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► To cite this version:

Vincent Dorval, Nicolas Leymarie, Sylvain Chatillon. Ray-based simulation of defect echoes for ultrasonic non destructive testing. *Physics Procedia*, 2015, 70, pp.636-639. 10.1016/j.phpro.2015.08.063 . cea-01827677

HAL Id: cea-01827677

<https://cea.hal.science/cea-01827677>

Submitted on 11 Jan 2024

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2015 International Congress on Ultrasonics, 2015 ICU Metz

Ray-based simulation of defect echoes for ultrasonic Non Destructive Testing

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Abstract

In order to compute flaw echoes, semi-analytical models commonly use scattering coefficients deduced from plane-wave approximations for incidence and observation waves. The proposed approach aims at improving the accuracy of methods used in the ultrasonic NDT module of the Civa simulation software. It relies on a representation of the ultrasonic field as a sum of rays, where plane wave approximations are applied to each ray, as opposed to the total field, allowing more accurate echo predictions. Several cases that illustrate the improvement brought by this new method are presented, with comparisons to results obtained by a finite element model.

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Peer-review under responsibility of the Scientific Committee of 2015 ICU Metz.

Keywords: UT simulation, plane-wave approximation, rays.

1. Introduction

There is an interest in simulations of ultrasonic Non Destructive Testing (NDT), as they can help designing inspection techniques and interpreting measurements. Numerical simulation methods and semi-analytical simulation methods can be distinguished. The former category includes Finite Element methods and Boundary Element methods. The latter relies on various exact or approximate analytical models that yield expressions of the fields radiated by probes and diffracted by flaws. Compared to numerical methods, semi-analytical methods allow for significantly faster computations but tend to be less generic and limited by their approximations. The work of

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Thompson and Gray [1] and of Schmerr and Song [2] and the UT inspection module of the Civa software are notable examples of semi-analytical approaches of ultrasonic NDT.

All the aforementioned methods rely on scattering models that express scattering amplitudes as a function of the directions and polarizations of incident and observed waves. As a consequence, they require that ultrasonic fields are approximated as plane waves or quasi-plane waves whose directions and polarizations can be identified. This approximation can lead to significant inaccuracies in unfavorable cases, such as for wide probe apertures, outside of the focal region, or for distortions of the beam due to irregular part geometries.

The work presented here aims at replacing the approximation by a more accurate one, where the fields are represented as several plane waves and not as a single one. The motivation of this work is the improvement of the Civa models. In this context, a representation of the field as a sum of ray is readily available, since fields are computed using a paraxial ray method as described by Gengembre and Lhémy [3]. Nevertheless, the approach could be applied to any semi-analytical simulation method. Depending on their representation of the fields, different techniques to express them as a set of rays or plane waves might be necessary.

2. Expression of the echoes

Using the expression given in the frequency domain by Auld [4] and introducing an input spectrum S_i , the following expression for the spectrum S_e of the echo response of a flaw F is obtained:

$$S_e = S_i \int_{\Sigma_F} (\mathbf{u}_{Em} \cdot \mathbf{T}_{ReF} - \mathbf{u}_{ReF} \cdot \mathbf{T}_{Em}) d\Sigma. \quad (1)$$

S_i is deduced from the electric signal that enters the acquisition chain and also accounts for all the filtering effects not related to ultrasonic phenomena. It is considered as an input parameter of the model. \mathbf{u} and \mathbf{T} refer respectively to the displacement vector and to the stress tensor projected on the normal of the defect of ultrasonic fields. The indexes Em and ReF correspond to two configurations. Em is the ultrasonic field radiated by the emitting probe when the flaw is absent. ReF is the ultrasonic field radiated by the receiving probe when it is acting as an emitter and when the flaw is present. Σ_F is the surface of the flaw. S_e , S_i and ultrasonic fields all depend on the frequency.

Equation (1) can also be written in the time domain by replacing multiplications with convolutions. In practice, the implementations whose results are presented in this communication mainly rely on time domain expressions.

