SELF-FOCUSING AND DEFECT CHARACTERIZATION WITH THE

FAUST SYSTEM

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INTRODUCTION

The FAUST (Focusing Adaptive UltraSonic Tomography) system was developed at
the French Atomic Energy Commission (CEA) to improve performances of ultrasonic non
destructive testing in terms of adaptability to various control configurations and defect
characterization. Unlike conventional techniques only allowing fixed focusing, this system
can dynamically modify the characteristics of the ultrasonic beam. This system relies on
optimized phased array transducers connected to a multi-channel acquisition system
supplying amplitude and delay laws allowing to drive the ultrasonic beam.

Previous works [1] have demonstrated the skills of this system for ultrasonic
beamforming. The reliability of the procedure was proved by comparison with theoretical
results, while comparisons with experimental results provided by conventional transducer
pointed out the improved capacities of the system.

In the first part of this paper, we briefly present the model used for the system
validation. This field computational model [2] developed at the CEA is used to design
optimized phased array transducers dedicated to NDE configurations (immersed
transducers used to focus through Fluid/Solid interfaces). Theoretical delay laws and
related ultrasonic fields are also calculated from this model.

In addition to its ability to dynamically form the ultrasonic beam by taking account of
the control configuration, we investigate in the second part of the paper the capabilities of
the system to extract informations from the received signals. The ability of the system to
store the signals received by all the elements of the array allows one to perform different
reconstruction procedures. Useful informations can be extracted from the received signals:
experimentally measured delay laws can be determined from reflected signals to obtain an
optimal imaging, while the related amplitude distribution over the array points out
geometrical characteristics of the reflector.
MODELING OF PHASED ARRAY AND ULTRASONIC FIELDS IN SOLIDS.

The model developed at CEA to predict ultrasonic fields radiated by wideband transducers through liquid-solid interfaces is based on a modification of the Rayleigh integral to take account of refraction. It is derived by means of the geometrical optics approximation [3] that introduces two factors: the transmission coefficient between the two media of elementary contributions from the source-points to the field-point and the so-called « divergence factor » ($DF$) of the transmitted rays, accounting for the principal radii of curvature of the refracted wavefronts (initially spherical in the coupling medium). This approximation allows us to express the elementary contribution to the transmitted displacement $u(r,t)$ generated by the incident field as

$$
du_{\alpha}(r,t) = DF(r_{TR},r) C_{\alpha}^s(\theta_f(r_{TR},r),t) \frac{v_n(t-T(r_{TR},r))}{2\pi} dS_{TR},
$$

where $r$ is a field-point in an elastic solid and $r_{TR}$ is a running point of elementary surface $dS_{TR}$ at the active surface of a transducer. The transducer is immersed in a liquid (of wavespeed $c$) and vibrates with (normal) particle velocity $v_n(r_{TR},t)$. $C_{\alpha}^s(\theta_f,t)$ is the time-dependent transmission coefficient relating the velocity potential in the fluid to the $\alpha$-displacement in the solid ($\alpha$ being either a $L$- or a $T$-wave) for an incident angle $\theta_f$, and $T$ is the travel-time from the source-point to the field-point. The path of stationary phase is obtained by applying Snell’s laws. The transmission coefficient is given by [4]

$$
C_{\alpha}^s(\theta_f,t) = A_{\alpha}^s(\theta_f) \left( \cos(\varphi_{\alpha}^s(\theta_f)) \delta(t) + \frac{\sin(\varphi_{\alpha}^s(\theta_f))}{\pi t} \right),
$$

where $A_{\alpha}^s$ and $\varphi_{\alpha}^s$ are the amplitude and phase of the transmission coefficient calculated in the harmonic regime. The wavepath between the source- and field-points is given by

$$
T(r_{TR},r) = \frac{R_f}{c} + \frac{R_a}{c_{\alpha}},
$$

where $R_f$ and $R_a$ are the lengths of the path of stationary phase in the fluid (wavespeed $c$) and in the solid (for the $\alpha = L,T$ wave of wavespeed $c_{\alpha}$, $\theta_{\alpha}$ being the refracted angle). The corresponding divergence factor for a plane interface $DF_{plane}$ is given by (see [5] for example),

$$
DF_{plane}^{-2}(r_{TR},r) = \left[ \left( R_f + R_a \frac{c_{\alpha}}{c} \right) \left( R_f + R_a \frac{c_{\alpha}}{c} \cos^2 \theta_f \right) \right].
$$

