultrasonic testing method which has emerged in recent years as an alternative to standard phased array inspection methods in non-destructive testing, due to its high resolution and the realistic images of defects that it provides.

In the case of crack-like defects, it provides images where the profile and the tips of the defects are reconstructed. TFM imaging is a procedure which yields the spatial position of the reflectors from which the main transient signals observed in the data are originated from. Thereby, diffraction echoes are located at the tips of the defect, and specular echoes appear along the profile of the defect. This signature allows the characterization of the planar nature of the defect.

However, a correct reconstruction requires the use of the relevant ultrasonic path to produce the echoes wanted among a large number of possible paths between the array transducer and the reflector.

In this paper, we have developed a method based on physical considerations, for predicting relevant paths. The tool is applied in several inspection configurations involving notches nearby welds. Validation is achieved from a variety of synthetic and experimental results.

1. Introduction

Defect characterization is essential in non destructive testing: the defect nature allows for predicting its potential evolution. Volumetric defects, such as porosity and inclusions, are generally not dangerous for the material, while plane defects, such as cracks, can lead to critical failures. For both kinds of defects standard conventional and phased array methods provide very close signatures, and it requires an analysis by a specialist operator to distinguish them.

The Total Focusing Method (TFM) [1–5] exhibits a main advantage for defect characterization by providing different signatures for different kinds of defects. TFM imaging focuses temporal signals at the spatial position of the reflectors. Thereby, in the case of crack like defects, diffraction echoes are located at the defect extremities, and specular echoes along the defect profile. The latter allows conclusions to be drawn about the nature of the defect.

Due to their unidirectional nature (Snell-Descartes' law), specular echoes are more sensitive to defect orientation than omnidirectional diffraction echoes. So, it is necessary to determine the relevant path producing the echoes wanted among a large number of possible paths between the array transducer and the reflector, due to direct paths, reflection on the back wall and wave mode conversion. Indeed, not all these paths will produce a true defect profile and in addition artefacts may occur, complicating image interpretation.

The present work investigates new methods to automatically determine relevant paths (also called reconstruction modes) depending on the known parameters of the inspection.

This paper is organized as follows: we recall the principle of TFM imaging, and we point out the echoes resulting from various modes of reconstruction. Then we show how to exploit diffraction and specular echoes for defect characterization. Thereafter, we propose a new tool, called Specular Echoes Estimator (SEE), which we have developed to predict relevant modes. Finally, experimental and modelling results are used to demonstrate the capabilities of this tool.

2. Principle of TFM imaging

TFM imaging is a method of focusing at any point of a defined region of interest (ROI). It is a post-processing method applied to data collected by Full Matrix Capture (FMC) acquisition [6], which involves

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a succession of ultrasonic shots from the elements of the array. For each such shot, a transmitter emits a wave which is received by all elements of the transducer after propagation within the medium. After digitization of the signal, we obtain the matrix of acquisition, also named inter-element matrix, which is a 3D matrix of size $N \times N \times Q$, where N is the number of elements of the sensor and Q is the number of time samples.

In the ROI, we compute from each couple of elements the time of flight required to travel between the transmitting element via the focusing point to the receiving element. At this time of flight is associated an amplitude from the signal of the inter-element matrix. The different contributions coming from the different elementary signals constructively sum up when a reflector is present, and cancel out otherwise.

Let K be the inter-element matrix acquired by FMC, the TFM amplitude $I^m(P)$, for a given mode of reconstruction m, at the focusing point P, is given by the relation (1)

$$I^m(P) = \sum_{i=1}^{N}\sum_{j=1}^{N} K_{ij}(t_{ij}^m(P)), \quad (1)$$

where $t_{ij}^m(P)$ is the time of flight necessary to follow the path between the transmitter i and the receiver j via the focusing point P, for a mode m. The reconstruction mode m is defined by the ultrasonic path used for the time of flight calculation.

2.1. Ultrasonic paths

The waves refracted in the specimen can propagate along different paths according to their refraction angle. These waves (longitudinal or transverse) can be converted at interfaces of the piece or when interacting with a defect. When the path between the elements and the running point P is without reflection on the backwall (Fig. 1), the mode is called direct mode. The combination of longitudinal (L) and transverse (T) waves leads to four reconstruction modes. LL (or TT) designates the mode for which the return trip is with longitudinal wave (or transverse wave) while LT and TT designate the modes with conversion on the defect.

Following the same principle, corner echo modes (Fig. 2), also called half skip modes, include reflection on the backwall before interaction with the defect. The combination of longitudinal and transverse waves yields eight reconstruction modes (LLL, LLT, LTL, TLL, LTT, TLT, TTL, TTT).