A usual approach for semi-analytical simulation methods to evaluate that equation takes two steps: first, they compute the fields radiated by the probe in the absence of the flaw. Then, they calculate an interaction coefficient C_F that depends on the directions \mathbf{d} and polarizations \mathbf{p} of a plane-wave approximation of the fields. They do not explicitly calculate the received field in the presence of the flaw ReF : the coefficient C_F expresses both the effect of the flaw on the received field and its projection of the emitted field. Since the projection on the vector quantities is handled by C_F , only the amplitudes A of the fields in the absence of flaw are necessary in the expression. This allows replacing the integrand of (1) by the following product:

$$S_e^{plane-wave} = S_i \int_{\Sigma_F} A_{Em} A_{Re} C_F(\mathbf{d}_{Em}, \mathbf{p}_{Em}, \mathbf{d}_{Re}, \mathbf{p}_{Re}) d\Sigma. \quad (2)$$

The ray-based method aims at a lesser degree of approximation than equation (2). The interaction is calculated for all the pairs of emitted and received ray that compose the two fields. Plane-wave approximations are used to calculate these interactions, but they are done for rays, not for entire field. Hence the following expression of the echo is obtained, where the contributions are summed over the N_{Em} and N_{Re} rays that compose the emitted and received fields:

$$S_e^{ray-based} = S_i \int_{\Sigma_F} \sum_{i=1}^{N_{Em}} \sum_j^{N_{Re}} A_{Em}^i A_{Re}^j C_F(\mathbf{d}_{Em}^i, \mathbf{p}_{Em}^i, \mathbf{d}_{Re}^j, \mathbf{p}_{Re}^j) d\Sigma. \quad (3)$$

3. Algorithmic considerations

Evaluating directly equation (3) would involve performing $N_{Em} \cdot N_{Re}$ evaluations of the function C_F for any given point of the defect, where equation (2) only required one evaluation. This can lead to severe increases in computation time, since, in practice, the number of rays can often be in the hundreds. In order to limit that increase, the coefficient C_F is decomposed into three terms: one that only depends on the emission quantities \mathbf{d}_{Em} and \mathbf{p}_{Em} , one that only depend on the reception quantities \mathbf{d}_{Re} and \mathbf{p}_{Re} , and one that depends on all. The first two terms need to be computed only N_{Em} and N_{Re} times respectively, only the third one needs to be computed $N_{Em} \cdot N_{Re}$ times. Choosing the decomposition so that the third term can be rapidly computed allows the approach to remain computationally efficient. It is possible, for some models, to entirely eliminate that third term.

Appropriate decomposition have to be implemented for all the flaws scattering models involved in the simulation. In the case of Civa, it includes the Kirchhoff, GTD, PTD and Born approximations as well as exact models for cylinders and spheres, as described by Darmon *et al.* [5]. Though the general principles of the decomposition remain the same, different solutions have to be found for each flaw scattering model depending on its specificities. For example, in the Kirchhoff approximation, diffraction coefficients can be suitably expressed as a combination of vectors such as the one of the integrand of equation (1), where quantities depending on emission and reception are clearly separated.

4. Results

The results presented in this section aim at illustrating a few notable benefits of the ray-based model compared to the one based on the plane wave approximation of the entire field. Results from the two models are compared to those of a finite element model used as a reference: the Civa-Athena model, described by Leymarie *et al.* [6].

The configurations presented here share the following characteristics: the specimen inspected is a steel block containing a side-drilled hole with a 2mm diameter and immersed in water. The probe is circular with a 12.7mm diameter and a 2MHz central frequency.

Figure 1 shows a simulated inspection configuration in normal incidence where a scan was performed by moving the probe from a distance of 100mm of the block to a distance of 0mm. The side drilled hole is at a 15mm depth. Results show that the ray-based method is in better agreement with finite elements than the plane-wave approximation, especially in the near field. This is interpreted as a consequence of the better accounting of the effects on probe aperture, which increases in the near-field, by the ray-based method.

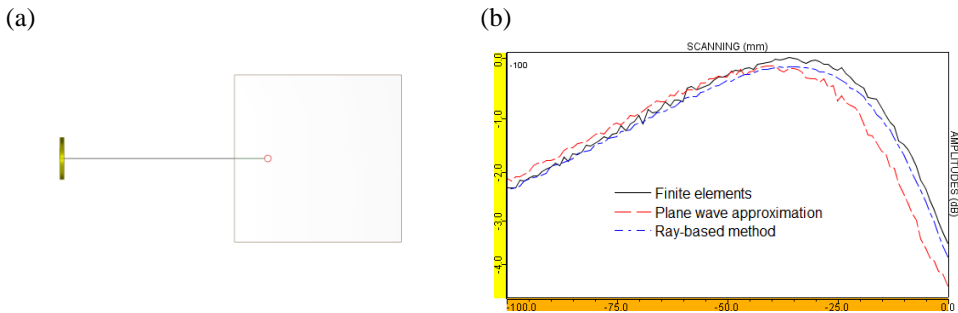


Fig. 1. (a) Simulated setup for the illustration of near-field effects; (b) Maximum amplitude of the echo from the side-drilled hole as a function of probe distance.

