Optimisation de la couverture en sensibilité pour l’inspection ultrasonore de pièces de géométrie complexe 3D en utilisant le logiciel CIVA

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RÉSUMÉ
Le développement d’une méthode d’inspection par ultrasons pour des pièces de géométrie complexe est souvent un processus difficile. Dans le cadre des qualifications de type « général », le but est de garantir la détection d’un éventuel défaut, avec une certaine sensibilité, quelle que soit sa position dans une zone d’examen donnée. EDF et le CEA ont étudié ensemble une méthodologie générale permettant, à l’aide du logiciel CIVA, d’aider à déterminer la trajectoire d’une sonde multi-éléments et un ensemble de lois focales associées adaptés à l’inspection d’une zone d’examen dans une pièce complexe.

La première étape consiste à déterminer géométriquement un nombre optimal de positions de la sonde pour inspecter la zone d’examen complète. Une trajectoire basée sur ces points optimaux peut ensuite être calculée ainsi que les lois focales associées. Ces lois sont utilisées pour dévier le faisceau ultrasonore pour couvrir toute la zone d’examen lorsque la sonde suit la trajectoire calculée précédemment. Enfin, des cartes de sensibilité sont calculées afin d’évaluer la qualité de la solution (la trajectoire et les lois de retard associées) et de vérifier que les performances en sensibilité requises sont bien atteintes.

Cette méthodologie, développée en utilisant les outils logiciels de CIVA, sera illustrée en considérant le cas de l’inspection d’une entaille située dans le congé de raccordement interne d’un piquage en utilisant une sonde matricielle flexible.

INTRODUCTION
The development of an ultrasonic inspection method to guarantee the detection of a critical defect whatever its position in a given examination zone is often a long process when phased array probes are involved on complex 3D geometries. In addition to the practical difficulty of the implementation of such an inspection technique (use of a robot, synchronization between the robot and the electronic system, precision on the positioning of the probe at the surface of the specimen,...), it must be demonstrated that the targeted sensitivity is guaranteed for detection of a critical defect whatever its position in the
examination zone. The use of the simulation is very useful to construct the solution and anticipate its performances before the practical implementation.

This methodology is developed using the CIVA software and it will be illustrated considering the case of an examination zone where a notch has to be detected in the internal surface of a nozzle (Figure 1) using a flexible matrix probe of 12x7 elements at 2 MHz (Figure 2).

(a)  
(b)  
*Figure 1: (a) Example of a nozzle, (b) Illustration of the examination zone in the internal surface of the nozzle.*

*Figure 2: Flexible matrix array probe.*

**METHODOLOGY AND RESULTS**

The principle of the methodology is the following. After the definition of the examination zone by the user (a), the first step consists in geometrically determining a set of optimal probe positions to inspect the whole examination zone (b). Based on these optimal points, the user defines a probe trajectory (c). Then, the focal laws associated to this trajectory are calculated by CIVA. These focal parameters are used to steer the ultrasonic beam in order to avoid any zone that is not properly insonified when the probe travels along the previously determined trajectory. Finally, sensitivity maps are calculated to evaluate the effectiveness of the proposed solution (the trajectory and associated focal laws) in order to verify that the sensitivity requirements are met (d).
Notations: The position and orientation of the probe at the surface of the specimen is described Figure 3. $R$ is the distance to the center of the secondary pipe, $\theta$ the angle to the axis of the primary pipe and $\beta$ the orientation of the probe. $Y$, the distance from the top of the nozzle, is specified by the geometry of the structure.

![Diagram of probe positioning](image1)

Figure 3: Positioning of the probe at the surface of the specimen.

DEFINITION OF THE EXAMINATION ZONE

The examination zone is the zone on which the performances of the inspection method must be guaranteed. In CIVA this zone is defined by describing the position of a set of defects. The aim is to guarantee to detect all these defects, which will be considered to be equivalent to cover the whole examination zone. This is true only if the density of the defects is sufficient (compared to the size of the focal spot) to be representative of all the possible positions inside the examination zone. In this paper the defects are located in the internal surface of the nozzle, from $\theta = 0^\circ$ to $\theta = 90^\circ$ (Figure 4). We have considered $N = 22 \times 5 = 110$ defects to define the examination zone.

![Diagram of examination zone](image2)

Figure 4: In this paper the examination zone is the internal fillet of the nozzle.
OPTIMAL PROBE POSITIONS AND ACCESSIBILITY ZONES

The next step of the methodology consists in determining a set of optimal probe positions from which all the defects of the examination zone are detected.

For each defect an acoustic ray is traced from a focal point on the defect to the surface of the specimen. The angle of the ray and the position of the focal spot on the defect are defined by the user and are the same for all the defects of the examination zone (Figure 5). The points at the surface are considered to be the optimal positions of the probe to inspect the whole examination zone (Figure 6).

Figure 5: CIVA GUI for the definition of the angle of the acoustic beam and the position of the focal spot on each defect of the examination zone.