We can apply the Rayleigh integral representation and calculate the three components of the displacement field $\bar{u}_\alpha$ resulting from the motion of the whole transducer by integration on the emitting surface. In the case of a phased array, another discrete sum takes into account each element of surface $\Sigma_i$, transmitting pulses of amplitude $A_i$ delayed of $T_i$:
\[ u_n(r,t) = \sum_{i=1}^{N} A_i \int_{\Sigma_i} d\mathbf{u}^{(n)}(r,t - T_i) d\Sigma_i \quad (5) \]

Delay laws are extracted from the calculation of ray paths between the focal point in the solid and each element of the phased array in the liquid according to Snell’s laws. Then, delays are applied to the model to calculate the field.

Different transducer geometries have been studied in order to investigate functional properties. Annular transducers are usually used for axial focusing at different depths, whereas 1D or 2D linear arrays are used to steer the beam in 2 or 3 dimensions. To avoid distortions of the beam induced by the spatial discretization of the transducers with a non-prohibitive number of elements, optimized geometries are deduced from the model. The array geometries are designed in order to limit phase fluctuations from inner and outer edges of each element of the array, for the most constraintable configuration to be used. For an annular designed transducer, the phase difference between the inner and outer limit of a ring is limited to one sixth of the pulse period. Figure 1 shows the geometry of a 1 MHz annular array designed to perform axial focusing from 10 mm in steel, with a water height of 100 mm at normal incidence. The phased array contains 66 elements, 11 rings divided into 6 parts, on a plane circular surface of 93 mm diameter. Experiments have been carried out showing the reliability of the model [1, 2]. The principle of these experiments was to measure the field generated by the phased array, to be compared with the numerical results predicted by the model.

OPTIMIZED RECONSTRUCTION AND ADAPTIVE TRANSMISSION USING EXPERIMENTAL INFORMATION

The FAUST system is based on analog pulsers with digital counters allowing to adjust amplitude and delay parameters for each ultrasonic channel. The acquisition system has been elaborated to allow different acquisition and imaging procedures. Thus, all parameters involved in focusing - delay at Transmission and Reception, input voltage amplification at reception, and width of the transmitting pulse - can be adjusted for each acquisition. All RF signals from each channel can be stored to allow different reconstruction and imaging procedures at reception.

Figure 1. Annular phased array design to focus at varying depth at normal incidence.
Self-Focusing at Reception

In the case of a detected defect, an adaptive reconstruction procedure can be performed using the information received on each channel. The received signals are processed to extract experimental delay laws and thus to perform self focusing at reception on the defect.

The process requires a preliminary acquisition to record the signals on each element of the phased array. This first acquisition can be performed with a delay law adapted to focus in the region to be inspected. The process of extraction of a delay law requires two steps. First, the scanning position related to the higher amplitude received by the transducer is determined from the measurement of the cumulated amplitudes of all the signals. Secondly, for this relevant position experimental delay laws are measured for the maximum amplitude on each element with amplitude thresholding and time-windowing. Time windowing is useful to select a region to inspect and also to reject some disturbing effects like geometrical echoes for example (see figure 2).

In what follows, the same acquisition is used with different experimental delay laws at reconstruction. Experiments have been carried out with a calibration steel block that contains 3 side drilled holes of 2 mm diameter located at 43, 63 and 83 mm depth. The array transducer shown on figure 1 is used in pulse-echo mode, with a transmission focusing pattern at 65 mm depth in the inspected specimen.

Since the 63 mm depth hole is located at the focal depth, the extracted delay law can be compared to the theoretical one used at transmission. Figure 3 represents, for each element of the array, time delay at transmission and extracted time delay. A good agreement is observed. Because of the control configuration at normal incidence, both curves look like stairs where each steps correspond to a ring. The relative phase shift between each ring increases with the distance separating the defect from the ring.

Figure 2. Display of all signals received by each channel at the position related to the maximum energy received.
Figure 3. Comparison between theoretical delay law used at transmission and experimental delay law extracted on a defect at the focal depth.