Figure 2 shows signals simulated for a configuration similar to the one of Figure 1 with the probe 10mm away for the specimen, with two probe positions: above the side-drilled hole and shifted 25mm sideways. All models predict similar shapes for the signals at the first position, but at the second one the effects of probe diffraction that spread the signals are only predicted by the finite elements and ray-based models. The plane-wave approximation is unable to reproduce it because a single plane wave implies a single time-of-flight, whereas probe diffraction is related to the width of the probe and the range of times-of-flight it implies.

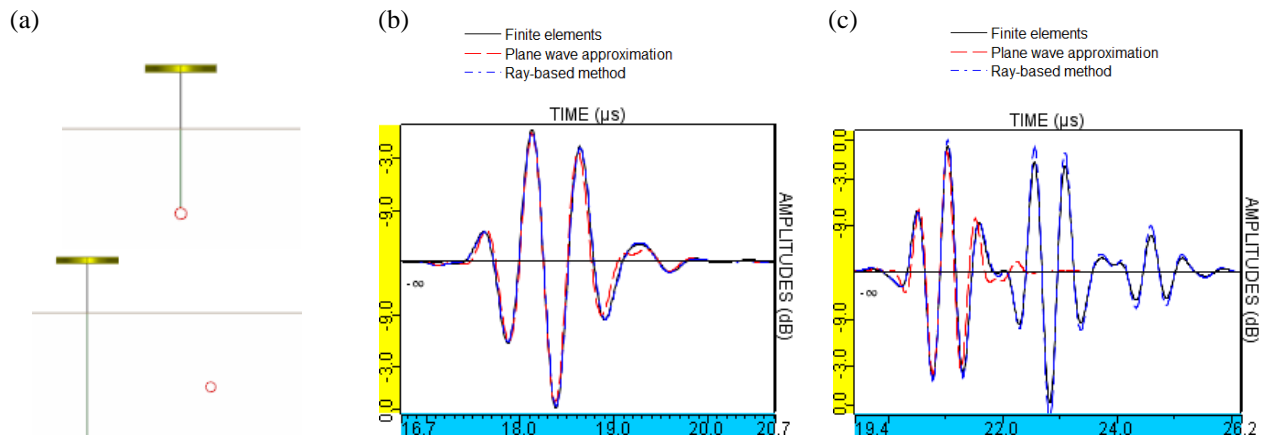


Fig. 2. (a) Probe positions; (b) Signals simulated when the probe is above the SDH; (c) Signals simulated when the probe is shifted 25mm away.

In the example of Figure 1, results were computed in 786s for finite elements, 0.8s for plane-wave model and 1.2s for the new ray-based model. In the example of Figure 2, they were computed in 1320s, 0.8s and 4.7s respectively. The increase in computational cost of the new model compared to the plane-wave approximation is therefore limited. Besides, these times were obtained with a preliminary implementation of the model and are expected to be reduced by further optimizations.

5. Conclusion

These examples illustrate that, even in very simple inspection configurations, the new ray-based model is able to provide an improvement compared to the plane-wave approximation. Its benefits were also observed in other cases not presented here, including cases where the ultrasonic beams are distorted or split due to part geometry, or when the response of the defect is very sensitive to wave direction (crack tip diffraction, for example). In general, the ability of the ray-based method to take into account several directions and several times-of-flight makes it more accurate than the plane-wave approximation. In a number of cases, it approaches the accuracy of the finite element method with a significantly lower computational cost.

References

- [1] Thompson, R. B., Gray, T. A., 1983, A model relating ultrasonic scattering measurements through liquid–solid interfaces to unbounded medium scattering amplitudes, *Journal of the Acoustical Society of America*, 74 (4), 1279-1290.
- [2] Schmerr, L. W., Song, J. S., 2007, *Ultrasonic Nondestructive Evaluation Systems: Models and Measurements*, Springer, New York.
- [3] Gengembre, N., Lhémy, A., 2000, Calculation of wideband ultrasonic fields radiated by water-coupled transducers into heterogeneous and anisotropic media, *Review of Progress in QNDE*, 19, 977-984.
- [4] Auld, B. A., 1979, General electromechanical reciprocity relations applied to the calculation of elastic wave scattering coefficients, *Wave Motion*, 1, 3-10.
- [5] Darmon, M., Leymarie, N., Chatillon, S., Mahaut, S., 2009, Modelling of scattering of ultrasounds by flaws for NDT, *Ultrasonic Wave Propagation in Non Homogeneous Media*, Springer Proceedings in Physics, Springer Berlin, 128, 61-71.
- [6] Leymarie, N., Calmon, P., Fouquet, T., Schumm, A., 2006, A Semi-analytical FEM Hybrid Model for Ultrasonic Simulation of Complicated Wave Defect Interaction, in *International Conference on NDE in relation to structural Integrity for Nuclear and Pressurised Component 2006*.