SIMULATION AND APPLICATION OF PHASED ARRAY TECHNIQUES TO NDT OF COMPLEX STRUCTURES

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Abstract

NDT techniques based on phased array technology are more and more applied in various industrial context, as they provide improved adaptability to different inspection configurations. Among those configurations, two specific items have to be assessed that usually limit the inspection performances : irregular geometrical profile and complex materials. As a conventional probe is moved over an irregular profile (whether the probe is used at contact or immersion) , the radiated beam may be drastically modified in terms of sensitivity and orientation, so that the detection and characterisation of actual defects may not be ensured. This paper presents some studies of phased array techniques to overcome those limitations. The simulation tools developed at the French Atomic Energy Commission allows to predict the radiation of arbitrary transducers through complex specimen (in terms of geometry and structure), as well as the interaction with defects. Those models are based on semi-analytical kernels for computation time cost and numerical integration for generic applications. Those models were used to optimise the array probes design and the delay laws settings to master the ultrasonic beam over the complex structures. The applications presented in this paper deal with the simulation and experimental assessment of beam-forming techniques over a complex geometry specimen to preserve the beam characteristics, so that the inspections performances are maintained optimal through the whole scanning pattern. Experiments carried out on realistic mock-ups containing artificial defects show the efficiency of these techniques.

Introduction

Ultrasonic inspection of complex – in terms of material and geometry - structures has to overcome major limitations : unknown actual direction and focusing pattern of the transmitted beam, which leads to degraded performances for detection and identification of defects, complex interpretation of results due to spurious echoes or multiple modes, low signal-to-noise ratio due to sensitivity loss, etc... The use of multiple transducers and/or settings allow to perform different (and possibly redundant) techniques which may give some help. Obviously, phased array techniques provide an efficient alternative way to improve the adaptability and flexibility of the inspection method, compared to standard probes, as they may be used to master the ultrasonic beam thanks to delay or amplitude laws, for instance for any scanning position of the array probe moved over a varying profile. Phased array probes may also be used to transmit/receive waves through a complex layered specimen, thus to select and to perform the optimum inspection mode.

Modeling tools for inspection simulation

Modeling tools allow to simulate realistic NDE configurations inspections. These models (for ultrasonic as well as eddy current techniques), gathered in the Civa software [1-2], aim at conceiving, optimizing and simulating a wide range of NDE methods. Such models may also be used for experimental data inversion or complex results interpretation.

A broad range of realistic configurations has to be dealt with, in terms of :

- Specimen (isotropic or anisotropic, homogeneous or heterogenous, of simple or complex – possibly CAD – geometry)
- Probes : standard or advanced, e.g. phased arrays (of linear, matrix, annular or sectorial splitting patterns)
- Scatterers : calibration defects or complex shaped defects, solid inclusions
- Inspection method : pulse-echo, TOFD, tandem applications
- 3D, transient regime for realistic simulation

Such configurations also need to be modeled with high speed computation codes for parametrical studies. Semi-analytical models have therefore been developed : they include the simulation of the beam propagation [3] as well as defect scattering [4].

Beam computation through a complex bi-layered specimen

The example presented below is related to a specimen composed of two layers : a ferritic isotropic steel layer of sound velocities for compression and shear waves 5900 m/s and 3230 m/s (respectively) , and an anisotropic stainless steel part, of orthorombic structure, with the following elastic constants : $C_{11}=C_{22}=C_{33}=250; C_{12}=112; C_{13}=180; C_{23}=138; C_{44}=117; C_{55}=91; C_{66}=70$. In both cases, the density is assumed as 7.8 kg/dm^3. Moreover, the anisotropic layer has an irregular profile.

The objective is to use a phased array probe to preserve the beam characteristics in spite of distortions due to both the complex geometrical and anisotropic characteristics of this component. This probe is a linear array of 36x20 mm² aperture, 24 elements, 1.5 mm pitch (one half-wavelength in longitudinal mode at 2 MHz).