Different reconstructions are performed that correspond to the delay laws extracted on each side drilled hole. The echodynamic curves represent the maximum of amplitude after reconstruction received by the phased array during its displacement over the holes. Figure 4 shows from left to right the echoes corresponding to the 83, 63 and 43 mm depth side drilled holes. These curves point out the efficiency of this technique. Using the adapted experimental delay law it becomes possible in each case to increase the lateral resolution and the signal to noise ratio in the reconstruction depth area. This process increases the focal area without any more control nor theoretical model.

Defect Characterization

As the experimental delay law is a result of the interaction between the defect and the ultrasonic beam, it contains some informations about the defect. We are now interested in comparing the delay laws extracted from the control of two defects of different shape: a side drilled hole and a flat bottomed hole both located at 63 mm depth. The first has a long and cylindrical shape of 2 mm diameter, while the second appears like a disc of 3 mm diameter smaller than the focal width of 6 mm.

Figure 4. Comparison of echodynamic curves obtained for different depth reconstruction delay laws: a) 43 mm, b) 63 mm and c) 83 mm.
Figure 5. Extracted delay laws obtained from a flat bottomed hole (a) and from a side drilled hole (b).

Figure 5 compares the experimental delay laws extracted on both defect. Both curves are composed with several steps regularly spaced that are characteristic of on-axis focus with an annular transducer. In the case of the flat bottomed hole, the steps are closer to the theoretical delay law used at transmission. The reason for this is that this defect, smaller than the focal width, may be considered as a point reflector unlike the side drilled hole.

The extraction process allows the determination of both time delay and amplitude distributions: the returned value is the amplitude for the measured time delay.

To increase the spatial resolution over the transducer surface, a 2D linear phased array composed of 6 mm squares was used. This array is composed of 96 elements on a flat circular surface of 73 mm diameter. All the elements generate pulses of 1 MHz central frequency. The testing configuration is the same as for the annular transducer. The main difference between both transducers results from the smaller diameter of the linear array that provides a focal width of 8 mm at 60 mm depth.

A new display has been developed that represents the amplitude distribution directly on the transducer surface using grey scale (dark grey represents high amplitude). Figure 6 uses this view to represent the amplitude distribution resulting from the control of the flat bottomed hole and of the side drilled hole. These visualizations clearly point out the distribution of field transmitted from each reflector to the transducer. In the case of the flat bottomed hole, the amplitude decreases symmetrically from the middle to the edges of the array. This distribution well reproduces the divergence of the field transmitted from the flat little disc. In the other cases, the field transmitted from the side drilled hole has a significant distribution over the phased array surface: high amplitude are located along an axis and decrease on both sides of this axis. This amplitude line is perpendicular to the axis of the hole. Rotating the transducer makes this axis rotate too. Two phenomena contribute to this result: on the one hand, the cylindrical shape of the reflector scatters the ultrasonic

Figure 6. Display of amplitude distribution received at the transducer surface from flat bottomed hole (a), from side drilled hole (b) and from the side drilled hole after a transducer rotation (c).
beam perpendicularly to the reflector axis, and on the other hand the transducer visualization shows the field transmitted from a thin long reflector. In the present case, the focal area is 8 mm width and the cylinder diameter is 2 mm width, so the extension of the reflector may have a stronger effect than the cylindrical form. Thus the analysis of the signals received on each part of the array brings informations on the defect shape and its orientation.

CONCLUSION

A model, predicting ultrasonic fields radiated through liquid-solid interface, is used both to design arrays of optimized shape and to calculate theoretical delay and amplitude laws. This model initializes all the necessary acquisition parameters by taking account of the testing configuration.

Different procedures are presented which point out the capabilities and the advantages of the FAUST system. In addition to the conventional ability to drive the ultrasonic beam, the FAUST system can use the information received by each element of the array to perform self focusing at reception and defect characterization. Self focusing increases the signal-to-noise ratio and the spatial resolution at reception, while the analysis of the amplitude received on each element of the phased array allows to determine some characteristics of the defect shape and orientation.

Experiments in progress aim at extending the analysis of received information and its applications to real defects. Other works in progress use the ability of the system to store all received signals coupled to electronically parametrizing of the phased array, to adapt in real time the system to the testing configuration (adaptation to degraded surface condition [6], to complicated surface geometry). Such a system offers a wide range of application in the field of non destructive testing.

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REFERENCES