Indirect modes, denoted also full skip modes (Fig. 3), include two reflection on the back wall, one after emission and one before the reception of the wave. It leads to sixteen indirect modes (LLLL, LLLT, LLTL …).

With the same reasoning, it is possible to take into account a large number of paths, generating as many reconstruction modes. Depending upon the selected path, in the case of crack-type defects, the signature of the specular echo along the defect and the one of the diffraction by the edges are additional information for the characterization of the defects.

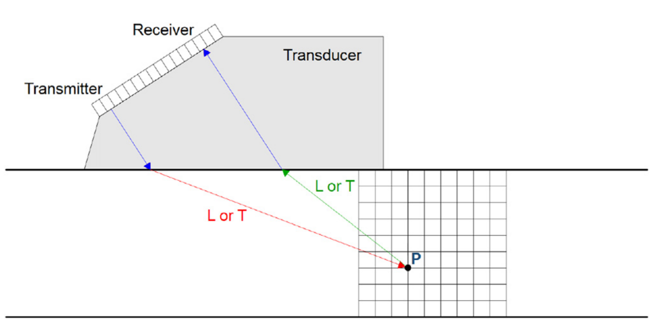

Fig. 1. Example of ultrasonic paths of the waves emitted by the array: direct mode.

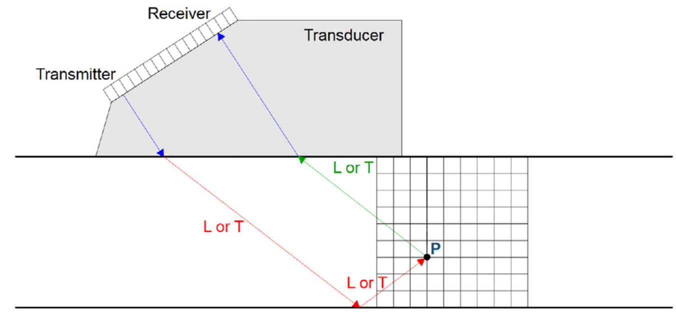

Fig. 2. Example of ultrasonic paths of the waves emitted by the array: corner echo mode.

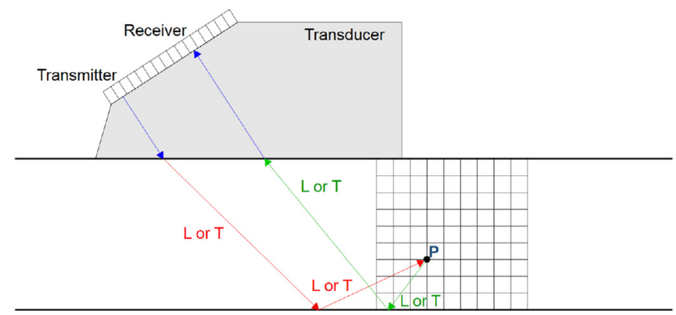

Fig. 3. Example of ultrasonic paths of the waves emitted by the array: indirect mode.

2.2. Diffraction echoes in TFM imaging

The conventional TFM (direct mode LL, TT) applied to crack, generally allows to find the signature of the diffraction [7] by the defect tips, which is relevant for the defect sizing.

The multidirectional behaviour of diffraction is a true advantage since it is little sensitive to defect orientation. However, diffraction energy is generally low and can be quickly embedded in noise or strongly attenuated in some materials. In addition, crack diffraction echoes are very similar to volumetric defects echoes, making it not easy to distinguish these two kinds of defect. One way to distinguish them is to exploit specular echoes which, when they exist, provide very different TFM images of both types of defects.

2.3. Specular echoes in TFM imaging

Specular echoes have the main advantage of being very energetic compared with diffraction echoes, but incident waves are reflected into a preferential direction according to the Snell-Descartes law, which depends on reflector orientation. Thus, during the TFM reconstruction, this is not all paths which respect this law. But if relevant paths are used, specular echoes, contained in the temporal signal, are spatially repositioned along the defect. This signature will make it possible to conclude upon the surface nature of the planar defect unambiguously.

2.4. TFM multi-modes

Several works [3–5,8,9] have shown the potential of multi-modes TFM imaging, particularly corner echo modes, for migrating specular echoes in the case of defects which interest us.

To illustrate the behaviour of multi-modes TFM imaging, the algorithm has been applied on experimental data, acquired for the inspection configuration in Fig. 4. The defect to be detected, 10 mm high, are inner surface-breaking notches which are generated artificially by electro-erosion, in ferritic steel piece.

The experimental acquisitions are obtained by an Imasonic array