As a reference, the beam radiated by the array probe through a planar and isotropic ferritic steel specimen is shown on figure 1.a. A delay law, also displayed on this figure, is applied to the array probe to radiate 45° longitudinal waves focused at 20 mm depth.

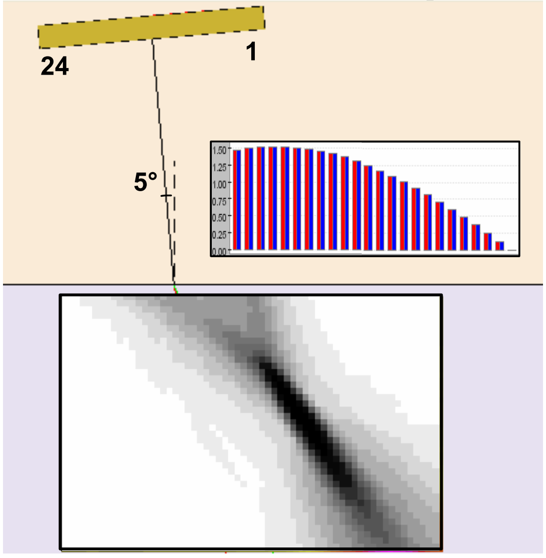

Figure 1: Field radiated through the planar isotropic steel surface.

The figure below shows the beam radiated through the anisotropic structure (homogeneous), if the same delay law is applied to the array probe. A slight modification of the refraction angle, as well as a deeper focusing point, are observed.

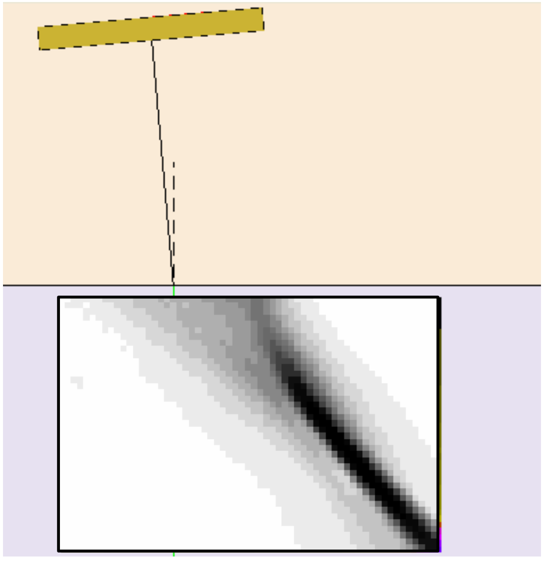

Figure 2: Field radiated through the planar anisotropic surface.

Figure below shows the beam distortions that occur as the transducer is located above the irregular profile. As the delay law computed relatively to the planar interface, the beam radiated through the complex profile shows very strong aberrations : the beam is deviated and sharp focusing effects are observed very close to the shortest curvature radius part of the profile.

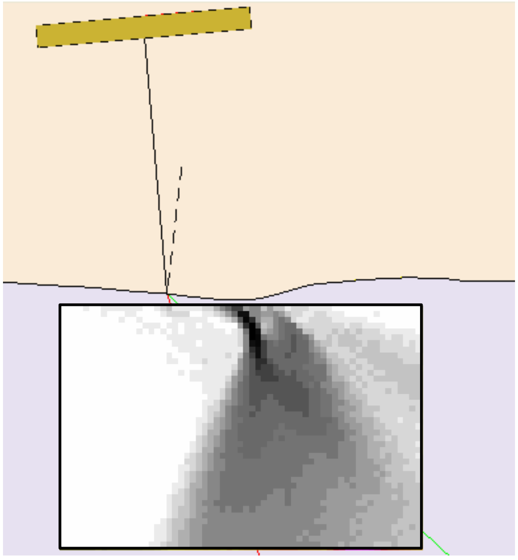

Figure 3: Field radiated through the irregular isotropic steel surface

The computation of delay laws taking account of both acoustical and geometrical characteristics of the upper complex and anisotropic upper layer allows to compensate these beam aberrations. Figure below shows the beam radiated to complex profile bi-layered specimen (the width of the complex and anisotropic layer is approximately 10 mm). One can observe on this figure that the beam is focused at the desired depth.