Figure 6: Set of optimal probe positions at the surface of the specimen for an incident angle of 45° on the defects.
However, in some cases it is not possible to place the probe on some or all of these positions. To deal with these cases the user can define a tolerance on the incident angle (Figure 7). He can also limit the parts of the specimens that are accessible, i.e. on which the “optimal” positions can be found: this is the accessibility zone. These parts are selected among those defined on Figure 8. A margin can also be defined to avoid positions being too close to the boundaries of the selected parts. This margin is a rough method to take into account the volume of the probe that can restrict its accessibility.

![Figure 7: Tolerance on the incident angle on the defect.](image7)

The “optimal” positions (without any accessibility constraint) of Figure 6 were on the internal surface of the nozzle. Anyway, if the only accessible zone is the primary pipe with a margin of half of the probe diameter and a tolerance of [-30°; +10°] on the incident angle on the defect, we obtain a new set of “optimal” probe positions presented Figure 9. The “optimal” positions are now at the boundary of the accessibility zone.

![Figure 8: Accessibility zone.](image8)
TRAJECTORY AND FOCAL LAWS

These positions are used to guide the user for its definition of the probe trajectory. Indeed, the trajectory is not calculated automatically by CIVA but chosen and parameterized by the user, and must be as close as possible to the optimal points determined previously.

From this trajectory (represented on the left of Figure 10 for the present configuration), CIVA computes a matrix of focal parameters adapted to the inspection of the examination zone, the electronic delay laws can therefore compensate the fact that the probe position and orientation is not optimal on the trajectory. On each point of the trajectory the full set (matrix) of focal laws is applied. These focal parameters are computed to guarantee that for each defect of the examination zone at least one law focuses on it when the probe travels along the trajectory. This matrix consists in focusing at different refraction and skew angles defined from the center of the probe (Figure 11).
The algorithm is the following:

- **Initialization of** $\theta_{a \min}, \theta_{a \max}, \varphi_{a \min}, \varphi_{a \max} = 0$
- **For each defect of the examination zone:**
  - The closest point of the trajectory to the “optimal” probe position determined previously is considered as the new position from which the defect will be detected (Figure 12)
  - From this point the refraction angle $\theta_a$ and the skew angle $\varphi_a$ necessary to focus on the defect are determined
  - If $\theta_a$ (respectively $\varphi_a$) is outside the actual values of $[\theta_{a \min}, \theta_{a \max}]$ (resp. $[\varphi_{a \min}, \varphi_{a \max}]$), then update the new boundary $\theta_{a \min}$ or $\theta_{a \max}$ (resp. $\varphi_{a \min}$ or $\varphi_{a \max}$)

At the end of the algorithm the minimal deviation in every direction ($\theta_{a \min}, \theta_{a \max}, \varphi_{a \min}, \varphi_{a \max}$) necessary to focus at least once on each defect from the trajectory is obtained. The user then defines the number of laws (= density of the matrix of focal spots) in accordance with the focal spot size to have a sufficient overlaying between two adjacent shots.

For the trajectory presented previously the matrix has $M$ (refraction) $\times$ $L$ (skew) = $13 \times 13 = 169$ focal parameters (Figure 13).
SENSITIVITY MAPS

In order to verify the quality of the solution (trajectory + associated focal parameters) determined in the previous steps, sensitivity maps are computed. The procedure used to compute these cartographies is the following:

- For each defect the probe is placed at the position on the trajectory determined in the previous paragraph (projection of the optimal position on the trajectory). The echo from the defect is computed using CIVA defect response module for each of the focal laws of the matrix.

At the end of these \( N \times M \times L \) (defects x refraction angles x skew angles) computations, the results are calibrated determining the response of side drilled holes (SDH) of 3 mm situated at the focal points for each of the \( M \) shots without skew (Figure 14). The value of calibration is kept for the \( L \) shots with the same refraction angle but different skew.
Examples of sensitivity maps for different law of the matrix are presented Figure 15. As expected on a complex 3D geometry that requires the use of a phased array probe, it can be noticed that each law has a limited coverage of the examination zone. However, considering the full set of focal laws we obtain the global sensitivity map of Figure 16, which shows that the full examination zone is inspected with a sufficient sensitivity. The closest region to the secondary cylinder is the most difficult to inspect (lowest amplitude) since it requires the most important angle of acoustic skew from the probe (in that case 20°). Due to the rectangular shape of the array of the probe’s piezoelectric elements, steering the beam with an important skew with this probe is not favorable which can explain the reduced sensitivity in this region.
CONCLUSIONS

We have presented in this paper a methodology to determine a trajectory and the associated focal parameters to inspect a given examination zone in a specimen of complex geometry taking into account accessibility constraints. The methodology provides the required beam steering (skew in particular) that the probe must be able to ensure given the constraints.

The relevance of the solution is evaluated through the computation of sensitivity maps which can highlight zones for which inspection is difficult.

In the context of UT development for the inspection of a 3D complex component, these simulation tools seem to be very helpful to design the NDE process; of course the solution derived from this methodology would have to be compared to experiments to validate the performances while developing the process.

The simulation tools were developed in order to be applicable to various configurations (other geometries, mono-element probes, …) and the methodology has been successfully simulated on a specific application (inspection of the internal surface of the nozzle using a flexible matrix array probe). This tool is not yet available in a CIVA commercial version and is being progressively implemented into the software.