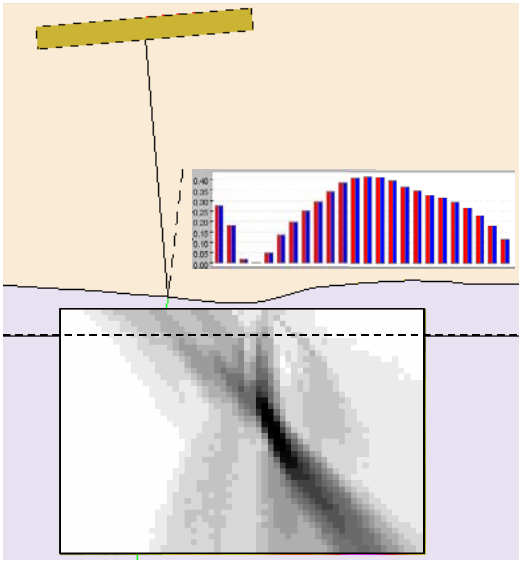

Figure 4 : Field radiated through the anisotropic/isotropic and irregular profile using adapted delay laws

Electronic commutation inspection through an irregular profile specimen

This second simulation example is related to the inspection of a specimen made of two parts : a planar one, and an irregular profile. This specimen contains two spherical holes of 1 mm radius, each of them being located below each part of the component, at 15 mm depth. A linear immersed phased array probe of 72x20 mm² aperture is used to scan this specimen using an electronic commutation technique : 16 elements over 48 are used at transmission and reception to insonify the specimen without any mechanical displacement, then this aperture of 16 elements is successively translated with a step of one element until to cover the whole array. This technique is classically apply to reach very high acquisition rates with a simplified mechanical device since one of the displacement direction can be replaced by an electronic commutation. However, for this configuration, it is required to take account of the complex part of this specimen.

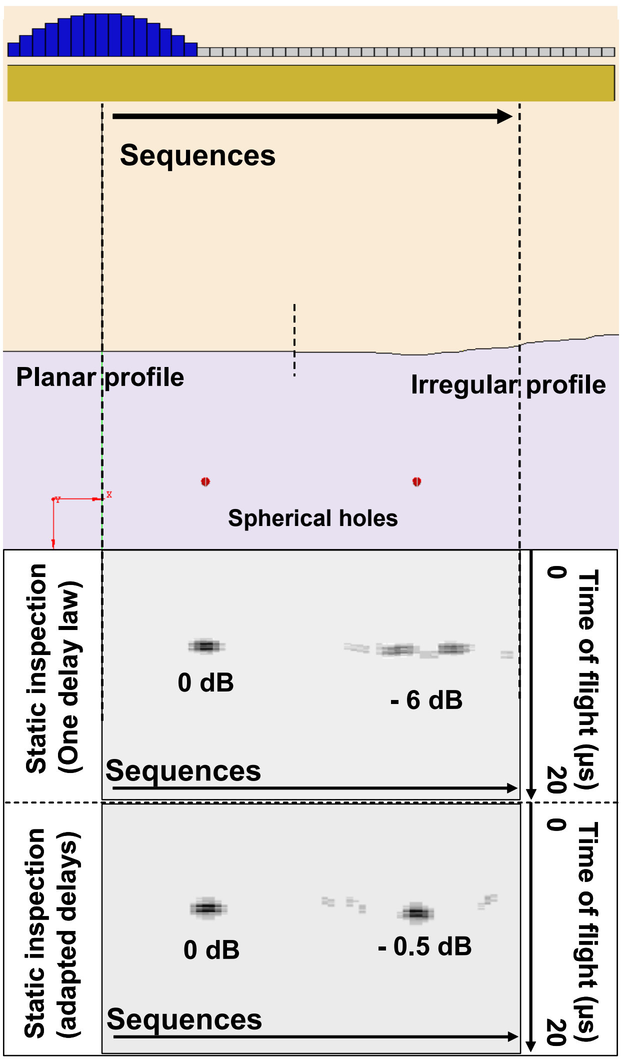

Figure 5: Electronic commutation with a linear array over a planar and complex profile. Inspection simulation using a static mode and a dynamic mode.

Two acquisition simulations are shown on the figure. The first one reproduces the "static" inspection. In that case the same delay law is apply to the array along for all sequences. This law has been computed in order to focus L0° waves at 15 mm, which is the depth of the two defects. The second one reproduces the "dynamic" inspection : a different delay law is computed and applied at each sequence of the moving aperture along the array probe.

The results of static inspection show that irregularity effects lead to very degraded performance for the detection of the defect located below the complex part. The maximum amplitude echo related to this defect is approximately 6 dB lower than the echo related to the defect located below the planar part. The echographic response of this defect also shows very strong phase fluctuations for a large scanning distance.

The dynamic inspection allows to recover the inspection performances for each sequence of the array probe. As shown on the echodynamic curves, the amplitude of the defect located below the complex part is almost as strong as the echo form the defect below the planar part. Although some phase fluctuations still remain, the echographic response of this defect is very similar to the response of the reference defect.

Adaptive inspection of an irregular specimen with a flexible array probe

This example is related to a specific phased array probe, that have been developed for several years at the French Atomic Energy Commission [5-6], in order to improve contact UT inspections of irregular surfaces. Such inspections may lead to degraded performances because of beam distortions occurring as the transducer lies on an irregular profile : loss of sensitivity due to the coupling layer between the specimen and the wedge, insonified area, beam misorientation or splitting, which may give rise to false calls or not detected flaws. To overcome these problems, the proposed smart flexible array probe acts as follows: its flexible radiating surface allows to get optimal coupling conditions, while an integrated deformation measure enables to determine optimized delay laws to preserve the beam characteristics in spite of the varying profile. This probe may therefore be used to perform beam-steering and electronic commutation, as described in the previous examples.

Figure 6 hereafter illustrates this principle and gives an example of beam computation. The array probe is a 20 elements of 2 mm pitch and 2 MHz frequency. The computed beam displayed on the figure is obtained using a delay law computed to radiate 45° longitudinal waves focused about 30 mm depth. This figure shows that one can control the beam orientation and depth focusing in spite of strong surface irregularities.

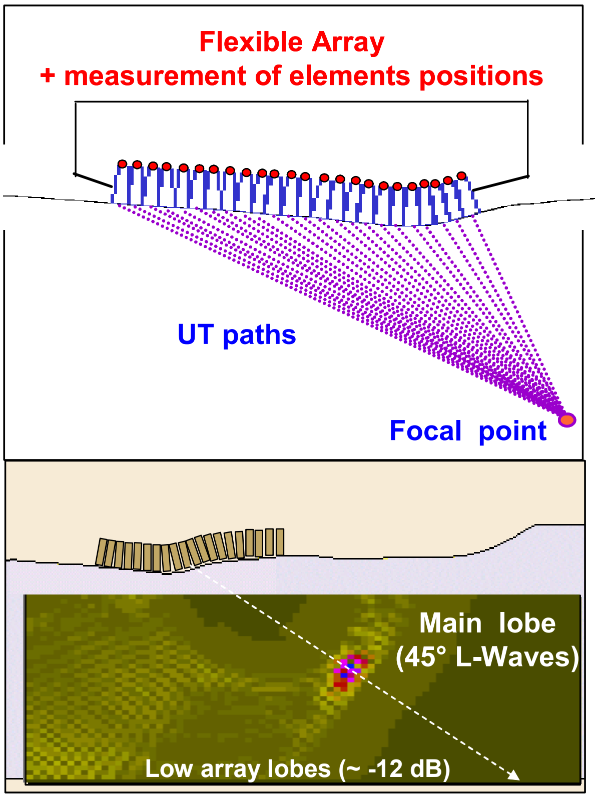

Figure 6: Principle and example of transient beam computation of a flexible array probe

Figure 7 shows two inspections performed on a complex machined mock-up, using a standard contact probe (with a solid wedge about 25 mm length) and the smart flexible array probe. Side drilled holes located at 20, 30, 40 and 50 mm depth should be detected using 45° shear waves.

The True Bscan image (Bscan image in spatial coordinates related to the piece) from the inspection carried out using the contact probe shows that some defects may not be detected (SDH numbered 2), not accurately located (SDH numbered 4) or detected using a very low sensitivity (SDH numbered 3). Only the first SDH is accurately detected and located, since the probe lies on a fairly planar surface.

The True Bscan image with the flexible array probe shows that all the defects are correctly detected and located. This acquisition was performed using 45° shear waves focused at 50 mm depth, using adapted delay law computed and applied at each scanning position to preserve the beam characteristics (orientation and depth focusing).

Conclusion

Modeling tools developed at CEA, in terms of wave propagation and echo formation simulations, allow both to optimise and predict performances of phased array techniques. Examples of beam and delay computation illustrate the ability of these models to predict and to compensate beam distortions or deviations which may occur through a complex shaped and/or anisotropic specimen. Electronic commutation techniques have also been simulated, which shows that one can efficiently compensate beam aberrations induced by an irregular profile. At last, the application of a flexible array transducer using optimal delays to match irregular profile specimen shows that one can greatly improve the performances compared to standard contact probes.

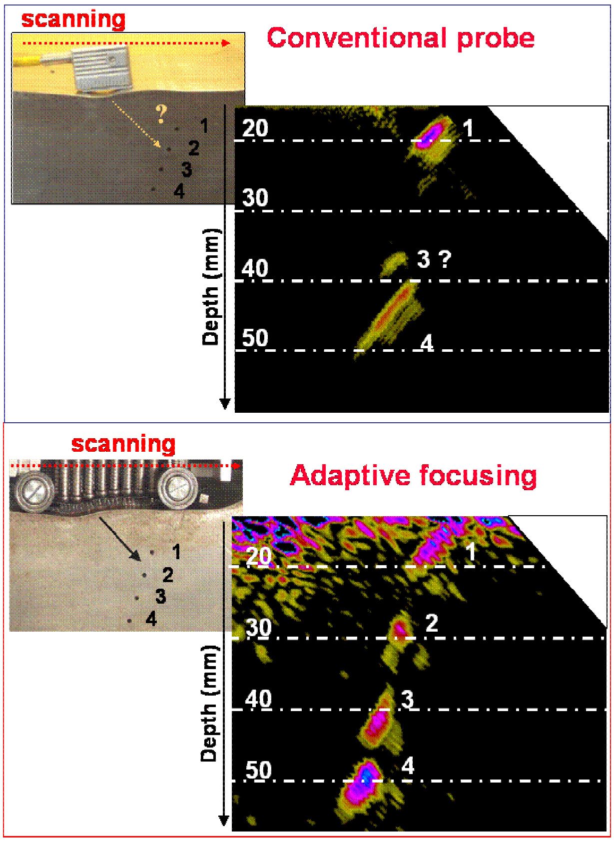

Figure 7: Inspection of a complex profile specimen with a standard contact probe (top) and the flexible array probe (bottom) using 45° shear waves

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